# MICROMORPHOLOGICAL AND MINERALOGICAL EVALUATION OF ULTISOLS DEVELOPED OVER DIFFERENT PARENT MATERIALS IN NORTHERN GUINEA SAVANNAH, NIGERIA

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**NIGERIA**

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## DECLARATION

I declare that the contents of this dissertation entitled 'Micromorphological and mineralogical evaluation of Ultisols developed over different parent materials in northern Guinea Savannah, Nigeria' has been performed by me in the Department of Soil Science under the supervision of Professors B.A. Raji, J.O. Agbenin and Dr. W.B. Malgwi.

The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree or diploma at any university.

HASSAN, Alhaji Muhammad

Name of student Signature Date

## CERTIFICATION

This dissertation entitled "MICROMORPHOLOGICAL AND MINERALOGICAL EVALUATION OF ULTISOLS DEVELOPED OVER DIFFERENT PARENT MATERIALS IN NORTHERN GUINEA SAVANNAH, NIGERIA'' by Hassan, Alhaji Muhammad, meets the regulations governing the award of the degree of Doctor of Philosophy of the Ahmadu Bello University, Zaria and is approved for its contribution to knowledge and literary presentation.

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## ABSTRACT

Micromorphological and mineralogical properties can provide insights and aid interpretation of soil classification. Field and laboratory studies were conducted on soil formed in two different parent materials in Plateau State. With a view to characterize physical, chemical and morphological properties of selected soils, investigating the micromorphological and mineralogical properties of Ultisols derived from basalts and granite-gneisses, and determining if differences in properties could be used in the classification of Ultisols at the lower levels of Soil Taxonomy and World Reference Base (WRB). Based on the geological map sheet used to identify different parent materials, eight (8) profiles were dung and described. Results obtained revealed that micromorphology of surface horizon in basaltic derived soils shows a porous (compound packing) and crumb microstructure. The groundmass consists mainly of fine iron hydroxides in crystallitic micromass. In the subsoil horizons, the microstructure varied between vughs and channels with subangular shapes. Compound coatings of radial distributed and isotropic ("amorphous") iron hydroxides line the pores. In many cases, several coatings of isotropic iron hydroxides, differing in colour intensity, fill the pores. In granitic soils, surface horizon was mainly crumb with vughs and channels microstructure. Complete infillings coating clay, orthic typic nodules and subhedral crystals, red and yellow mineral colour indicate finely dispersed hematite/some amorphous Fe gels and goethite respectively. The subsurface horizons were mainly vughy microstructure. Anhedral to euhedral crystal mineral grains with interference colour, strongly impregnated groundmass iron hydroxides nodules (anorthic and orthic) with black dotted micromass. On the whole, granitic derived parent material compares in terms of pedofeatures characteristics, speckled groundmass and vughy microstructures. Micromophologically, old parent materials have porphyric c/f related distribution pattern, low

c/f 2u ratios, poor sorting and common infilling and coatings of voids as compared to enaulic c/f related distribution, high c/f 2u ratio in young parent materials. Similarly, self-mulching as a pedofeatures was observed in basaltic soils as opposed to granite parent material. The micromorphological properties of all soils are affected by their parent materials and genesis. The coarser textured soils have compact grain structure while the finer-textured soils have an apedal microstructure. Mineralogical composition of the soils were similar (kaolinite, mica-vermiculite, chlorite, rutile, quartz, goethite, hematite and gibbsite) between parent materials but different in proportions, except for gibbsite and chlorite which was absent in granitic derived soils and quartz, rutile and halloysite were absent in basaltic soils. According to the USDA system of classification, profiles BST01 and BST02 (basaltic PM) and GNT03 and GNT04 (granite PM) were classified as Typic Haplustults while GNT02 was Typic Plinthaquults. The evidence of pedofeatures such as porphyric c/f and typic orthic nodules confirms highly weathered soils. Profiles BST03 and BST04 are classified as Andic Haplustepts and GNT01 as Oxic Haplustepts. In the FAO/WRB system, profiles BST01 and BST02 are classified as Ferralic Acrisols, BST03 and BST04 as Andic Cambisols. While profiles GNT02, GNT03 and GNT04 are classified as Haplic Acrisols, GNT01 as Arenic Cambisols. Therefore, the distinct differences in micromorphological features among these soils might be employed as diagnostic horizons to differentiate soils while the quantifiable micromorphological features might potentially be selected as diagnostic indices for soil taxonomic classification.

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# CHAPTER ONE

# INTRODUCTION

## 1.1 Background Information

Ultisols are highly weathered soils which occupy about 9% of the pedosphere (Brady and Weil 1999). In Nigeria, particularly in the Guinea Savannahs, Ultisols, Inceptisols, Entisols, Alfisols and Vertisols constitute the bulk of the soils, while Ultisols take greater percentage (Harpstead, 1973; Hill and Rackham, 1974; Ojanuga, 1979; Kparmwang 1993; Olowolafe 1995). The processes active in the formation of Ultisols include dissolution of clay and silt-sized quartz, accumulation of aluminium and ferric iron, translocation of clay and clay sized minerals, neoformation of clay, and segregation of aluminium and iron increasing into plinthite and concretions (Brady and Weil, 1999). Ultisols have been reported to develop under moist condition in warm tropical climates on old land surfaces, under different vegetation (Brady and Weil, 1999).

As such, Ultisols are more highly weathered and acidic than Alfisols but less acid than Spodosols and less weathered than Oxisols. Ultisols pose principal soil constraints which may be grouped into four broad categories namely: nutrient availability and retention, nutrient toxicities, water availability and physical degradation due to erosion. Despite the above constraints, Ultisols possesses good micro-aggregate stability, good workability etc. In comparison, with the Alfisols, which has high cation exchange capacity and aluminium toxicity is not a problem. Potassium and ammonia fixation are important consideration in Alfisols that have notable contents of slightly weathered illite components of the clay fraction. Weak aggregation, high soil bulk density, and poor soil nutrition are common features of Ultisols under long-term cultivation, throughout the sub humid and dry savannah ecologies of Nigeria.

## 1.2 Justification

The earliest studies of soils in Nigeria and, in particular, the Guinea Savannah ecological zone have been limited to general soil survey and macro-characterization (Jungerius and Levelt, 1964; Hill and Rackham, 1973/4; Gallez, *et al.* 1975; Mbagwu, *et al*. 1983; Ojo-Atere and Olomu, 1987; Kparmwang, 1993; Olowolafe, 2002). These studies have explained positive attributes and negative constraints but the information is not complete as knowledge gaps still exist because of lack of micromorphological information. The pedons have characteristics ranging from humic, spodic, argillic, kandic, orthic and oxic properties. The present understanding of their genesis and classification is mainly general and "static" views through the interpretation of "macro" morphology and bench mark (or bulk) data for the physical, chemical and mineralogical compositions. There is very limited information about the microfabric and practically, studies about micromorphology of these pedons/soils are non-existent. The investigation of these properties will provide the needed scientific basis for proper understanding of these constraints and how to manage them.

Indeed, the increased precision of the classification system alters neither the properties of the soils nor the interpretation of these properties but it contributes towards a standardization of soil classification that should facilitate communication of soil information and permit both the extrapolation of information and its interpretations to areas far removed from the site where the data were obtained. Similarly, the need to study Ultisols is of paramount importance. It occupies one-third of the agricultural area, formed from different parent materials. Historically, Ultisols have invited agricultural development, since they are located mostly in long frost-free and abundance of rainfall for good crop production. The silicate clays of Ultisols are usually of

the non-sticky type, which along with the presence of iron and aluminium oxides, assure ready workability (Brady and Weil, 1999).

The research therefore hypothesizes as follows: H*o*= Micro-morphological and mineralogical properties of old soils are not influenced by parent materials. In other words, old soils are similar in properties irrespective of varying parent materials.

## 1.3 Objectives of the Study

Keeping the aforesaid in view, this research is with the general aim to increase the understanding of soil classification through evaluation of micromorphological and mineralogical properties of soil as emphasized by World reference basa for soil resources (WRB, 1998). In specific terms, the research was aimed at:

1. Characterizing the physical, chemical and morphological properties of the selected soils.
2. Investigating the micromorphological and mineralogical properties of Ultisols derived from basalts and granite gneisses.
3. Determining if differences in properties could be used in the classification of Ultisols at the lower levels of Soil Taxonomy (2003; 2006) and WRB (1998; 2005).

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1. Importance of Micromorphology to Soil Genesis and Classification

'To see what is in front of one's nose needs a constant struggle' George Orwell (1903-1950) (cited in Ringrose-Voase, 1991). This quote seems doubly appropriate to the role of Micromorphology in understanding soils in general. Firstly, in seeking to understand the behavior of soil as it is affected by or as it affects soil structure, it is easy, in the midst of hypothesizing, measuring or stimulating, to forget to observe the morphology of the soil being studied in all its heterogeneity, non-stationary and anisotropy. Secondly, there are the problems of how to observe soil structure without disturbance and how to parameterize what is observed so that objective comparisons can be made between different soil types or treatments or so that observations can be incorporated into behavioral models. Soil Micromorphology characteristically provides abundance of detailed information, obtained with polarized light microscopy, on soil features. However, the terminology used is so specialized that access to this information is limited to specialists, who, despite their expertise, are able to identify the degree of soil evolution only after a careful, time-consuming examination of the accompanying exhaustive descriptions.

Soil micromorphological study plays an important role in understanding of genesis and proper classification. Johnson and Peterson, 1941; U.S.D.A; 1960 emphasized micromorphological features as criteria for classification at different levels of generalization. This could not have been possible without micromorphological studies in soil genesis. The French sol "lessivage" is also another example where micromorphology plays an important role

in classification. According to Stoops (1986), soil micromorphological studies will yield without doubt many elements to ameliorate the criteria used in soil classification.

Stoops (ibid) also indicated that micromorphology is also used in soil management, particularly in the study of the influence of different cultivation techniques and drainage systems on soil structure e.g. structure degradation, formation of plow pans, and crust-formation. Stephen (1960) insisted that one of the most important uses of thin section analyses is in deciding whether clay migration has been an operative process in the development of textural profiles as it is becoming abundantly clear that clay content increasing with depth is not proof of illuviation, as seems often to have been assumed in earlier pedological investigations.

Micromorphology is a powerful technique for studying chronosequence, since it enables the result of both mineral alteration and clay illuviation to be seen. The stages of pedogenesis on basalt under rainforest in Nicaragua have been described by thin section (Eswaran, 1972). In the early stages of the soil processes and weathering stages, the plasma itself is destroyed and may be lost in the soil solution or the products of weathering may recombine to form plasma again.

## 2.2. Influence of Parent Material on Soil Macro and Micromorphological Properties

Pedologists have used thin sections for microscopic studies of soil features for over 60 years in the analysis of coatings, concretions, weathering rims on grains and void networks. Thin sections were often shared with colleagues to answer questions about specific features. The rapid development of imaging techniques, the reduction in costs of storing digital data, the readily available image analysis software, and the Internet as a way of efficiently transferring large amounts of data, make it possible to systematically analyze features in soil space over any

period of time (Protz and VandenBygaart 1998). The use of petrological microscope and soil mount on thin section for the study of soil genesis and classification is not very common in Nigeria probably this might be due to scarcity of equipment and chemicals used needed in this kind of study. Ojo-Atere and Olomu (1987) also observed that the tedious and expensive process of preparing thin-sections and the number of counts needed to get the confidence at 1% level are often difficult to achieve.

Eswaram (1970) opined that the study of soil micromorphology entails a description of the pedological features observed and an interpretation of these features. He however, concluded that soil micromorphology not only gives evidence of current pedogenesis but also indicates processes which the soil has undergone during its evolution. In this respect, it is frequently noted that pedogenesis leaves its mark and it is the duty of micromorphologist to identify, evaluate and interpret these marks. In the same line of argument Brewer (1972) remarked that micromorphology is not a magical means of solving pedological problems; it is simply a microscopic technique for collecting particular kinds of data on soil materials and profiles. He emphasized that the kinds of data obtained are especially useful in studies of the history and processes of development of soil profiles. This is so because the scale of observation is generally suitable to show the arrangement of constituents in soil materials and by comparison with successive soil horizon and the parent material, to show the kinds of re-arrangement that have occurred during the history of development of the profile. Even when individual grains of certain constituents are too small to resolve with light microscope, concentrations of these constituents can be recognized in thin section.

Brewer (ibid) concluded that the preposition which seems quite reasonable is that many soil-forming processes leave their imprint on various horizons of soil profiles in a form that can

be recognized microscopically and even evaluated, at least semi-qualitatively. He warned that some processes leave virtually no trace of their operation within the profile, for example, processes that remove constituents completely beyond the depth of the profile.

Rudeforth (1967) observed porphyroskelic fabrics with a voskelmossepic s-matrix in upland brown earths, although he recognizes that some ochreous B horizons have fabric like intertextic spodic horizons. He added that in the voskelmosepic fabrics, clay is oriented parallel to rock fragments and planes as stress cutans. Interpretation is purely deductive and depends very on experience of one kind or another.

## 2.3. Influence of Parent Material on Soil Physical Properties

Increasing knowledge of soil genesis and development has led to an understanding that not all soils develop from the parent rock they overlay (Ahn, 1970; Gupta and Tripathi, 1992). However, except in cases of the soils derived from alluvial, glacial or Aeolian deposits which may be transported from very distant places, the soils of an area generally reflect overall geology of the region (Ugwu, 1983). Klinkenberg and Higgins (1968) observed that where the parent material was solid blocky lava with weak joints, poorly-firm clay with vertic tendencies results, and where parent material was a tuft or agglomerate, a better-drained loamy soil was formed. They also opined that well-drained soils are generally found wherever weathering is strong enough to produce a deep regolith especially on pyroclastic rocks and also on nearly level tops of lava flows.

Despite the fact that many tropical soils have weathered to the extent that their clay fraction consists almost entirely of kaolinite and oxides of iron and aluminium (sesquioxides), the influence of original parent material often appears to persist in physical properties. Young

(1976) as well as Akamigbo and Asadu (1983) postulated that parent material dominates over climate as a determinant of soil texture. The latter, thus, reveals the geologic strata of an area. Similarly, the soils on more basic parent materials have higher clay content and a more stable aggregation than similar soils developed from intermediate or sialic parent material (Greenland, 1981). Extensive research and review were done on the parent materials, although Hole (1961) classified it as a passive factor in soil formation. Nasta *et al*. (1991) opined that textural composition not only differs significantly between parent material and soil, but also between soils of different age. He added that percent sand generally decreases with age and percent clay increases. Cady (1950) reported the mineralogical differences of two soils derived from chemically similar rocks in the North Carolina Piedmont. He concluded that physical conditions such as volume changes at the initiation of rock weathering, as influenced by mineralogy and texture of the rock, were important factors that produced the different soils.

## 2.4. Influence of Parent Material on Soil Chemical Properties

The understanding of the genesis of soil profile requires knowledge of the type of the parent material and specifically it is essential to determine whether the deposits were derived from basic or acidic rock or from a mixture of both (De Kimpe *et al*; 1973). They added that it was clear from various observations (presence of fibrous material, slates, or quartzite fragments; magnetite content; particle size analysis) that most of Profile1 and the C horizons of Profile 4 were derived from basic rock and that Profile 2 and 3 were formed in till derived from acidic material. This indicated that the influence of parent material is still evident.

Meaningful comparisons of base saturation revealed that, base saturation declines with increasing soil age and bases also become more concentrated in the top soil (Harrison *et al.*,

1990). They opined that although, trends in total exchangeable bases and base saturation are difficult to interpret, trends in exchangeable Al appear much more straightforward. Their results indicated that exchangeable Al increased with soil development. Heilman and Gass (1974) reported similar chemical properties in the upper horizons in spite of some wide differences in parent materials. However, with soils formed on basalt and limestone, influence of parent material on chemical properties was evident only in the lowest horizons: pH increased with depth in the solum. The highest pH apparently reflects the influence of the underlying limestone bedrock; highest exchange capacities in the mineral horizons were found in the spodic (B2) horizons with high values also occurring in the lower organic matter-rich horizons. A soil derived from sedimentary sandstones is generally poor in plant nutrients and become readily acidic because of low contents of exchangeable bases ($Ca^{2+}$, $Mg^{2+}$, $K^{+}$ and $Na^{+}$) and is subjected to leaching. Exchange capacity has been shown to be closely correlated with the presence of organic matter in southeast Alaska Spodosols (Stephens, 1969).

The existence of a close relation between the concentration of a trace element in a soil and its parent material would obviously be a value in agricultural research. Weathering of rocks is the principal resource from which soils derive their micronutrient. Therefore, apart from influence of certain soil properties in conjunction with soil moisture regime, wide inconsistencies in total micronutrient contents in soils are a reflection of diversity in parent materials from which the soils originated. Mitchell stated that the trace element content of a soil was dependent almost entirely on that of the rocks from which the soil parent material was derived and on the weathering processes to which the soil-forming material have been subjected (Bear, 1955). He then discussed the distribution of trace elements in rocks and concluded (loc. c. t., p.261) that a knowledge of this distribution enables one to anticipate with some degree of

accuracy the approximate total content of some constituents to be expected in any particular soil. However, this relationship can be obscured as a result of weathering and pedogenesis, as observed by Oertel (1961).

Accordingly, Taylor (1954) reported granite, an acid igneous rock, showed micronutrient contents close to those present in gneiss. Otherwise, it is known that granite contains significantly lower levels of Zn, Cu, Mn, and Fe than basalt- a basic igneous rock. Katyal and Sharma (1991) in their critical review of 57 benchmark Indian soils observed that metamorphic rock(Green schist) contained the highest concentration of Zn, Cu, Mn, and Fe, while among the sedimentary rock, Limestone had the maximum and sandstone displayed the least concentration of these micronutrient. They also confirmed that soils formed on granite had far less micronutrient than those developed on basalt.

## 2.5. Influence of Pedogenesis on Micromorphological Properties

In the study of tropical soils it has often been established that profiles from a certain climatological zone, developed in the same hydrological situation and derived from the same kind of parent material, can be arranged according to stages of development. Such arrangement deepens the insight into the genesis of profiles studied (Bennema *et al*., 1970). Eswaran (1972) was of the view that soil micromorphology not only gives evidence of current pedogenesis but also indicates processes which the soil has undergone during its evolution and it is the duty of the micromorphologist to identify, evaluate and interpret these marks. In his study of Ultisols derived from parent material-basalt, he found that the skeleton consists of a few, medium to coarse sand-sized, quartz grains and fine silt-sized crystallites of magnetite scattered randomly

in the s-matrix. While a related distribution was argillamatrix and where quartz was present in significant quantity, it was porphyroskelic.

Similarly, many pedogenetic studies of Quaternary soil sequences illustrated polycyclic soil development with increasing age of the soils (Bornand, 1978; Chartres, 1980; Macaire, 1986; Chittle-borough *et al.,* 1984). Kubeina (1970) elucidated in his classic study of soil development on limestone in the Vienna Woods of the Mull Rendzina with abundant dark colloidal humus as conditioned by accumulation of sufficient quantities of clay components in the topsoil above calcareous rock. In the studied soils, humus, vermiculitic clay, and iron oxides were the agents of stable aggregate formation which provided stable aggregation of soils.

Furthermore, plasma is one of the three components of the s-matrix; the other two being skeletons and voids. These three components, at various stages in soil formation, are subjected to modifications either individually or in combination with the other components to give raises to the various pedological features. Of the three components, plasma is perhaps the most dynamic. The dynamism of the plasma is primarily due to its power of mobility-being the colloidal fraction of the soil. The mobility includes not only its ability to move vertically or laterally but also its property to become oriented. As a result of this mobility, all soil formation processes affect the plasma directly or indirectly and so a study of plasma could indicate the evolution of the soil as a whole.

Indeed, with progress in pedogenesis, the translocation, diffusion and alteration of the plasma occurs; plasma combines with other materials to form pedological features; physical changes in the soil mass cause a modification in the arrangement of the plasma. All these processes are acting at various intensities in the soil, but less than one set of condition some of these processes will dominate over others. Hence interpretation of the plasma forms is an

important step in our knowledge of the pedogenesis of the soil. Eswaran (1967) and Stoops (1968) observed in the evolution trend of plasmic fabric the role of free iron content. In accordance with the earlier authors, Eswaran and Sys (1979) have shown the ability of iron to form crusts on soil clays. It is now believed that as a result of the crust formation, the birefringence of the clays is markedly reduced. Eswaran (1972) observed changes in plasmic fabric that are due to a combination of the following factors: (1) increase in free iron; (2) reduction in stresses within the soil mass; and (3) changes in type and amount of clay mineral.

Micromorphologically, changes in the second and third stages of the weathering sequences can, according to current conceptions (Kubiena, 1962) best be described as : Braunlehmplasma changes in mountainous area frequently into erdige braunlehm; in tropical areas with varying humidity, and in sub-tropical areas with a hot dry period, into rotlehm, and finally even into roterde. These processes are characterized by flocculation or crystallizing out of the iron hydroxide present and eluviations of braunlehm plasma which is accompanied by an increase in porosity. In the course of laterization, large crystals and crystal aggregates are formed among others such as goethite, lepidokrokite, and hematite.

Johnson *et al.* (2004) reported from macro and micromorphological studies that transfer, or eluviation and illuviation of silicate clay is the dominant soil-forming process under pine. Illuviation is favoured by (i) the presence of water which serves as the means of transportation, (ii) the lack of burrowing macrofauna that disrupt horizonation; and (iii) the presence of organic acids that alter the surface charge properties, thereby encouraging dispersion. The coating of clay particles with organic materials has been reported to increase colloidal stability and enhance dispersion (Gibbs, 1983; Kaplan *et al;* 1993; Kret-zschmar *et al.,* 1993).

Distribution fabrics are the patterns arising from the relationship between different kinds of material, for example sand and clay, and are very dependent on particle size distribution. The component of distribution fabrics are the pedofeatures which are coarser particles, usually sand-sized, and the groundmass, consisting of finer material (Stoops 2003). The actual size of the pedofeatures depends on the soil, but should be such that they are distinct from the groundmass. He opined five (5) major distribution fabrics: monic, gefuric, chitonic, enaulic and porphyric. Chitonic, gefuric, enaulic distribution fabrics, together with angular blocky and crumb and granular physical fabrics, are all types of poric fabric, that is the pore space results from the packing of individual particles or physical units. Porphyric and monic fabrics are aporic fabrics in which the pore space is unrelated to the packing of units or particles.

Brewer (1979) investigated the fabrics of the soils with different particle size distributions. He found that soils with more than about 25% clay-silt have porphyric fabrics. In soils with less than 25% clay-silt, those with more silt than clay tend to have gefuric fabrics, whereas those with more clay than silt have chitonic fabrics. This relationship seems to hold across many soil types representing many pedogenic processes. Accordingly, Brewer's explanation possibly lies in wetting and drying cycles which are common to all soils. Where clay is the predominant fine material, it tends to coat mineral grains as the soil dries. When the fine material is silty, the silt particles, because of their larger size, tend to be deposited between mineral grains and around their points of contact where menisci form during drying.

Observations of distribution fabrics can aid understanding of the properties of minerals with different particle size distributions. For example, soils with a range of textures from sand to clay will exhibit different mechanical properties as the proportion of clay increases. The change in mechanical properties will probably not be linear but will occur more rapidly over a

small range of sand: clay+silt ratios. This range is likely to correspond to the change from chitonic to porphyric fabric (around 75% sand). In the former the mechanical properties will be determined essentially by the sand fraction and in the later by the clay fraction.

Smith (1984) observed that a minimum clay content of 35% is required for a soil to be self mulching. Little *et al.* (1992) found that a non-self-mulching variant of the grey clay studied had 27% clay and a mono spaced porphyric fabric, whereas a self mulching variant had 58% clay and tri-spaced porphyric. They suggested that, during drying, the wide spacing of f-members (pedofeatures) in the self-mulching variant allowed aggregates to form because the clay matrix could shrink *en masse* without interference from the grains coming into contact. In the non-self-mulching variant, touching grains would prevent the clay matrix shrinking *en masse*, so that stresses would be relieved by flaws between the grains leaving the soil unaggregated. This explanation is consistent with the self-mulching mechanism proposed by Grant and Blackmore (1991).

## 2.6. Influence of Pedogenesis on Physical Properties

Soil properties that change with duration and intensity of weathering have been used in studies (Harden and Matti, 1989; Kendrick and Mc Fadden, 1996; Kendrick and Graham 2004). Torrent *et al.* (1980) opined an intensity of reddening soil surface was an indication of duration of pedogenesis. They suggested that physical disturbance such as freezing and thawing, wetting and drying, and root pressure play an active role in pedogenesis.

Jogmans *et al.* (1991) observed three major chronosequences on the basis of pedogenesis: The Holecene $P_1$ and $P_2$ soils of group 1 show the formation of $A_1$ horizon with biological homogenization as the main process, and little (no) evidence of other soil-forming processes. The late Pleistocene soils $P_3$ and $P_4$ of group II show (1) biological homogenization to a greater depth, (2) pronounced mineral weathering in the A horizon and (3) distinct clay illuviation. The groups I and II showed soil under continuously well-drained conditions as a result of absence of compaction by periglacial processes. Group III comprises the Middle and Early Pleistocene soil P5–P9, which display distinct polycyclic soil formation, increasing in complexity with age.

## 2.7. Influence of Pedogenesis on Chemical Properties

Numerous events may take place simultaneously or in sequence to mutually reinforce or contradict each other (Rode, 1962) for example, calcification and podzolization. Properties that have been used as indicators of the duration of pedogenesis include, but are not limited to, clay accumulation (Birkeland, 1991), accumulation of $CaCO_3$ (Gile *et al.*, 1966), and Fe oxide content and composition (Alexander, 1974; Mc Fadden and Hendricks, 1985). A long duration of pedogenesis is required for silica cementation sufficient to form a duripan, particularly in the absence of volcanic glass. Kendrick and Graham (2004) reported pedogenic silica as an important soil component even when duration is insufficient for designation of a duripan. They opined desilication is concurrent with the loss of $K^+$ and $Na^+$, and likely reflects the dissolution of feldspars minerals. They concluded that pedogenic silica increases with increasing soil age in both the San Timoteo and Cajon Pass chronosequences.

A study by Melfi *et al.* (1983) on granite weathering elucidates the most abundant minerals in the profiles to be quartz and K-feldspar. Though within the feldspar group, the rate of dissolution of $Na^{+}$ and $Ca^{2+}$ feldspar far exceeds that of K-feldspar and kaolinite dominates the secondary mineral which principally formed from feldspar breakdown. They observed small quantities of smectite and illite as mica weathering products in less leached region as opposed to biotite altered products with inter-layered mica-vermiculite, vermiculite as well as kaolinite, and feldspar weathering sometimes leads to gibbsite formation in more humid conditions. By implication, P levels would appear low, which could be explained by the rapid loss of $Ca^{2+}$ which at normal ground water concentrations would buffer the dissolution of apatite. Davis, 1964; Melfi, *et al*., 1983 concluded that vegetation and surface temperature had little influence on rates of silica removal and stressed that the common notion that tropical weathering rates are more rapid relative to those in temperate and sub-arctic climates must be treated with extreme caution. Accordingly, researchers who studied soil diversity attributed changes in pedogenesis to principally soil age and landform age (Singer, 1988; Muhs *et al.*, 1990; Muhs, 2001; Sedov *et al.*, 2008).

## 2.8. Influence of Parent Material on Soil Mineralogical Properties

The importance of the parent bedrock in determining the mineralogical composition of the derived soils is of paramount importance. Stephen (1952) noted the dominant mineral in the clay of the granitic soil as a member of the dioctahedral illite (clay-muscovite) group, whose presence can be attributed to the alteration of the feldspar of the bedrock. He added that hydrothermal and weathering are the processes which lead to its alteration and definite boundary between these processes are difficult or impossible. In the apparently unweathered

granite, shred-like white mica is widespread as a secondary mineral derived mainly from the acid plagioclase, and the orthoclase is turbid and clouded with secondary products. On the other hand, weathering proceeds in the biotite revealed dominantly chloritic material which is later converted into a vermiculitic material, a process of vermiculitization (Kerr, 1930; Walker, 1949).

Mineral transformations during rock weathering are governed by the chemistry of pedologic and geologic micro environments, which may vary considerably over short distances (Eswaram, 1979). Micro-environmental conditions are time-dependent both on a small scale, such as during wetting and drying cycles, and on a large scale, in response to major climatic fluctuations. These leave an imprint on mineral transformation in the soil and are related to the age and stability of geomorphic surfaces on which the soils occur. It is in this line, Glasmann and Simson (1985) reported alteration of basalt from mineral dissolution which leads to the formation of etchmits and hair-line cracks on mineral surfaces to S-matrix.

Clay minerals from the basaltic soils have been intensively investigated in tropical and sub-tropical regions. Chang (1963) reported kaolinite, gibbsite, hematite, and in younger soils montmorillonite in tropical soils derived from basalt on Hainan Island. In Hawaii, Bates (1960) found that basaltic rocks produce large amounts of halloysite and gibbsite together with variable quantities of allophane and nontronite. In Madgascar, Segalen (1957) found mainly meta-halloysite, gibbsite, and goethite, with montmorillonite in the younger soils. Pecrot *et al.* (1962) reported the presence of kaolin in well-drained basaltic soils and montmorillonite in the poorly drained ones.

Smith (1957) and McAleese and Mitchell (1958) found that the clay from basaltic soil profiles in northern Ireland contained mainly kaolin and vermiculite, with montmorillonite

occurring only in poorly drained sites. Smith (1962) found in soils from Scotish basic rocks mainly vermiculite or saponite, kaolinite, and sometimes chlorite. In Central Europe, Bolter (1961) found among weathering products of basalt rock, mainly Mg and Fe-rich monmorillonite, kaolin and some goethite, while Pendias (1961) found in Silesia in weathering basalt nontronite, kaolin, metahalloysite, and palygorskite. Ogunwale (1985) found kaolinite as the dominant clay mineral on the basaltic soils of the Biu Plateau. Markus *et al.* (2008) reported dominance of kaolinite, goethite, and hematite on the basaltic soils developed from Kuantan, Malaysia.

From the cited data, kaolin minerals and crystalline oxides of Fe and Al as stable end products of basaltic clays are associated with high rainfall and high mean temperatures. Montmorillonite, in those conditions, occurs only as a transitional phase. Under conditions of impeded drainage both montmorillonite and halloysite may be formed. Okusami *et al.* (1987) reported that low permeability of the parent materials may have attenuated mineral weathering and diagenesis. Similarly, lower temperatures and precipitation in Central and NW Europe seem to favour mainly the formation of montmorillonite and vermiculite as stable products, and to a smaller extent kaolinite (Singer 1966).

## 2.9. Soil Classification

Soil classification seeks to group soils together so that the land can be utilized and managed efficiently for various purposes. It is in this regards, that soils are grouped together into categories or classes in various ways and according to various criteria. The classes are defined in such a way as to be useful in understanding the formation, properties and uses of soils (Ahn, 1993). The type of system employed depends fundamentally on the purpose of classification of soils fall into two parts, firstly, nomenclature and classification of horizons, and

secondly, nomenclature and classification of the whole soils at present, there is no internationally agreed soil nomenclature and classification system but, the most widely reference systems are the USDA and FAO/WRB.

Several studies conducted on Jos Plateau, Nigeria classified the soils into: Entisols, Inceptisols, Alfisols, Vertisols and Ultisols. Olowolafe and Dung (2000) reported four major soil orders in biotite-granite areas on the Jos Plateau to be Entisols, Inceptisols, Alfisols and Ultisols. Entisols are found on the hill/mountain crests, side slopes and upper footslopes. They also occur on interfluvial crests and drainage channels. Inceptisols are soils that have undergone little weathering, having cambic B-horizons with soil structure and significant amount of weatherable minerals. They are found on the upper footslopes, middle footslopes, interfluvial areas and alluvial floodplains. Alfisols and Ultisols are the soils found with argillic/kandic horizons in the area. They both contain lateritic concretions and similar morphological characteristics but are distinquished from each other on the account of their base saturation. They are found on the lower footslopes, and level plains.

Similarly, Kparmwang (1993) classified the basaltic soils of Jos Plateau to be Inceptisols, Vertisols, Alfisols and Ultisols. Vertisols are found in the depressions and the alluvial area with heavy clays but are minor soils in the area (e.g. Panyam).

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1. Physical Setting of Study Area

The study was sited in Kuru and Ryom, Jos in Plateau State under the Northern Guinea ecological zone.

### 3.1.1 Location.

The Jos Plateau forms a highland area standing above the surrounding plains. It occupies an area of about 8,600 $km^2$ in the central part of Nigeria. It lies between latitude $8^0$ $30^{'}$ and $10^0 10^{'}$N and longitudes $8^0 20'$ and $9^0$ $30^{'}$E (Fig.1) Its boundary is marked for the most part by a steep fall to the surrounding plains, though it is more gradual in the east (Hill, 1978).

### 3.1.2. Climate.

The climate of the Jos Plateau is primarily controlled by the position and altitude of the hills in relations to the general circulation in West Africa (Alford and Tuley, 1974). The climate is the wet and dry type classified as tropical rainy (Aw) climate by Koppen (1923). The study area is characterized by a mean annual rainfall of 1300mm (1008.6-2184.70) Table 1 and mean annual temperature of about 22ºC. The soil moisture regime is ustic while soil temperature regime is isohyperthermic (Eswaram *et al*., 1997). The area falls within the northern Guinea Savannah vegetation zone which is open woodland with tall grasses but the native vegetation has been considerably altered by human activities (Keay, 1953).

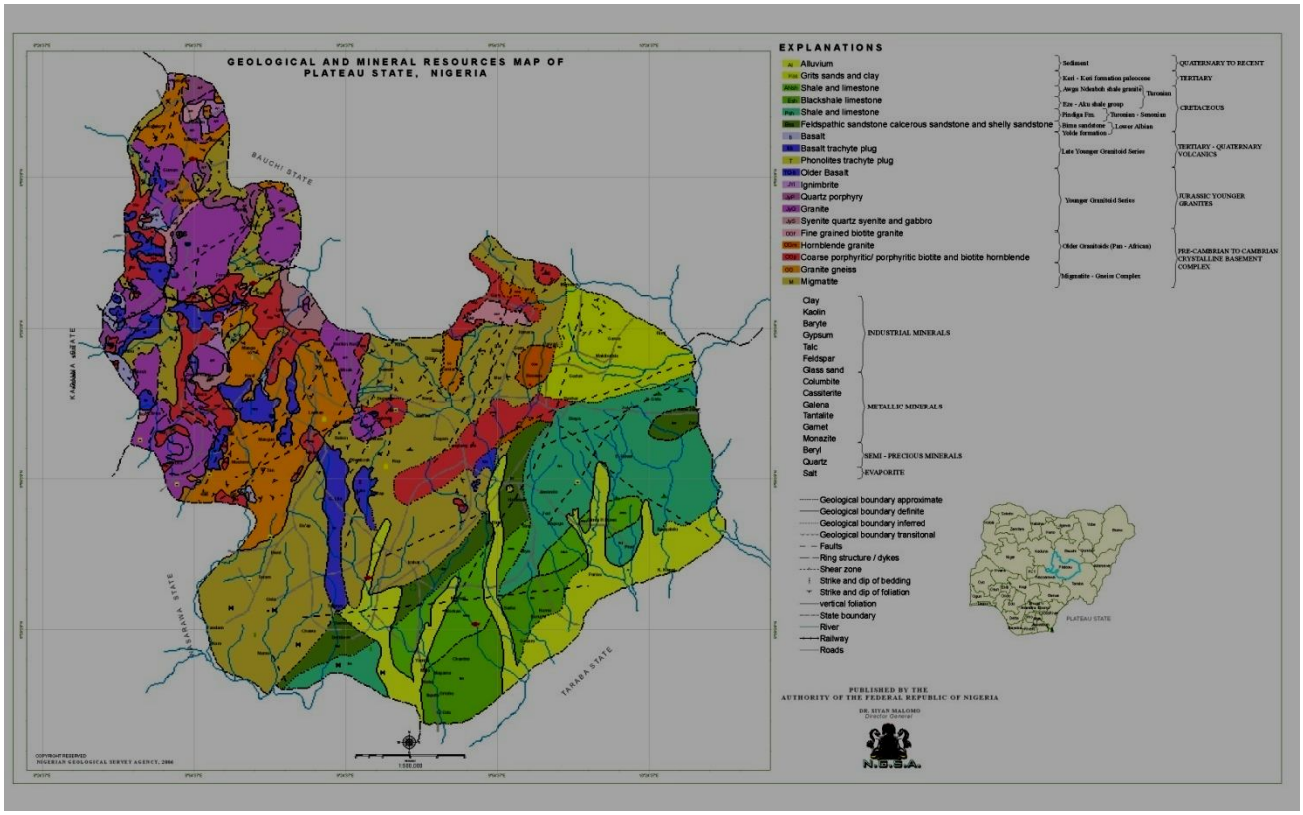



Fig.1. Geological and mineral resources map of Plateau State

Fig.1. Geological and mineral resources map of Plateau state

Table1. Monthly and annual mean rainfall distribution (mm) of Kuru and Riyom area from 2002-2008

Table1.Monthly and annual mean rainfall distribution (mm) in Kuru and Riyom areas from 2002-2008

| period | Jan | Feb | Mar | April | May | June | July | Aug | September | October | November |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2002 | 0.0 | 0.0 | 7.0 | 155.9 | 81.9 | 365.4 | 418.7 | 266.0 | 209.3 | 91.0 | 0.0 |
| 2003 | 0.0 | 0.0 | 0.0 | 199.90 | 185.20 | 183.70 | 160.90 | 283.10 | 257.50 | 36.30 | 0.0 |
| 2004 | 0.0 | 0.0 | 0.0 | 94.8 | 218.4 | 199.4 | 246.3 | 249.4 | 129.0 | 4.1 | 0.0 |
| 2005 | 0.0 | 0.0 | 0.0 | 19.40 | 170.80 | 144.30 | 175.70 | 339.40 | 173.40 | 64.60 | 0.0 |
| 2006 | 0.0 | 0.0 | 0.2 | 100.4 | 355.2 | 125.8 | 281.8 | 310.8 | 326.9 | 35.1 | 0.0 |
| 2007 | 0.0 | 0.0 | 28.6 | 311.02 | 398.17 | 476.7 | 183.4 | 294.7 | 91.7 | 7.2 | 0.0 |
| 2008 | 0.0 | 0.0 | 1.30 | 34.80 | 155.30 | 188.20 | 477.40 | 976.60 | 264.00 | 73.70 | 0.0 |

Source: NCRI-VOM, Yakubu Gowon Airport-Heipang, Jos Plateau and PADP Hqt, Jos.

### 3.1.3. Vegetation and land-use

Being in the northern Guinea savanna, vegetation of the study area consists of grassland. The dominant tree and shrub species include: *Tamarindus indica, Parkia clapertonia, Acacia* spp *and Piliostigma breticulum*. Native vegetation has been considerably affected by human activities (Keay, 1953). Major communities now are Adansonia parkland, *Acacia albida* parkland and shrub savanna (Plate 1). The grass family include: Gamba grass, Spear grass and Ironweed (Andropogon *gayanus, Imperata cylindrical and Vernonia perrotteetii*) respectively. Other planted vegetation in the area is Mango, Guava, Citrus and Locust bean trees (*Mangifera indica, Psidium guajava, Citrus* spp *and Parkia biglobosa*) respectively.

Crop that are grown include maize *Zea mays*, Irish potatoes *Solanam tuberosum*, sorghum *Sorghum vulgae*, soya bean *Glycine max*, millet *Pennisetum americanum*, acha or Hungary rice *Digitaria exills*, sweet potatoes *Ipomoea batatus* and cocoyam *Coloscasia* spp . The traditional farming system on the Plateau was characterized in the 19$^{th}$ Centuary by mixed agriculture, including shifting cultivation and intensive terrace farming in the hills and shifting cultivation on the plains (Grove, 1952). The development of tin mining and rapid population growth has transformed the subsistence-oriented agriculture, leading to the expansion of the area under cultivation (Adepetu, 1986).

### 3.1.4. Geology and geomorphology

Geologically, according to Macleod *et al*. (1971) Jos Plateau comprises of Precambrian Basement Complex rocks (gneiss, migmatites and older granites) known in general as the Basement Complex rock (BCR). Medium to coarse grained granites,



Plate 1: General overview of the basaltic cultivated soils in the study area.

known as the younger granites (mostly biotite-granites) have intruded into the Basement complex and form a series of ring complexes: they are thought to be of Jurassic age (Jacobson *et al*., 1958). The Jos Plateau has been affected by volcanic activity from Tertiary to recent times. They are distinguished as: (a) Lateritised older Basalts; (b) unlateritized older Basalts, generally associated with (a); and (c) Newer Basalts that are typically large flows that can be traced to reasonably well preserved cones  Erosion of the lateritized older Basalt has led to the formation of a secondary iron pan and deep unconsolidated deposits on the valley side slopes.

## 3.2. Field Studies

### 3.2.1. Soil profile citing

Profile pits were dug with dimension of 2x2x1m for detailed profile description. A total of eight (8) pits; four each on: Granite-gneiss and Basalts parent materials. A geological map was used to identify the varying parent materials in the study area.

### 3.2.2. Morphological description

The profile pits were described for their range of morphological properties in the field following the pattern outlined in the Soil Survey Manual (Soil Survey Staff, 1981; 1994).

### 3.2.3. Soil sampling

Three sets of soil samples were collected from each pedon; the first was the bulk sample of each pedogenic horizon used for routine chemical and some physical analyses, the second was the core samples of each horizon for bulk density determinations, and thirdly Kubiena

boxes made of flat metal and with dimensions 10x6x6cm$^3$ were used to collect undisturbed soil samples from every 10cm of the entrire B and C horizons for micromorphological investigations.

### 3.3. Laboratory Studies

#### 3.3.1. Sample preparation

Soil samples (first set) of about 5kg collected were subsequently air-dried and passed through a 2mm sieve for bulk physical and chemical analysis.

#### 3.3.2. Particle size distribution analysis

The air dried soil samples were dispersed in 5% calgon (sodium hexametaphosphate) solution, by shaking on a reciprocating shaker for 24 hours for proper or complete dispersion of the particles. On dispersion, particle size distribution was determined by the hydrometer method as described by Day (1965).

#### 3.3.3 Bulk density and porosity

Bulk density was determined by the core method using a 7.5cm diameter core sampler (McKeague, 1981). The undisturbed soil samples collected were oven-dried to constant weight at 105 $^0$C, and dividing the dry weight of the sample by the total volume of the sample. Total porosity of the soils was calculated mathematically from the results of bulk density and assumed particle density of 2.65gcm$^{-3}$ using the relation:

$$F = 100(1-Pb/Pp)$$

Where; F = total porosity (%)
Pb = bulk density Mgm$^{-3}$

Pp = particle density 2.65 $gcm^{-3}$

### 3.3.4. Soil pH

The pH values in $H_20$ and $CaCl_2$ were determined with pH-meter for 1:1 and 1:2 soil: solution ratio, respectively.

### 3.3.5. Exchangeable bases, CEC and exchangeable acidity

Cation exchange capacity (CEC) and the amount of extractable cations were determined by extraction with I*M* $NH_4OA_C$ ($pH_7$). The CEC was calculated from the measured amount of exchangeable $NH_4^+$ absorbed as determine with an auto-analyses, while extractable cations were read with Atomic Absorption Spectrophotometer (AAS). Exchangeable acidity was analyzed by $BaCl_2$TEA (pH8.2) method (Page *et al.*, 1982).

### 3.3.6. Cation exchangeable capacity (CEC) of the clay fraction

CEC was determined by the neutral (pH 7.0) $NH_4$OAc saturation method. The cation exchange capacity of the clay fraction was calculated using the method proposed by Sombroek and Zonneveid (1971) as follows:

$$CEC\ (clay) = CEC\ (NH_4OAc) - (3.5x\%OC) / \%\ clay\ x\ 100$$

### 3.3.7. Effective CEC

Effective CEC was determined as the sum of total exchangeable bases by $NH_4$OAc and 1MKCl extractable acidity.

### 3.3.8. Base saturation (BS)

Base saturation was calculated for both $NH_4OAc$-CEC and ECEC from the formula:

*% Base saturation = (Total exchangeable bases / CEC or ECEC) x 100*

### 3.3.9. Organic carbon (OC)

The acid-dichromate wet oxidation method of Walkley and Black as described by Nelson and Sommers (1982) was used in the determination of organic carbon. The heat of dilution of added concentrated sulphuric acid ($H_2SO_4$) hastened the reaction.

## 3.4. Micromorphological Study

### 3.4.1. Preparation of thin section

Soil samples collected with Kubiena boxes from every 10cm of the entire B and C horizons of the profile pits (Plate 2) were air-dried and samples were carefully removed from boxes and trimmed. Blocks of air-dried and undisturbed soil samples were hardened with aradite HY 905 and hardner HY 951 in a ratio of 10:1. The treated samples were then cut with cut-rock machine and polished with medium and fine grained carborundum powder (Silica carbide) and paraffin on glass plate.

The polished samples were mounted on a glass slide by heating the slide and melting the lakeside on it to glue the samples. The mounted samples were thinned down to desired thickness (0.03mm) on a grinding plate and powder. Finally, the slide of each sample prepared in triplicate was covered with a cover glass with the aid of Canada balsam and washed with xylene or acetone. The soil thin-sections prepared were studied with swift model petrological

microscope for detailed fabric and mineral analysis under plane polarized light and cross nicol (Bullock *et al.,* 1985).

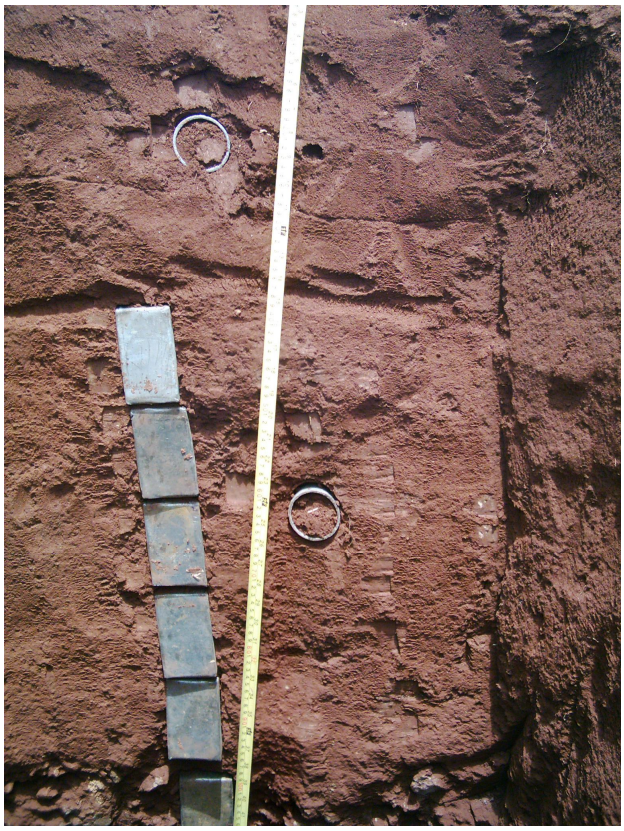





Plate II: Kubeina boxes used for thin section preparation

The boxes with a diameter 10x6x6 cm were constructed at the Agricultural Engineering Department, Ahmadu Bello University, Zaria. While the preparation of the thin sections were conducted and read with petrological microscope at the Geology Programme of the Abubakar Tafawa Balewa University, Bauchi.

### 3.4.2. Mineral identification

Qualitative assessment and identification of the primary minerals were conducted by viewing the soils on petrological microscope with plane polarized light, cross-nicol and by fixing the quartz-wedge to the analyzer of the petrological microscope (Smith, 1973)

### 3.4.3. Micromorphological terminologies

The terminologies used followed those of Brewer (1964), Bullock *et al*. (1985), and Stoops (2003).

## 3.5 Clay Mineralogy

Less than 2µm clay fraction was collected by sedimentation method of each soil sample after decomposing the organic matter with hydrogen peroxide. The clay mineralogy was determined by the XRD technique. Non oriented samples were used after saturation with magnesium. The magnesium saturation of the samples was achieved by washing the flocculated

clay three times with ethanol and twice with acetone. The samples were air-dried and ground into fine powder. The non-oriented samples were scanned using the same XRD machine type PW1800, using Cu-radiation (Cu K and wavelength (Å) = 1.54 speed of $2^{o}$ $min^{-1}$). The clay fractions were

subjected to X-ray examination of K-saturated samples with diffractometer and a scanning speed of $1^{o}$ 20/min.

All the XRD were run at the National Steel and Raw Materials Exploration Agency, Malili, Kaduna.

### 3.6 Data Analysis

The soil aggregate stability indices were subjected to t-test and analysis of variance (ANOVA) test to assess treatment differences. Where the observed F-values and t-test were significant at $p \leq 0.05$, the least significant differences (LSD) was used to compare difference between treatment means (Little and Hills, 1978; GenStat Release 7.22DE).

### 3.7. Soil Classification

With the aid of the field and laboratory results, the soils were classified according to the criteria of USDA Soil Taxanomy (Soil Survey Staff, 1975; 1999; 2003; 2006) and the FAO/UNESCO Soil Map of the World Legend and World Reference Base for Soil Resources (WRB) (1974; 1988; 2005).

# CHAPTER FOUR

# RESULTS AND DISCUSSION

## 4.1. Morphological Properties

Soil morphological properties of the pedons under investigation have been presented in Appendix A; a summary was given in Table 2. Morphological properties, some of which are paramount important in the classification of the soils, include soil depth, colour, texture, structure, consistence and horizon differentiation. They also indicate the degree of pedogenesis and soil development.

### 4.1.1 Soil depth

Soil depth varied both within and among soil parent materials. Soil profiles BST01, BST02, BST03, and BST04 from the basaltic parent materials (Table 2) were generally very deep, that is greater than 150 cm. The Ap horizons of BST02 and BST04 are generally thin due to the high clay content of the soils, which complexes humus and thus reduces its ability to move downwards in the profiles. Accordingly, Kparmwang *et al.* (1998) opined that the thin Ap horizons might be partly due to cultivation which is usually on the flat, resulting in minimal deep mixing of the topsoil which is prone to moderate sheet erosion. While the granitic parent materials were shallow except Profiles GNT 01 and GNT 04. The depth of these soils was restricted by iron pan (petroplinthite or indurated plinthite). The accersions for the thin Ap horizons in the basaltic parent materials also holds for the granitic soils.

### 4.1.2. Soil colour

The surface horizons of soils formed in basaltic parent material were dominantly dark reddish brown as determined on moist state: 5YR 3/3; 5YR 3/4; 5YR 3/4; 5YR 3/3 in Profiles

BST01; BST02; BST03, and BST04 respectively. Profiles BST01 and BST02 have dark reddish brown (2.5YR 3/4) subsoils, while pedons

Table 2. Summary of the morphological features of soil profiles**

Table2. Summary of the morphological features of soil profiles**

| | Depth | Munsell colour | | mottle | | | Consistency | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Horizon | (cm) | moist | dry | colour | Texture | Structure | wet | moist | dry | Boundary | |
| | | | | | | **Basaltic Parent Materials** | | | | | |
| **Profile No: BST 01** | | | | | | | | | | | |
| Ap | 0-35 | 5YR 3/3 | 5YR 4/6 | - | C | 2msbk | SP | fi | sh | gs | |
| Bw1 | 35-60 | 2.5YR 3/4 | 2.5YR 4/6 | - | C | 2msbk | SSPS | fi | sh | cs | |
| Bw2 | 60-88 | 2.5YR 3/6 | 2.5YR 4/6 | - | CL | 1fsbk | SP | fi | sh | cs | |
| Bt1 | 88-130 | 2.5YR 3/4 | 2.5YR 3/6 | - | C | 2msbk | SP | fi | sh | ds | |
| Bt2 | 130-178+ | 2.5YR 3/4 | 2.5YR 3/6 | - | C | 2msbk | SSPS | fi | sh | - | |
| **Profile No: BST 02** | | | | | | | | | | | |
| Ap | 0-16 | 5YR 3/4 | - | - | CL | 2msbk | SP | fi | S | cs | |
| Bt1 | 16-70 | 2.5YR 3/4 | 2.5YR 3/6 | - | C | 2msbk | SP | fi | H | cs | |
| Bt2 | 70-117 | 10YR 3/4 | 2.5YR 3/6 | 7.5R 4/8 | C | 2msbk | SP | fi | H | cs | |
| BC | 117-152 | 5YR 3/4 | - | - | C | 2msbk | SSPS | fi | H | cs | |
| C | 152-175+ | 5YR 3/4 | 2.5YR 3/6 | - | C | 2msbk | SP | fi | h | - | |

Table 2. Cont'd

| | Depth | Munsell colour | | mottle | | | Consistency | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Horizon | (cm) | moist | dry | colour | Texture | Structure | wet | Moist | dry | Boundary |
| **Profile No: BST 03** | | | | | | | | | | |
| Ap | 0-37 | 5YR 3/4 | - | - | C | 1msbk | SSPO | Fi | S | gs |
| Bw1 | 37-100 | 5YR 3/4 | - | - | C | 2msbk | SP | Fi | H | cw |
| 2BC1 | 100-110 | | - | - | C | - | - | - | - | - |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2BC2 | 110-143 | 5YR 3/4 | - | - | C | 2msbk | SP | Fi | H | cs | C |
| 2Cr | 143-190 | 5YR 3/4 | - | - | C | 2msbk | SP | Fi | H | - | I |
| **Profile No: BST 04** | | | | | | | | | | | |
| Ap | 0-15 | 5YR 3/3 | - | - | C | 1fsbk | SPO | Vfr | S | cs | I t |
| Bw1 | 15-110 | 5YR 3/4 | 5YR 4/6 | - | C | 2csbk | SP | Fi | H | ds | I r |
| Bw2 | 110-156 | 5YR 3/4 | 5YR 4/6 | - | C | 2msbk | SP | Fi | H | cg | I c r |
| BC | 156-190 | 5YR 3/4 | - | - | CL | 2csbk | SP | Fi | H | - | I I |

Table 2. Cont'd.

| | Depth | Munsell colour | | Mottle | | | Consistency | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Horizon | (cm) | Moist | dry | Colour | Texture | Structure | wet | Moist | dry | Boundary | |
| | | | | | | **Granitic Parent Materials** | | | | | |
| **Profile No: GNT 01** | | | | | | | | | | | |
| Ap | 0-25 | 10YR 5/3 | - | 7.5YR 4/6 | CL | 2msbk | SP | Fi | h | cs | I t |
| AB | 25-60 | 10YR 5/3 | 10YR 6/3 | 10YR 6/8 | CL | 2csbk | SP | fi | h | ds | I f |
| Bw1 | 60-100 | 10YR 6/2 | - | 7.5YR 4/6 | CL | 2msbk | SSPO | fi | h | ds | I i |
| Bw2 | 100-140 | 10YR 6/2 | - | 7.5YR 4/6 | SiCL | 2csbk | SSPO | fi | h | dw | I r |
| C | 140-195 | 10YR 6/2 | - | 7.5YR 5/8 | SiCL | 2msbk | SPO | vfr | vh | - | I |
| **Profile No: GNT 02** | | | | | | | | | | | |
| Ap | 0-20 | 10YR 4/4 | - | 7.5YR 6/8 | L | 2msbk | SP | fi | s | cs | I r |
| Bt1 | 20-78 | 10YR 5/3 | - | 7.5YR ¾ | C | 2msbk | SP | fi | h | cs | I r |
| Bt2 | 78-115 | 10YR 5/3 | - | 2.5YR 4/6 | CL | 2msbk | SP | fi | h | dw | I r |
| C | 115-130 | 10YR 5/2 | 10YR 7/2 | 5YR 4/6 | SCL | 2msbk | SSPO | fi | sh | - | Y c r |
| **Profile No: GNT 03** | | | | | | | | | | | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ap | 0-11 | 7.5YR 4/6 | - | - | SL | 1fsbk | SSPS | vfr | s | cs | |
| BA | 11-38 | 7.5YR 5/8 | - | - | CL | 2msbk | SP | fi | h | cs | |
| Bt1 | 38-66 | 7.5YR 5/8 | - | - | SCL | 2msbk | SP | fi | h | cw | |
| | 66-101 | 10YR 8/4 | - | 7.5YR 5/8 | L | 2msbk | SP | fi | h | cs | |
| | 101-148 | 7.5YR 7/2 | - | 7.5YR5/ 8 | CL | 2msbk | SP | fi | h | - | |

Table 2. Cont'd.

| | Depth | Munsell colour | | mottle | | | Consistency | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Horizon | (cm) | moist | dry | colour | Texture | Structure | wet | moist | dry | Boundary | |
| **Profile No: GNT 04** | | | | | | | | | | | |
| Ap | 0-11 | 7.5YR 4/6 | - | - | SCL | 1fsbk | SSPS | fr | s | cs | |
| Bt1 | 11-48 | 7.5YR 5/8 | - | 2.5YR 3/6 | C | 2msbk | SSPS | fr | h | cs | |
| Bt2 | 48-120 | 10YR 6/2 | - | 5YR 5/8 | SCL | 2msbk | SSPS | fr | s | cs | |
| BC | 120-165 | 7.5YR 4/4 | - | 2.5YR 3/6 | SCL | 2msbk | SP | fi | h | - | |

**Interpretation of symbols used in describing morphological properties of the pedons in Table 2.

**Soil Texture**

| | | |
|---|---|---|
| L | = | Loam |
| CL | = | Clayloam |
| SL | = | Sandyloam |
| SiCL | = | Siltyclayloam |
| SCL | = | Sandyclayloam |
| C | = | Clay |

**Soil Structure**

| | | |
|---|---|---|
| 1fsbk | = | Weak fine subangular blocky |
| 1msbk | = | Weak medium subangular blocky |
| 2csbk | = | Moderate coarse subangualar blocky |
| 2msbk | = | Moderate medium subangular blocky |

**Soil Consistence**

Wet

| | | |
|---|---|---|
| SSPO | = | Slightly sticky, non-plastic |
| SSPS | = | Slightly sticky, slightly plastic |
| SPO | = | Sticky, non-plastic |
| SP | = | Sticky, plastic |

Moist

| | | |
|---|---|---|
| Fr | = | Friable |
| vfr | = | Very friable |
| fi | = | Firm |

Dry

| | | |
|---|---|---|
| s | = | Soft |
| sh | = | Slightly hard |
| h | = | Hard |
| vh | = | Very hard |

**Boundary**

| | | |
|---|---|---|
| cs | = | Clear, smooth |
| dw | = | Diffuse, wavy |
| ds | = | Diffuse, smooth |
| cg | = | Clear, gradual |
| gs | = | Gradual, smooth |
| ds | = | Diffuse, smooth |

BST03 and BST04 have (5YR 3/4; 5YR 3/3) surface horizon and a dark reddish brown (5YR 3/4; 5YR 3/4) subsoils. Similarly, the only difference in the surface and subsoils is the hue in pedons BST01 and BST02 and brightness of the subsoils of pedons BST03 and BST04. Oxidation-reduction of goethite coupled with leaching was suggested by Fanning and Fanning (1989) to give hues 5YR to 2.5YR in some soils formed under the tropical conditions. Presumably, hematite could cause the reddish colour in the subsoils. The darker colour of the Ap horizons is probably a result of melanization from humified organic matter, while the bright colour of pedons BST03 and BST04 are probably due to better drainage conditions in those pedons, thus allowing greater oxidation of iron thereby imparting the red colour to it (Plate 3a).

On the contrary, pedons on granitic soils exhibits dull yellowish brown to brown (10YR 5/3; 7.5YR 4/6) in the suface horizons. Profiles GNT01, GNT02, GNT03, and GNT04 were poorly drained as depicted by grayish yellow brown (10YR 6/2; 10YR 5/3) in their subsoil horizons (Plate 3b). The brown colour seen in the surface horizons is an indication that chemical weathering is taking place. This might be due to oxidation of Fe (II) to Fe (III), and an eventual release of Fe (III) and sand-sized grains. The Fe (III) appears to be responsible for the braunification of soils (Buol *et al.*, 1980) as indicated by their brown colour. Indeed, gleization processes in the subsoil horizons concurred with the grayish yellow brown as a result of reduction of iron under anaerobic soil conditions. The brown-dark brown-reddish brown-dark reddish browm mottles seen (7.5YR 4/6; 7.5YR 5/8; 7.5YR 3/4; 5YR 4/6; 2.5YR 4/6; 2.5YR 3/6) is an indication of poor drainage condition at the lowest part of these profiles.

**Plate III:** Profile pits from basaltic and granite parent materials respectively.

### 4.1.3. Soil structure

Soil structures are dominantly moderately developed, medium to coarse subangular blocky types, most likely as a result of the high clay contents and the dominance of the bivalent $Ca^{2+}$ and $Mg^{2+}$ over the monovalent $K^{+}$ and $Na^{+}$ on the exchange complex, which has resulted in the soils being well flocculated. In addition, a subangular blocky structure throughout the profiles is an indication of greater pedogenic development. With the exceptions of profiles GNT03 and GNT04 that posess weak fine subangular blocky structures (Plate IV) in the Ap horizon others were moderately developed, this might be in connection with low clay contents of the horizons. The horizons have the least clay contents of (16 and 24%).

The texture of the parent material also greatly influences the development of structure. Clay (< 2μm size material) is the only material in the soil that expands and contracts significantly upon wetting and drying. The basaltic soils of the study area revealed higher clay content over the granitic parent material which favor stronger grades of structure and blocky over prismatic structural types. In addition, the type of clay also affects structure formation. The amount of soil volume change varies with vermiculite and montmorillonite giving much greater change than kaolinite or illite (Ciolkosz *et al.*, 1979).

### 4.1.4. Soil consistence

Basaltic parent material had consistence ranging from sticky, plastic to slightly sticky, non plastic and sticky, non plastic (wet); firm to very friable (moist) and soft to slightly hard (dry) in the Ap horizons. The subsoil horizons were generally sticky and plastic to slightly

sticky, non plastic (wet); firm (moist) and slightly hard to hard (dry). While the granitic soils had sticky, plastic to slightly sticky and slightly plastic

Plate IV. Granite parent rock at Riyom, Plateau State

(wet); firm to friable and very friable (moist) and soft to to hard in the surface horizon. The subsoils were generally irregular in terms of consistence except profile GNT04 that was slightly sticky and slightly plastic (wet); friable (moist) and soft to hard (dry). The friable nature of the soil (moist) despite the high clay content and this is attributed to good aggregation of the soil particles. Daniels *et al.* (1978) reported firm to very firm (moist), hard to very hard (dry) consistence, as criteria that separate plinthite from the red mottles or hardening bodies.

### 4.1.5. Miscellaneous

Soil horizon boundary conditions in basaltic soils were generally clear and smooth with the exception of BST03 and BST04. Though, the Ap horizons were quite distinct from the B horizons and marked by clear boundary due to melanization by organic matter in the Ap horizons. Thus, there is a greater degree of horizon differentiation in profiles BST01 and BST02 than BST03 and BST04, indicating a greater degree of soil development in BST02, but in pedon BST04 this is due to non-soil layers. The granitic soils posses' clear and smooth boundary differentiation in the surface horizons with irregular subsoils, GNT04 possess clear and smooth horizon boundary differentiation an indication of greater soil development.

The Ap horizons of the studied soils irrespective of the parent materials have common medium pores to common fine pores. Similarly, the subsoil horizons in the studied area had common medium to common fine pores. There were few medium to common very fine roots in the Ap horizons of all the studied soils. Generally, the contents of roots decreased with increase in soil depth. Many roots were found mostly in the Ap horizons, which are the zones of root

activities. The iron nodules/or concretions were almost absent in the Ap horizons of basaltic soils while its granitic counterpart posses nodules.

Thin to thick clay and Fe (sometimes with Mn) cutans were evidence under the hand lens and petrographic microscopic (x 10 magnification) in the basaltic and granitic soils. The presence of thin slickensides in BST01 and BST02 sometimes tend to obscure the cutans except that in the former were concentrated along the walls of fissures that run from the surface to about 135 cm depth, but in BST02 they were found mainly on ped faces. Termite nests and channels were common in all the soils studied, especially at the Ap horizons, indicating that termites also contribute significantly to faunal pedoturbation in the soils. Mica flakes and fine quartz grains were the common minerals observed in these soils.

## 4.2. Physical Properties

### 4.2.1. Particle size distribution

Particle size distribution data for the soils is presented in Table 3. The sand fraction in the surface horizon of soils developed on basaltic parent material had values ranging from 10-38% with a mean (26%). One striking feature of the sand fraction in the soil type is decrease with abrupt increase in the third horizons of the profiles except Profile BST03. The sand fraction in Profile BST03 had near similar values with depth except for horizon 2BC1 that has increased (Table 3). Sand fraction was the dominant in granitic parent material, its content was the highest and decrease with depth in all profiles except Profile GNT01 with 24%. The overall distribution of sand fraction in surface soils develop on granite ranged from 24-64% with a mean (45%).

Table 3: Particle size distribution, bulk density and porosity of the pedons

| Horizon | Depth (cm) | Sand (2000-50 μm) | Silt (50-2μm) | Clay (<2μm) | Bulk density Mgm-3 | Porosity $m^{-3}m^{-3}$ | Textural class |
|---|---|---|---|---|---|---|---|
| | | | **BST01 CHAHA** | | | | |
| Ap | 0-35 | 30 | 20 | 50 | 1.049 | 0.396 | Clay |
| Bw1 | 35-60 | 16 | 20 | 64 | 1.141 | 0.431 | Clay |
| Bw2 | 60-88 | 44 | 22 | 34 | 1.304 | 0.492 | Clayloam |
| Bt1 | 88-130 | 20 | 22 | 58 | 1.212 | 0.457 | Clay |
| Bt2 | 130-170+ | 18 | 26 | 56 | 1.008 | 0.380 | Clay |
| | | | **BST02 NITA** | | | | |
| Ap | 0-16 | 38 | 34 | 28 | 1.171 | 0.442 | Clayloam |
| Bt1 | 16-70 | 12 | 22 | 66 | 1.010 | 0.381 | Clay |
| Bt2 | 70-117 | 20 | 22 | 58 | 1.008 | 0.380 | Clay |
| BC | 117-152 | 26 | 26 | 48 | 1.010 | 0.381 | Clay |
| C | 152-175+ | 38 | 18 | 44 | | | Clay |
| | | | **BST03 RA-HOSS** | | | | |
| Ap | 0-37 | 10 | 26 | 64 | 0.978 | 0.369 | Clay |
| Bw1 | 37-100 | 14 | 26 | 60 | 0.945 | 0.357 | Clay |
| 2BC1 | 100-110 | 24 | 28 | 48 | | | Clay |
| 2BC2 | 110-143 | 14 | 24 | 62 | 0.544 | 0.205 | Clay |
| 2Cr | 143-190 | 14 | 32 | 54 | 0.913 | 0.345 | Clay |
| | | | **BST04 TA-HOSS** | | | | |
| Ap | 0-15 | 24 | 22 | 54 | 0.770 | 0.291 | Clay |
| Bw1 | 15-110 | 20 | 22 | 58 | 0.602 | 0.227 | Clay |
| Bw2 | 110-156 | 38 | 24 | 46 | 0.783 | 0.295 | Clay |
| BC | 156-190 | 38 | 26 | 36 | 0.641 | 0.242 | Clayloam |
| | | | **GNT01** | | | | |
| Ap | 0-25 | 24 | 42 | 34 | 1.314 | 0.504 | Clayloam |
| AB | 25-60 | 38 | 26 | 36 | 1.141 | 0.431 | Clayloam |
| Bw1 | 60-100 | 36 | 30 | 34 | 1.405 | 0.530 | Clayloam |
| Bw2 | 100-140 | 18 | 48 | 34 | 1.456 | 0.549 | Siltyclayloam |
| C | 140-195 | 20 | 42 | 38 | 1.568 | 0.592 | Siltyclayloam |
| | | | **GNT02** | | | | |
| Ap | 0-20 | 34 | 38 | 28 | 1.518 | 0.573 | Loam |
| Bt | 20-78 | 24 | 32 | 44 | 1.385 | 0.523 | Clay |
| Bt2 | 78-115 | 26 | 36 | 38 | 1.467 | 0.554 | Clayloam |
| C | 115-130 | 60 | 16 | 24 | 1.701 | 0.642 | Sandyclayloam |
| | | | **GNT03 RIYOM** | | | | |
| Ap | 0-11 | 64 | 20 | 16 | 1.742 | 0.657 | Sandyloam |
| Bt1 | 11-38 | 44 | 20 | 36 | 1.518 | 0.573 | Clayloam |
| Bt2 | 38-66 | 52 | 22 | 26 | 1.395 | 0.526 | Sandyclayloam |
| Bt3 | 66-101 | 50 | 30 | 20 | 1.548 | 0.584 | Loam |
| Bt4 | 101-148 | 44 | 24 | 32 | 1.680 | 0.634 | Clayloam |
| | | | **GNT04 RIYOM** | | | | |
| Ap | 0-11 | 58 | 18 | 24 | 1.558 | 0.588 | Sandyclayloam |
| Bt1 | 11-48 | 40 | 20 | 40 | 1.507 | 0.569 | Clay |
| Bt2 | 48-120 | 50 | 16 | 34 | 1.660 | 0.626 | Sandyclayloam |
| BC | 120-165 | 58 | 14 | 28 | 1.518 | 0.573 | Sandyclayloam |

Silt contents of the soils in basaltic parent material ranged from 18-34%, which is relatively higher than 14-27% as reported by Kparmwang (1993) for Jos Plateau. The silt fraction is much lower compared to 12-42% of Eshett (1987) studies on basaltic soils of Ikom and Obubra areas of Cross River State, Nigeria. The differences in silt fraction in the different region might be attributed to rainfall intensity and duration. Due to climate change experience nowadays the rainfall intensity and duration is shorten as compared with the studies in 19$^{th}$ Century. Indeed, low intensity of weathering condition is expected to prevail (Table 3). However, the silt contents in granite parent material ranged from 14-48%. All the profiles in granite parent material had higher silt content except Profile GNT04 that exhibits lower contents of 14-20%. Murashkina *et al. (*2007) reported similar values for California granitic parent material. The silt content might indicate the degree of weathering, therefore, the order of weathering stage would be basalt>granite soil.

The clay fraction for basaltic parent material is generally above 40%, giving a dominantly clay texture to the soils. The fraction ranged between 28-66% in basaltic soil. The surface horizon ranged from 28-64% with a mean of 49 percent. The clay content was high in surface horizon with the exception of BST02 (28%) and increased with depth, nevertheless an irregular distribution pattern was observed in the study. The clay content shows marked increases in the Bt horizons of the profiles (Table 3), but it decreases with depth in Profile BST03. Thus, the field evidence of clay translocation from the surface horizons into Bt horizons of the pedons, strongly suggesting that the Bt horizons of this parent material is argillic/kandic horizons. Studies conducted on basaltic parent material revealed high clay contents with iron

oxides as subsidiary weathering products (Singer, 1966; Turner, 1971; Ogunwale, 1985; Eshett, 1987; Kparmwang, 1993; Abayneh *et al.,* 2007; Markus *et al.,* 2008).

However, the clay contents on granitic soils were lower than values on the basaltic soils. The values ranged from 16-44% while, the surface horizons of the profiles ranged from 16-34% wih a mean (24%). Among the parent materials under investigation, granite seems to produce coarse-grained soils consisting of significantly high sand and silt contents with lower clay percentage (Table 4). Researchers like Olowolafe (2002); Burke, (2002); Kooijman *et al.* (2005) investigated the effect of parent materials on soil properties established similar findings. The clay and sand fractions of the studied soils significantly ($P<0.001$) differed.

### 4.2.2. Bulk density and porosity

The bulk density values for surface horizons in the basaltic soils ranged from 0.770 to 1.171 $Mgm^{-3}$ with a (mean 0.992$Mgm^{-3}$) Table 3. The bulk density decreased with depth, except profile BST01 that increased with depth which is irregular in distribution. Bulk density is <1.0 $Mgm^{-3}$ in all horizons of profiles BST03 and BST04. The low bulk density, a requirement of, but not exclusive to andic properties, occurs in volcanic soils as a consequence of the development of a porous soil structure arising from the interaction of non-crystalline materials and soil organic matter content (Wada, 1989; Shoji *et al.,* 1993; Vacca *et al.,* 2009). The bulk density values of the Ap horizons in granitic soils ranged from 1.314 to 1.742 $Mgm^{-3}$. Result of this study was different from Gokbulak and Ozcan (2008) on granite sites but similar with that of (Olowolafe, 2002). This can be attributed to effect of land use. Because even under the same climatic and topographic conditions and vegetation types, type of land use can cause soil compaction which may result in higher soil bulk density (Gokbulak, 1989). The basaltic formed

soils compared favourably with the granite soils as evidence in Table 4, an indication of significantly difference ($P<0.001$).

Table 4: Comparism of some physical properties based on parent materials

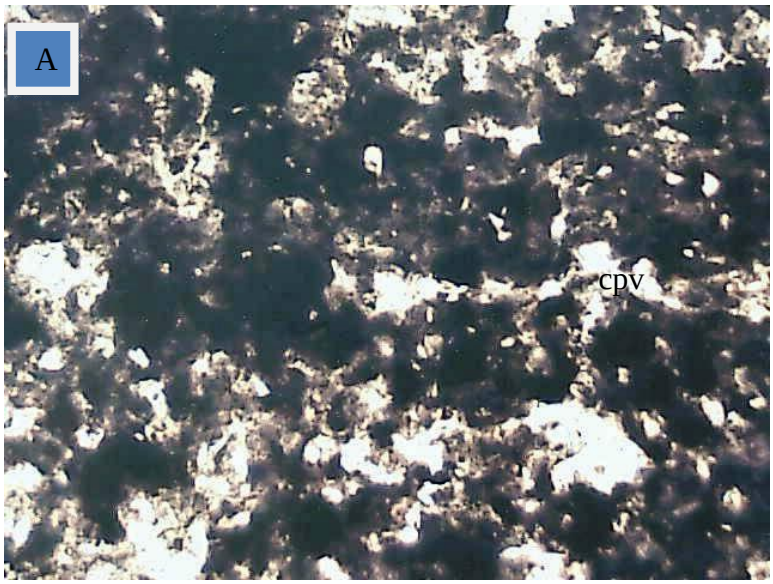
Interestingly, a horizon beneath the Ap horizon of granites and some basaltic soils were lower in value compared to the overlain (Ap) horizons. The result is similar with the findings of Hassan (2004) on Kerrikerri sandstones of Bauchi State, an indication of compaction due to cultivation. The lowest horizons in granites formed soils were high in bulk density. Variable bulk density among the soils points to the differences in clay content (Table 4) and the extent of structural development. A good plant growth is obtained with a bulk density below 1.4 $Mgm^{-3}$ for clay and 1.6 $Mgm^{-3}$ for sandy soils (Donahue *et al.,* 1990). Further, a bulk density between 1.45 and 1.65 $Mgm^{-3}$ for clayey soil and a soil porosity <0.40 $m^{-3}m^{-3}$ have been shown to inhibit root growth (Veighmayer and Hendrickson, 1948). In view of the above assertions, all the basaltic soils and granitic soils except profile GNT03 of the studied area with 0.77 to 1.56 $Mgm^{-3}$ bulk density and 0.40 to 0.63 $m^{-3}m^{-3}$ porosity in the root zone appear favourable for root penetration as well as elongation, aeration, infiltration, and free water movement.

Soil porosity ranged between 71 and 56% with a mean value of 63% in basaltic soils. Its value increased with the exception of profiles BST01 and BST04 that have inconsistent values with increased depth. However, granitic soils behaved differently and have regular pattern of distribution increasing with depth.

### 4.3. Chemical Properties

Exchangeable bases, exchangeable acidity, cation exchange capacity, base saturation, effective cation exchange capacity and cation exchange capacity (clay) are the parameters measured under chemical properties and presented in (Table 5).

Table 5: Soil chemical properties of the pedons



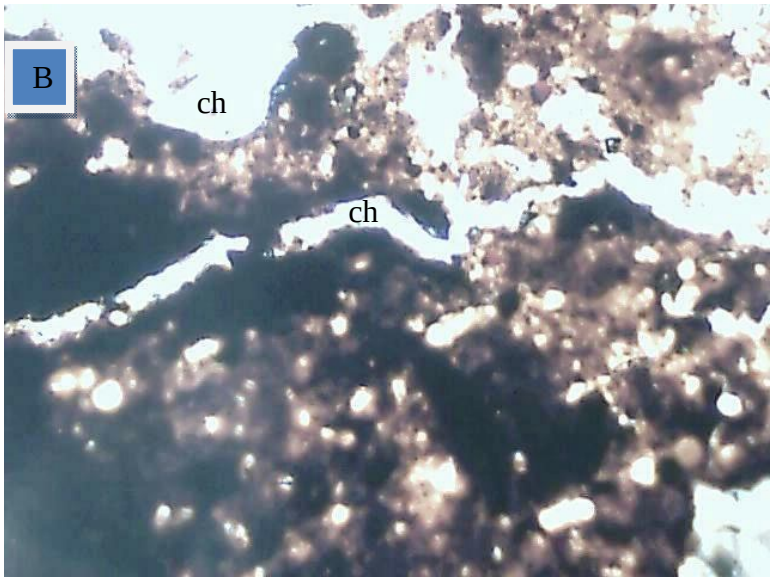




**Plate X.** Void types (a) Ap 25-35 cm PPL (BST03) with compound packing voids (cpv); (b) Bt2 48-58 cm PPL (GNT04) channel voids (v)

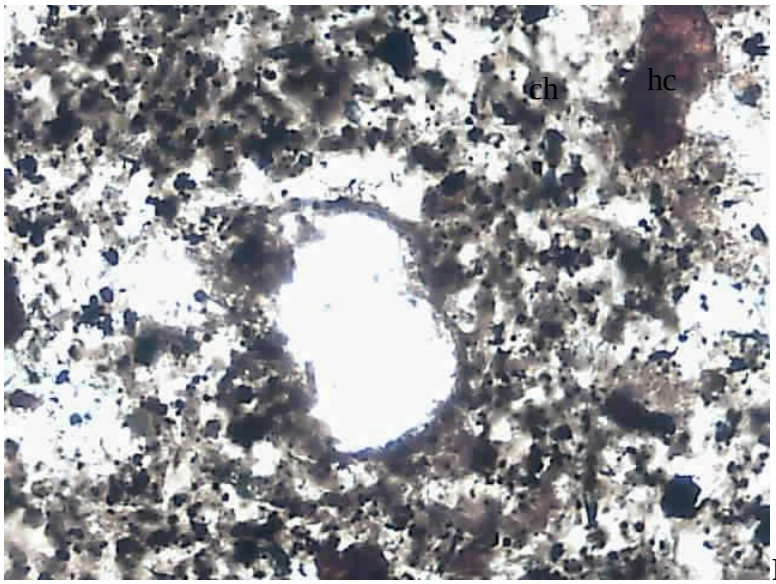
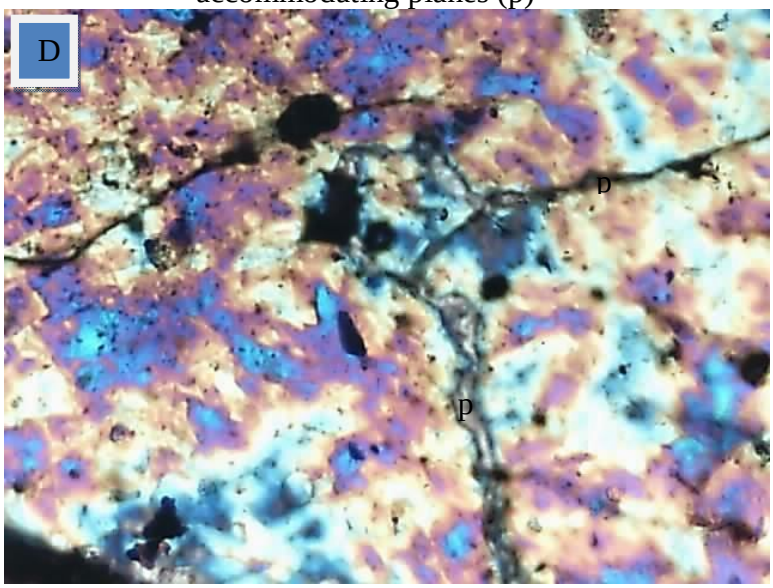



**Plate XI.** Void types: (c) C 162-172 cm PPL compound packing voids superposed by vughs (cpv-v) and crescent coatings (hc); (d) Bw1 30-40 cm XPL planes accommodating planes (p)



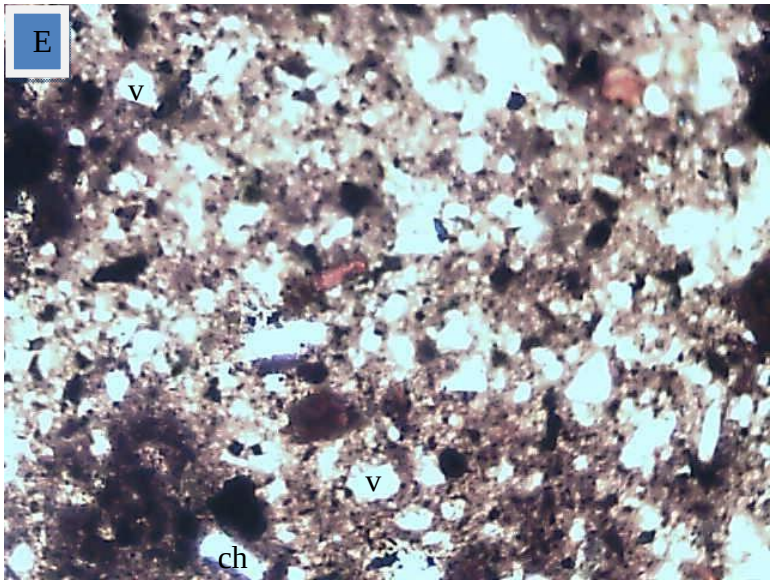



**Plate XII.** Void types: (e) Bt1 38-48 cm PPL vughs superposed by channel voids (v-ch).

### 4.3.1. Exchangeable bases

The dominant basic cations are calcium (Ca) and magnesium (Mg) with Ca>Mg for most horizons. Values of Ca ranged between 0.89 and 4.83 cmol (+) $kg^{-1}$ (mean, 1.62) in basaltic soils and 0.47 to 3.05 cmol (+) $kg^{-1}$ (mean, 1.31) in granite soils. Kparmwang (1993) and Eshett (1987) reported similar results for basalts in Nigeria. Though, Kparmwang *et al.* (1998) reported high values for Biu basaltic soils and attributed it to dominance of olivine and Ca-plagioclase in the mineralogy and low weathering and leaching capacity. Olowolafe and Dung (2000) reported low to very low calcium content in biotite-granites of Jos Plateau which is similar to the result obtained in this study. While comparing them with the volcanic soils in the area, it was observed that the dominant silicate clay mineral in the Inceptisols and Ultisols is kaolinite (Kparmwang, 1993).

Magnessium was next to calcium in content. Its values in basaltic profiles ranged between 0.002 and 0.501 cmol (+) $kg^{-1}$ (mean, 0.163). While the granite soils ranged from 0.020 to 0.435 cmol (+) $kg^{-1}$ (mean 0.186). However, Mg generally ranged from very low to moderately high in all the soils (Hill and Rackhman 1973; Valette and Ibanga, 1984). As pointed out earlier, annual rainfall of about 1440mm in the study area. Leaching of basic cations by rainfall and the low pH values of the soils are among the factors that further favour kaolinite formation.

Exchangeable potassium (K) ranged from 0.027 to 0.294 cmol (+) $kg^{-1}$ (mean 0.195) in basaltic profiles and between 0.033 and 0.334 cmol (+) $kg^{-1}$ (mean 0.185) in granite soils. Although, K might have also suffered the leaching losses but its derivation from K-rich parent materials appeared to have maintained its dominance in the soils. This result is similar with Olowolafe and Dung (2000) in biotite-granite of Jos Plateau. According to Landon (1991), in

general terms, a response to K is likely when a soil has exchangeable K value of below 0.2 meq/100g soil, depending upon the soils type and the crop in question.

Exchangeable sodium (Na) content in the basaltic soil profiles ranged between 0.030 and 0.124 cmol (+) $kg^{-1}$ (mean 0.061) and 0.036 to 0.139 cmol (+) $kg^{-1}$ (mean 0.074) in granite profiles. Exchangeable Na is rated very low to low in all the soils irrespective of the parent materials under consideration. The decrease in the content of these bases with depth further supports the argument of leaching ability. These soils may be said to be free from salinity/or sodic-saline problems.

### 4.3.2. Exchangeable acidity (EA)

The exchangeable acidity for basaltic parent material soils ranged from 0.8 to 3.3 cmol (+) $kg^{-1}$ (mean 1.763). Indeed, the Ap horizons had highest values across the profiles. The result is in contrast with Ogunwale (1985) and Moberg and Esu (1991) and Kparmwang *et al.* (1998), who reported zero exchangeable acidity values for the Biu soils. However, they are similar with the low exchangeable bases and high exchangeable acidity of Eshett (1987) for the Ikom soils and Markus *et al.* (2008) for Kuantan series. Buol *et al.* (1980) reported that exchangeable Al is generally low in basaltic soils. It is therefore possible that the high exchangeable Al obtained is a result of excessive weathering that might have led to the subsequent release of structural Al from clay minerals.

The granite soils exchangeable acidity ranged from 1.2 to 7.9 cmol (+) $kg^{-1}$ (mean 4.67) across the profiles. Higher values were obtained in granite than basaltic soils. High values recorded in Ap horizons of basaltic soils follow similar trend in granite soils. Ananthanarayana and Ravi (1997) reported range (1.2 to 18.3) cmol (+) $kg^{-1}$ for a wide range of Indian soils.

### 4.3.3. Cation exchange capacity (CEC)

The CEC values of Ap horizon in basaltic soils ranged from 8.5 to 14.2 cmol (+) $kg^{-1}$ (mean 11.63). In general, CEC values across the profiles in the basaltic soils ranged between 5.0 and 18.7 cmol (+) $kg^{-1}$. Interestingly, the values decreased with depth. It appears that the type of clay that first forms in the soils is a 2:1 type, as depicted by the increase in CEC in the lowest horizons (BST02 and BST03), where the weathering process is more active. This result is in concordance with the X-ray studies of the soils. The 2:1 clay types minerals: mica-vermiculite, hydroxyl-interlayered vermiculite led to the neoformation of kaolinite and hydroxyl-iron oxides minerals due to weathering intensities.

However, granitic soils CEC-NH4OAc values ranged from 4.3 to 8.9 cmol (+) $kg^{-1}$ (mean 6.094). This result compare favourably with that of Olowolafe and Dung (2000) who obtained 3.42 and 9.20 cmol (+) $kg^{-1}$ across the twenty-six profiles sited in biotite-granites of Jos Plateau. Leaching of basic cations by rainfall and the low pH values in the soils are among the factors that favour kaolinite formation. The dominance of low activity clay minerals has undoubtedly contributed to their low to very low CEC and the minimal to moderate levels of exchangeable cations of the soils. Certainly, these have pronounced influence on the productivity of the soils (Tables 5 and 6).

The cation exchange capacity of clay fraction ranged from 5.35 to 42.21 cmol (+) $kg^{-1}$ (mean 16.71) in basaltic soils. The profile distribution of CEC (clay) follow similar trend with that of CEC-$NH_4$OAc except profile BST04. This result compare favourably with those of Moberg and Esu (1991) and Ogunwale (1985) respectively. More so, the granitic soils varied from 9.4 to 26.94 cmol (+) $kg^{-1}$ (mean 14.85). The relatively moderate CEC, particularly that of the clay fraction >15 cmol (+) $kg^{-1}$ is attributed to the presence of 2:1, 1:1; hydrous mica and

iron oxides minerals. Further, Landon (1991) gave CEC(clay) as <10; 15-40; 80-100; about 100 and about 200 cmol (+) $kg^{-1}$ for kaolinite and halloysite; illite; montmorillonite; vermiculite and organic matter respectively. The t-test analysis showed significantly ($p<0.001$) difference among the PMs.

### 4.3.4. Base saturation

The base saturation percentages for the soils irrespective of the parent materials are very low to low <35% by $NH_4OAc$ summation. This is an indication of intensive weathering taking place. The profiles distribution in basaltic soils ranged from 5 to 46% (mean 20%) and in granitic soils varied between 7 and 46% (mean 28%). The t-test analysis to compare the difference in parent materials revealed significantly differences ($P<0.001$) among the PMs (Table 6).

### 4.3.5. Soil pH

The soil pH in water varied from 5.0 to 5.5 in the surface horizons of the basaltic parent material while the granitic soils ranged from 4.6 to 5.4. The overall variation of soil pH in water in both parent materials across the profiles ranged between 4.6 (GNT 01) and 5.6 (BST 01). With the exception of Profiles BST 02 and GNT 02, other pedons increase in value with depth.

### 4.3.6. Soil organic carbon

Soil organic carbon (SOC) contents of the soils decreased with increase depth in all the soil parent materials except profiles BST01 and GNT03 (Bt1). The surface soil values were rated low with the exception of profiles BST03 (1.08%) and BST04 (1.23%) respectively. Generally, the subsoil horizons were rated very low to low in all

Table 6: Comparism of some chemical properties based on parent materials

the parent materials studied. The Ap horizons of the basaltic soils ranged from 0.54 to 1.23% (mean 0.88) while the subsoil horizons ranged between 0.24 and 0.68% (mean 0.45)

On the other hand, OC in granitic soils ranged from 0.54 to 0.83% (mean 0.70%) in the Ap horizons and 0.15 to 0.79% (mean 0.43%) in the subsoil horizons, in addition, basaltic soils are richer in OC in the surface horizon than the granitic soils. This result is in conformity with the findings of Markus *et al.* (2008) even though the basaltic OC values are lower than their study. This may be attributed to different ecologies and luxuriant forest vegetation (Udic moisture regime). Kparmwang (1993) and Kparmwang *et al.* (1998) reported similar values for the Jos and Biu Plateau basalts, probably due to similarity in vegetation but, much lower than that reported by Eshett (1987) who attributed the high OC contents of his soils to contributions from litter or the luxuriant forest vegetation.

### 4.4. Micromorphological Properties

Soil micromorphology is a method to study the characterization of undisturbed soil samples using microscopic and submicroscopic techniques to identify soil components and establish their spatial, temporal, genetic, and functional relationships (Bullock *et al.*, 1985). Two basic principles of micropedology are the use of undisturbed (oriented) samples and the concept of functional research whereby all observations are directed towards reaching an understanding of the function of soil components and the relationship between one and another.

Micromorphology is the better way to understand the pedological history of those profiles. The main micromorphological results obtained from thin sections are summarized in Table 11 Appendix B and the details of thin-sections interpretations are in Appendix C. Systems for description of soil thin sections are not simply dictionaries of terminology (Ringrose-voase, 1991), but provide a conceptual framework which guides observations and organizes the data obtained. The micromorphological examination in the study area revealed differences in the fabric of the soil horizons (Table 7). The well-structured soil had a porphyric distribution fabric consisting of skeleton grains (in this case quartz) embedded in a clay matrix. The basaltic soils contained clay contents over 35% as opposed to granitic soil parent material. Thus, the former has the tendency of self-mulching. Smith (1981, 1984) and, Grant and Blackmore (1991) suggested that, during drying, the wide spacing of pedofeatures in the self-mulching variant allowed aggregates to form because the clay matrix could shrink *en mass* without interference from the grain coming into contact. The micromass is characterised by high degree of homogeneity, a red brown colour, a cloudy limpidity, a very weakly developed speckled or undifferentiated b-fabric and it has a pronounced porphyric c/f-related distribution; all characteristic of an oxic material (Stoops *et al.*, 1994; Stoops and Buol, 1985);

### 4.4.1. S-matrix (groundmass)

Groundmass is a general term used for the coarse and fine material and packing voids, which forms the base material of the soil in thin section, other than that in pedofeatures (Stoops, 2003). The colour of micromass as observed in thin sections partly depends on thickness, light source properties and magnification. In this study, only small variations in colours were observed. The horizon A/Bw has a brown to dark brown colour. The horizon BC generally has a

lighter colour compared to the other genetic horizons. Surface horizons and buried A horizons have the darkest colour.

Table 7: Micromorphological features of the modal soil profiles for basalts and granite parent materials**

**** Interpretation of symbols used in describing micromorphological features of the pedons in Table 7.**

**Optical Techniques**

PPL = Plane Polarize Light

XPL = Crossed Polarize Light

**Microstructure:**

**Shape**

C = Crumb

Sab = Subangular blocky

**Pedality**

W = Weak

M = Moderately

S = Strongly

**Voids**

CP = Compound packing voids

Ch = Channel

V = Vughs

Cham = Chamber

P = Planes

**S-Matrix (ground mass):**

**Coarse: Fine Ratio (c/f)**

M = Monic

P = Porphyric

OP = Open Porphyric

C = Chitonic

E = Enaulic

G = Gefuric

**b-fabric**

C = Crystallitic

S = Striated

P = Porostriated
G = Grano
**Pedofeatures:**
**Nodules**
O = Orthic
T = Typic
An = Anorthic
**Coatings**
HY = Hypocoatings
CR = Crescent coatings
MI = Micropan
**Cryatals**
E = Euhedral
SE = SubEuhedral
A = Anhedral

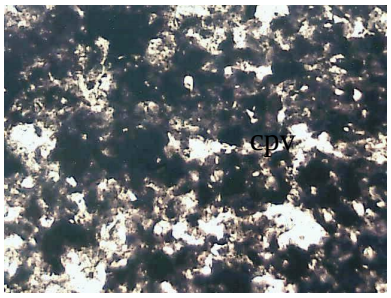
The micromass colour in the thin sections was generally more brownish than the field soil capacity colour. Rainfall and parent material appear to have no significant effect on the micromass colour. There are variations within the basaltic soils; profiles BST01 and BST02 are lighter than the BST03 and BST04 this might be probably due to soil age and decomposition of organic residues which may impart humus. In general basaltic soils compared favourably with the granitic soils in the study area. This indicates that the older parent materials have a lighter colour than the younger parent materials. These results compared favourably with the findings of (Arifin and Devnita, 2008).

### 4.4.2. Microstructure

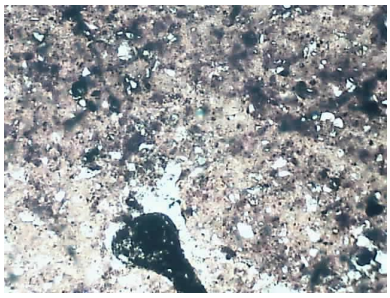
Microstructure refers to the shape, size and arrangement of soil aggregates and pores that are generally observed at a rather low magnification. The complete summary results of observation of the microsture are presented in (Table 11) and modal profiles are in (Table 7).

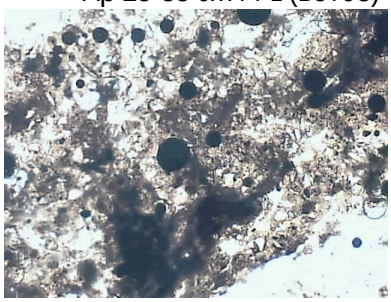
Some examples of soil microstructure features are presented in plates V, VI and VII. The surface horizon generally has crumb and granular microstructure whereas the subsoil horizons have angular blocky to subangular blocky microstructure.

The surface horizon (Ap) of Profiles GNT03; BST03; BST04; GNT01; GNT02 are characterized by a more strongly developed pedality (and darker colour) than BST01; GNT04 which are weakly separated and lighter in colour. This suggests



Ap 25-35 cm PPL (BST03)


Bt1 35-45 cm XPL (BST04)


Ap 0-10 cm PPL (BST01)



Bt1 16-26 cm PPL (BST02)

**Plate V:** S-matrix of the fabrics

that there is a relationship between organic matter content and pedality. Besides, the granular/crumb peds in the Ap horizon of soils developing on older parent materials are generally larger and have a denser groundmass than the younger soils. The chemical analysis indicates that the Ap horizon has a high organic carbon content and also contain: Al- and Fe-bearing organic complexes. Those materials are predicted to play a role in forming a stable granular microstructure. In all the horizons, the size of the peds shows a rather wide range (0.02-11.00 mm). The degree of accommodation ranges from well accommodated to unaccommodated, and is generally partly accommodated.

### 4.4.3. Related distribution patterns (c/f)

Horizons in the studied soils (basaltic and granitic) parent materials have porphyric and enaulic c/f related distribution patterns, i.e. they are composed of coarse materials embedded in a finer material (porphyric) or they have a skeleton of larger fabric units with aggregates of fine material in the interstitial spaces or enaulic (Goenadi and Tan, 1989; Stoops, 2003) where the aggregates do not completely fill the interstitial spaces, and the larger units support each other.

Surface horizon generally has enaulic c/f related distribution patterns especially in profile GNT01 which developed on young parent material. Profiles BST01; BST02 that developed from old parent material have porphyric c/f related distribution patterns in their surface horizons. The granular or crumb structure in the surface horizon could be related to a high biological activity (e.g., termites, ants), and the intensive growths of roots. In basaltic soils, the allophane content in the surface




**Plate VI.** Medium separated and developed pedality (m) granular microstructure (g) with compound packing voids (cpv) BST03 Ap 25-35 cm PPL.

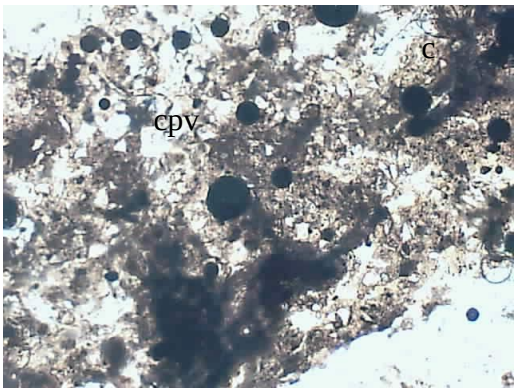
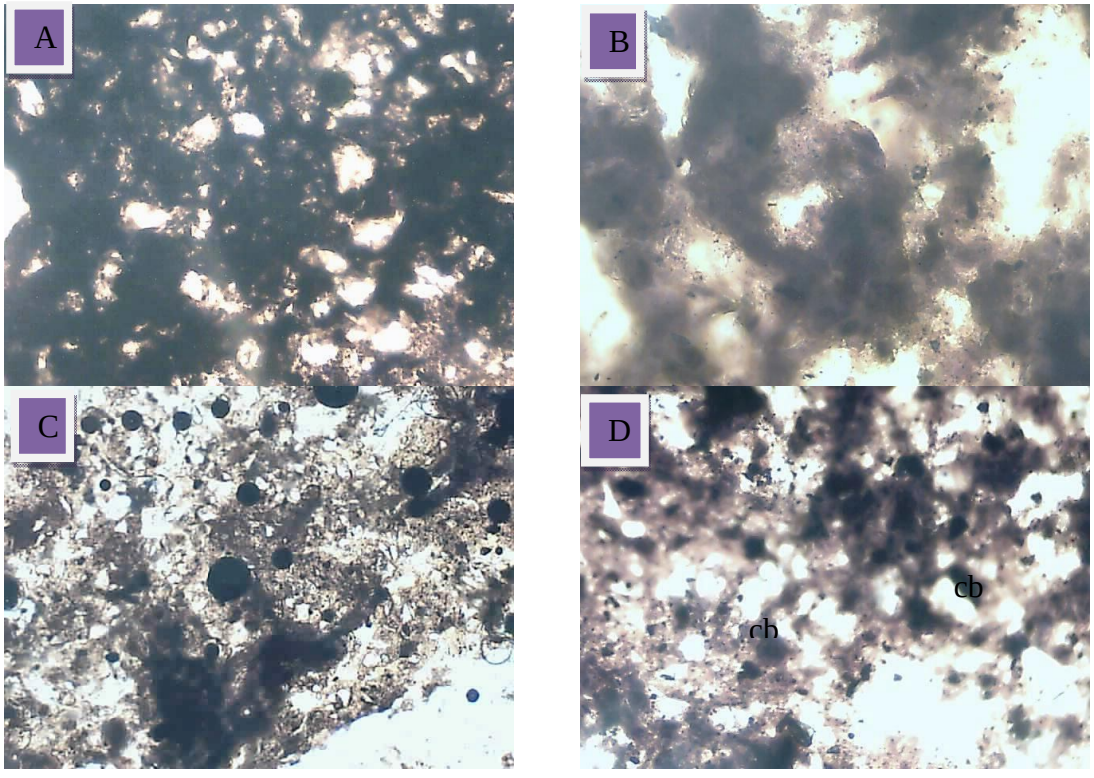



**Plate VII:** Weakly separated pedality (w) crumb microstructure (c) with compound packing voids (cpv) BST01

horizons is generally lower than in subsoils due to the strong accumulation of organic matter in the surface horizon, preventing the formation of allophane because of the formation of Al-humus complexes (Maeda *et al.,* 1997).

The subsoil horizons have porphyric c/f related distribution patterns. These horizons have a high total density, with porous and nonporous parts. Pores in the porous parts can be filled with material derived from upper horizons. With time, they can develop into nonporous materials in this way. Additionally, the change from enaulic to porphyric c/f related distribution patterns in profiles GNT01 and Bw2 (BST01) could be partly due to short range-order minerals weathered to crystalline minerals like halloysite and gibbsite. This result is similar with the findings of (Arifin and Devnita 2008).

Similarly, Brewer (1979) was with the view that soils with more than about 25% clay + silt have porphyric fabrics while those with less than 25% clay + silt, and have more silt than clay tend to have gefuric/enaulic fabrics (Table 3) Plate XII. Though, those with more clay than silt have chitonic fabrics. This relationship seems to hold across many soil types representing many pedogenic processes. According to Brewer, the explanation possibly lies in wetting and drying cycles which are common to all soils. Indeed, the observation of chitonic, gefuric and enaulic distribution fabrics, together with angular blocky, crumb and granular physical fabrics (poric) are indications of pore space resulting from the packing of individual particles. More so, porphyric and monic fabrics (aporic) might partially be ascribed as pore space unrelated to the packing of particles.



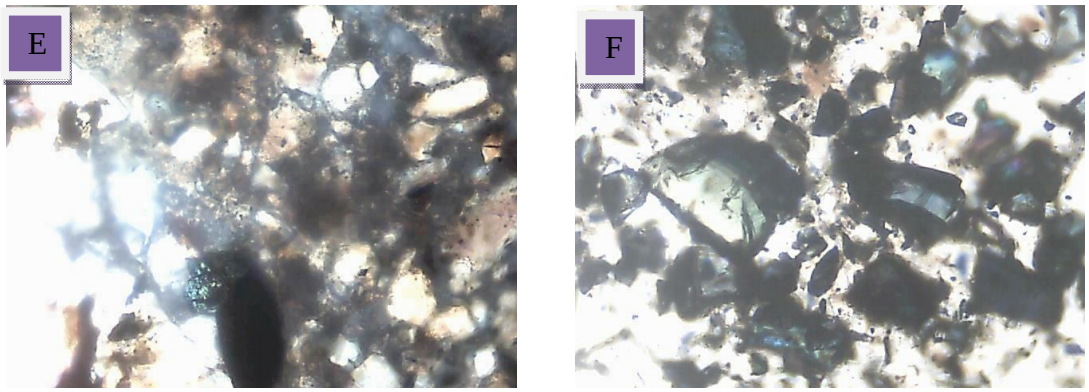



**Plate VIII:** Showing types of coarse fine ratios of the fabric (c/f) related distribution patterns: (a) Ap 0-10 cm PPL (GNT02) open porphyric; (b) AB 25-35 cm (GNT01) double spaced coarse enaulic c/f; (c) Ap 0-10 cm PPL (BST01) open porphyric c/f; (d) Bt1 78-88 cm XPL (BST03) gefuric (cb: clay bridge; (e) Bt2 70-80 cm XPL (BST02) double spaced porphyric c/f; (f) BC 180-190 cm XPL (BST04) chitonic c/f

Inferences from the mechanical analysis of the studied soils revealed high clay contents of the soils especially in the basaltic parent material. Where material is more of fine clay, it tends to coat mineral grains as the soil dries and a porphyric c/f related distribution patterns is likely to be formed. In young parent material especially the pedon GNT01 is dominated by silt content (the highest silt content fraction of 48%). The silty tend to be deposited between mineral grains and around their point of contact, so therefore, enaulic-chitonic-gefuric c/f related distribution patterns was observed.

### 4.4.4. Pedofeatures

The types of pedofeatures that have been recognized are amorphous and crystalline texture, fabric, and excrement pedofeatures (Bullock *et al.*, 1985; Stoops, 2003). Weak indications for the clay illuviation are only recognized for the B'wb horizons in profiles BST01; BST03; BST04 originated from old parent material (Plate IX). These horizons do not fulfill the prerequisite of an argillic horizon in Soil Taxonomy (Soil Survey Staff, 1992) due to the small total volume of illuvial clay (<1%) and the low degree of orientation within the clay coatings. Maeda *et al.* (1997) also reported a few coatings in basaltic soils. Mineral grains in pedons originated from old parent materials (GNT02; GNT03; GNT04; BST01) generally have anhedral shapes (and low $c/f_{2u}$ ratios), whereas grains in younger pedons (GNT01 and BST04) usually have subhedral to euhedral shape (and higher $c/f_{2u}$ ratios). Iron nodules are found in dominance in granitic soils. The nodules were formed by residual accumulation of iron compound, related to weathering of primary minerals.



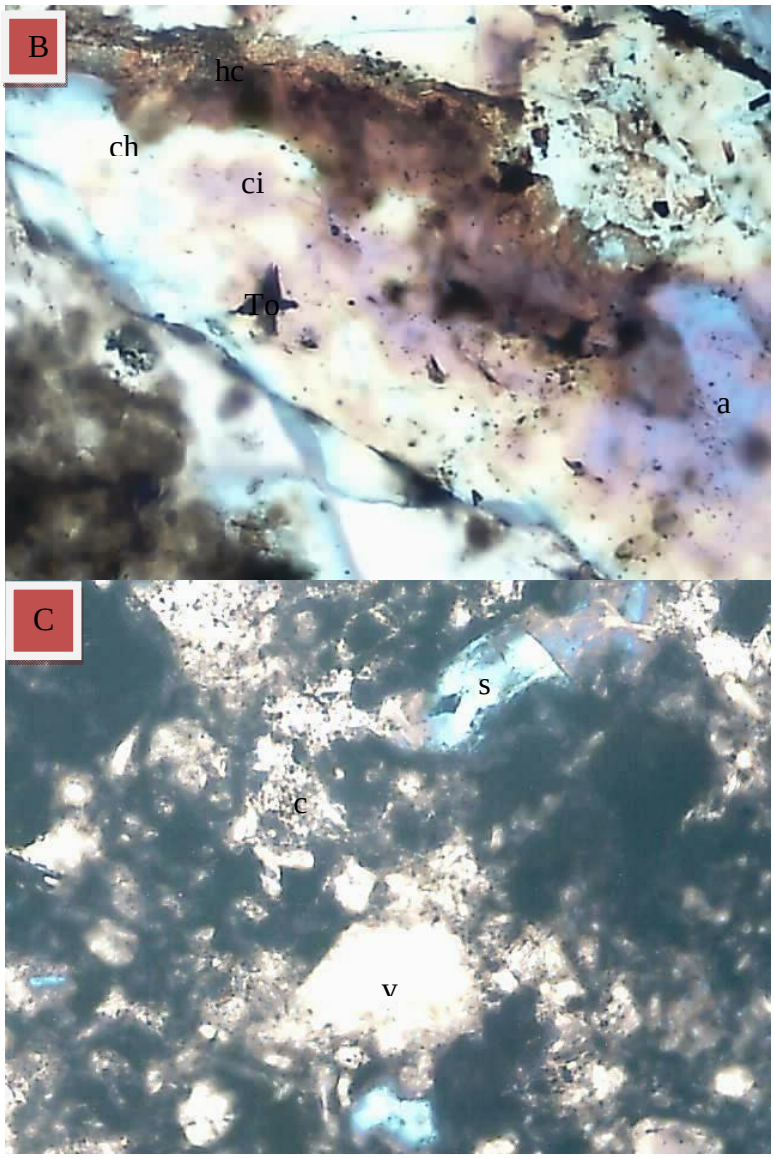


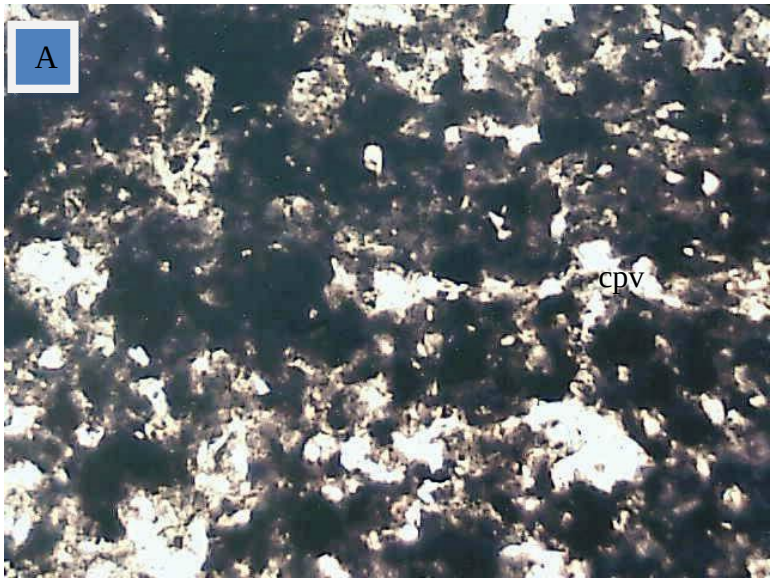

**Plate IX.** (a) Bt1 55-65 cm XPL (BST04) subhedral crystal mineral (S) with porostriated b-fabric orientations (b) Bt1 90-100 cm XPL (BST01) anhedral crystal mineral (a), hypo-coating of fine clay parallel to the voids (hc) and clay infillings (ci) with strongly impregnated typic orthic nodules (To) (c) AB 25-35 cm XPL (GNT01) Subhedral crystal grains(S), vughy microstructure with superposed weak crumb microsturcture.

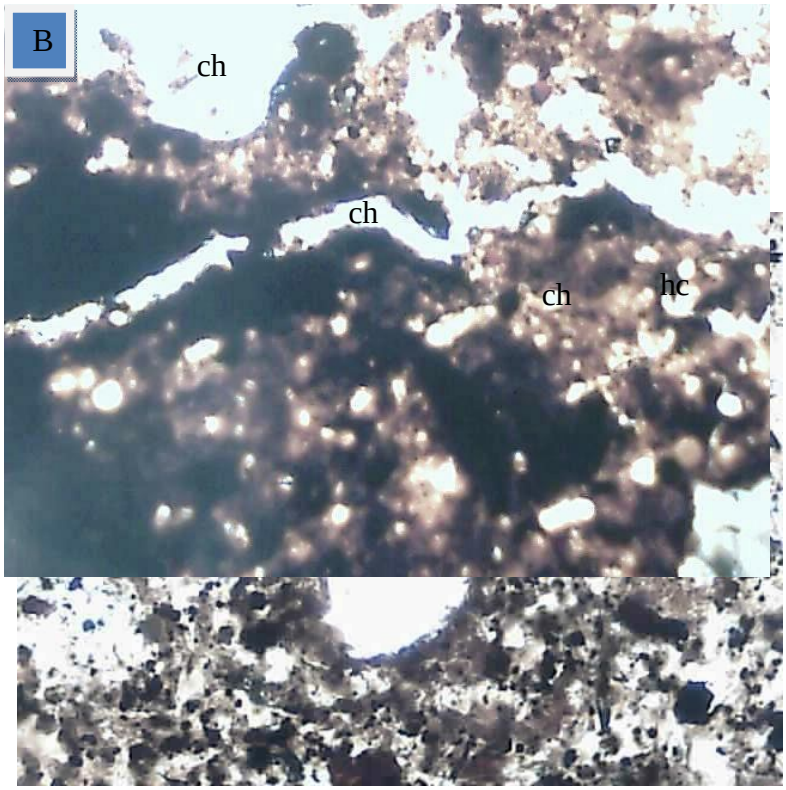
### 4.4.5. Miscellaneous

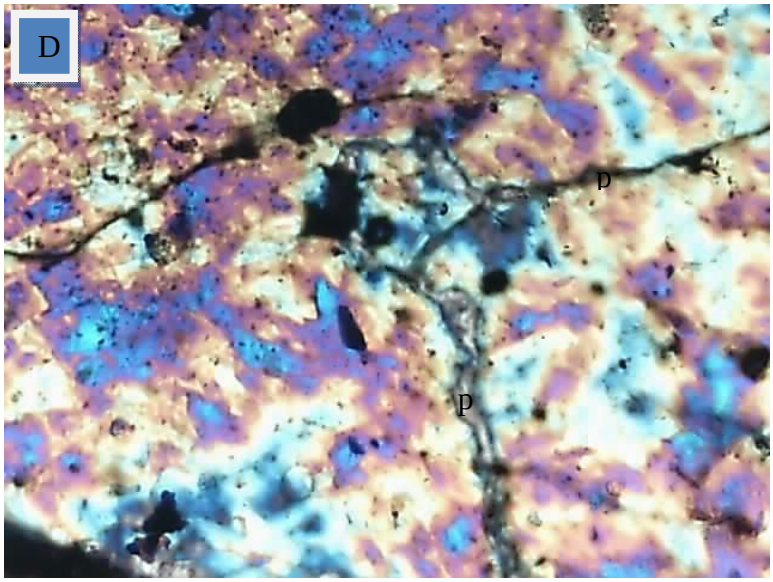
In surface horizons, compound packing voids are observed. The voids that are equant to elongate, interconnected, occur between granular, crumb and subangular blocky peds, which are unaccommodated. Other void type that was recognized is planar voids: chambers, channels, and planes vughs.

Subsoil horizons, subangular blocky microstructures, with or without pores, generally have planar voids, or planar voids with compound packing voids. In subsoil horizons (Bw; Bt; BC),

planar voids, vughs, channels, chambers and vescicles are recognized to develop on old parent materials (BST01; BST02; GNT02; GNT03; GNT04). Planar voids in the surface horizon (Ap) generally develop along root residues or microfauna remains. In the subsoil horizons, planar void is mainly formed by a development of crack in a dense groundmass material. Micromorphologists have described the following void types: Vughs as void which occurs in a wide particle size distribution, including clay size particles composed in part of layer-lattice types (flocculatate and adhere to each other) and Channel as void which occur as a result of cavity of fauna or plant root system or possibly by certain geological processes (Brewer, 1964; Brewer and Sleeman, 1963; Bullock *et al.*, 1985; Stoops, 2003). Others are Planes which originate primarly through shrinking and swelling during wetting and drying. Geologists' propsed stresses and tensions due either to earth movement in sedimentary rocks or to stresses from crystallization in igneous rocks such as columnar basalts.


A
cpv


B
ch
ch
ch
hc


D
p
p

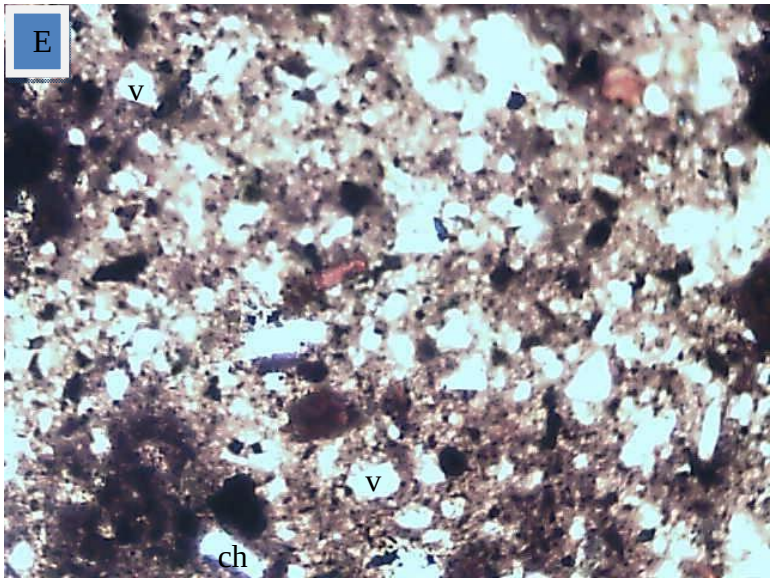

E
v
v
ch

**Plate 14:** Showing different voids types (a) Ap 25-35 cm PPL (BST03) with compound packing voids (cpv); (b) Bt2 48-58 cm PPL (GNT04) channel voids (v); (c) C 162-172 cm PPL compound packing voids superposed by vughs (cpv-v) and crescent coatings (hc); (d) Bw1 30-40 cm XPL planes accommodating planes (p); (e) Bt1 38-48 cm PPL vughs superposed by channel voids (v-ch).

## 4.5. Mineralogy Distribution of the Soil Profiles

### 4.5.1. Clay mineralogy

The surface horizon of the soils formed in basaltic parent material was predominantly occupied by 2:1 and 1:1 phyllosilicate clay minerals. The X-ray diffractograms of the non-oriented magnesium saturated clay fractions treated with glycerol and K-heated is shown in Figs. 2, 3, 4, and the mineral distribution along the profiles in Table 8, while the mineral peaks are in Appendix D. In the surface soil, mica-vermiculite peak (19.96 Å) was predominat upon treated with glycerol and K-saturation heating Hydroxy-interlayered vermiculite peak (11.79 Å), Hydroxyaluminium interlayered vermiculite peak (14.68 Å) and Mixed layer Maghemite peak (5.84 Å) respectively. In contrast, the soils developed on the same parent material (basalts) BST04 was preoccupied by Kaolinite peaks (7.07 Å, 2.31 Å) other minerals detected in dominant rate were Mn (IV) oxides peak (4.01 Å), Birnessite (3.55 Å) and Potassium feldspar (3.25 Å). On K-saturation and heating, strong peak of hydro-mica montmorillonite interstratifications (4.25 Å) and minor vermiculite (10.30 Å) were detected.

In subsoils, the following minerals were predominant (>75%) Kaolinte peaks (4.31 Å, 6.98 Å, 6.74 Å, 6.98 Å, 6.94 Å,) followed by Sepiolite peaks (12.15 Å, 12.08 Å), Smectite (saponite) (18.63 Å) and Sillica (26.66 Å). Upon solvated with glycerol and K-saturation heating respectively, Maghemite (5.80 Å, 3.76 Å), Lepiodocrocite kaolinite (6.82 Å), Saponite (19.31 Å), Kaolinite (6.98 Å,) and Plagioclase feldspars (6.51 Å) were predominantly observed.

Other minerals observed in dominat rate (50-75%) includes Vermiculite (9.21 Å), Microcline silica (26.42 Å), Chlorite peak (2.40 Å) and Illite (4.55 Å). Geothite peak (4.14 Å), Vermiculite goethite (2.35 Å), Gibbsite

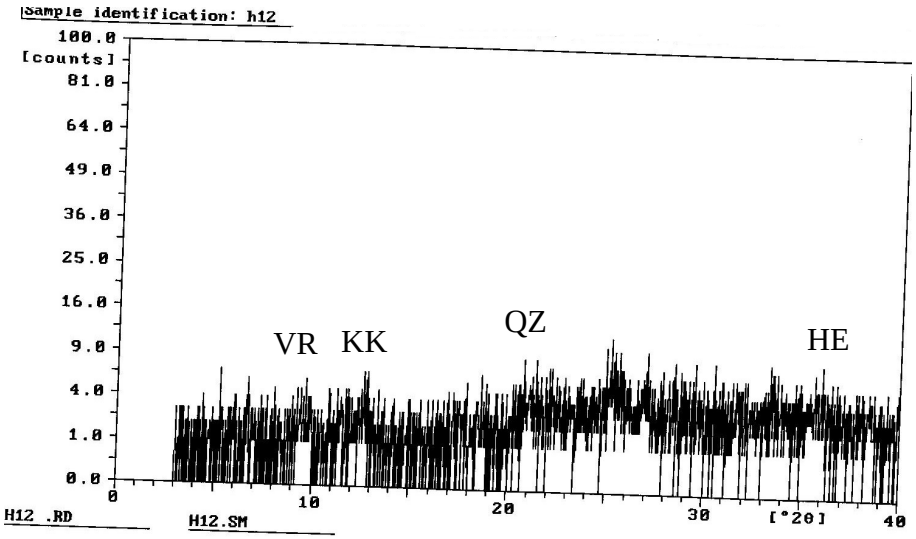



Fig. 2. X-ray diffractogram of clay fraction (Oriented) of Bt1 15-110 cm BST04
VR= vermiculite, KK= kaolinite, QZ= quartz, HE= hematite.

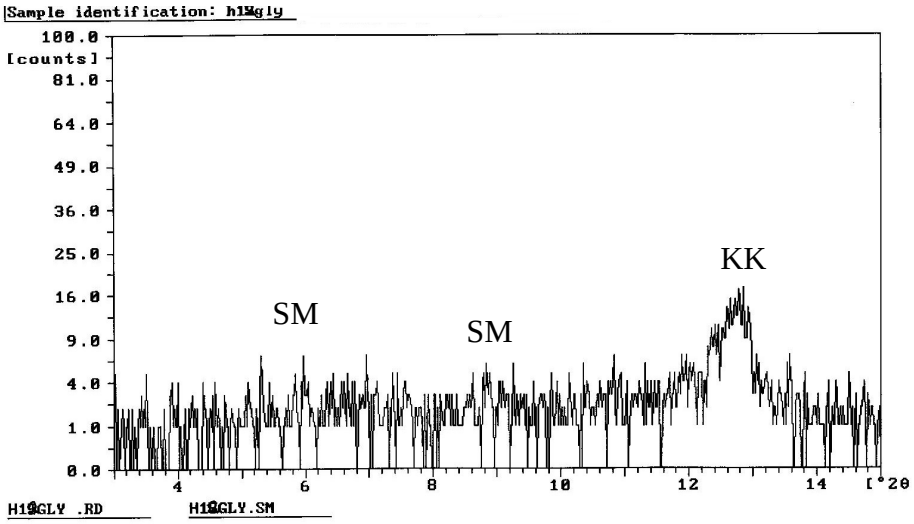



Fig.3. X-ray diffractogram of clay fraction (Glyl) of Bt1 15-110 cm BST04

SM= smectite, KK= kaolinite.

(2.39 Å), Plagioclase lepiodocrocite (6.29 Å), Quartz (4.25 Å, 4.23 Å) and Hematite (2.53 Å) were detected in medium rate.

The C horizon of soil shows kaolinite (7.04 Å) as predominant mineral which reduced to (6.90 Å) and disappeared upon K- sat and heating respectively. Mg-sat depict chlorite (3.50 Å) which increases upon glycerolation Hydromica-vermiculite (HIV) (12.52 Å, 19.89 Å). Plagioclase feldspars (6.66 Å) and microcline (27.23 Å) were observed in dominant rate. On heating, maghemite (3.76 Å) and silica (26.82 Å) were detected. In deed, the BC horizon of Profile TA-HOSS BST04 shows kaolinite (7.02 Å), Mackinawite ($Fe^3S_8$) (5.04 Å) and Quartz-hydro-mica montmorillonite (4.26 Å) to be predominantly occupied. Other minerals observed in medium to dominant were Lithiophorite-layered Mn (4.73 Å), Lepiodocrocite (6.02 Å) and Iron

microcline (6.54 Å). Medium rate of 2:1 phyllosilicate clay minerals (19.91 Å) with Mg-sat, upon glycerolation HIV (24.83 Å) was detected. On K-sat and heating mica-vermiculite interstratified peak (11.04 Å) was observed.

Clay minerals from basaltic soils have been intensively investigated in tropical and sub-tropical regions. The predominantly smectite and other 2:1/2:1:1 layer, kaolinitic, and Fe and Al oxides in the study area are in conformity with the previous works on the basaltic soils. The dominantly smectite clay has been attributed to cryoclastic particle-size reduction of hydrothemally altered rock minerals (Jeoag and Yaooan 2001; Simas *et al.*, 2006). In Hawaii, Bates (1960) found that basaltic rocks produce large amount of halloysite and gibbsite together with variable quantities of nontronite. Higushi and Aomine (1958) in Kyushu Japan found mainly halloysite with illite, vermiculite, chlorite and amorphous iron oxides. Pecrot *et al.* (1962) reported from Kiwu, Republic of Congo, the presence of Kaolin in well-drained basaltic soils and montmoriIlonite in the badly drained ones.

Kaolin minerals and crystalline oxides of Fe and Al as stable end products of basaltic clay are associated with high rainfall and high mean temperature (22°C).

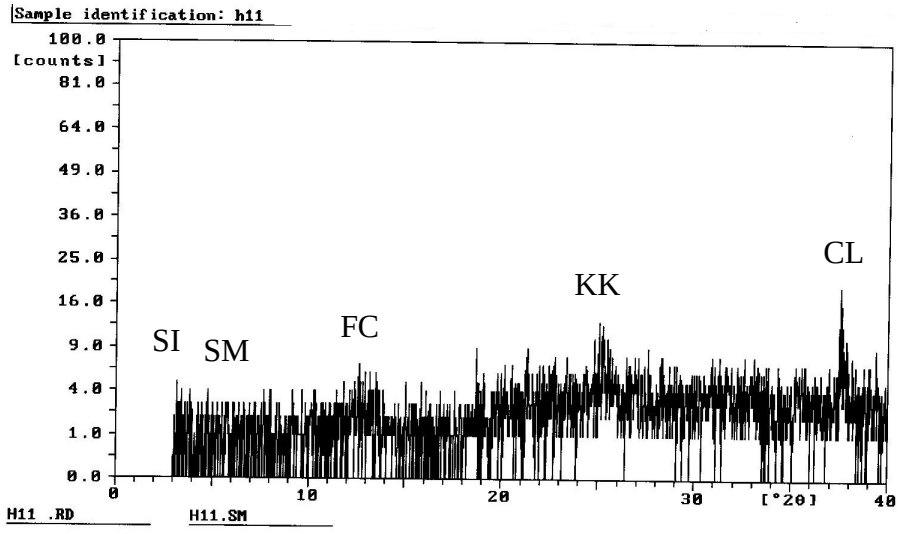


Fig.4. X-ray diffractogram of clay fraction (Oriented) of Bt2 110-150 cm BST04

SI= silica, SM= smectite, FC= microcline, KK= kaolinite, CL= chlorite

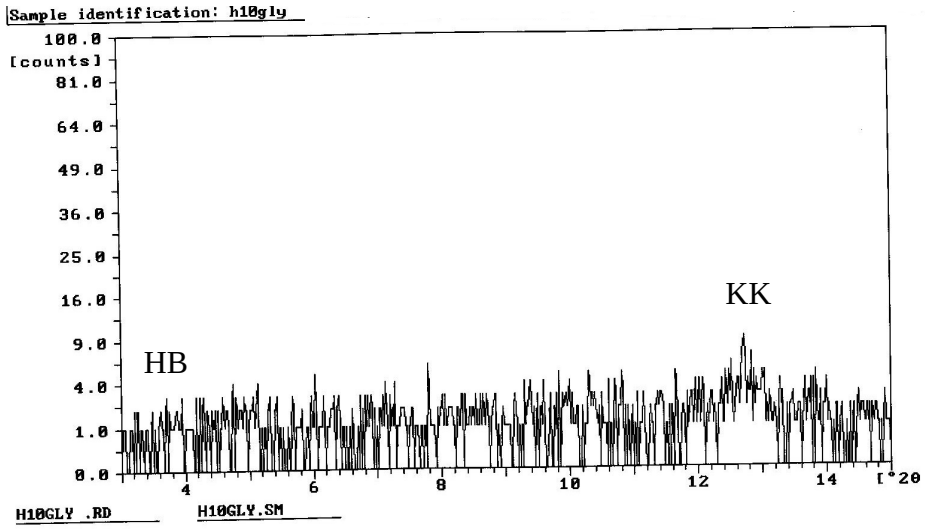


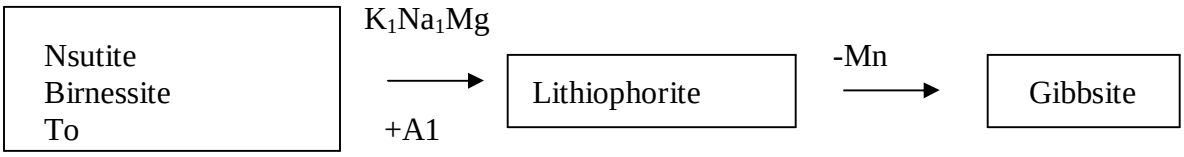

Fig.5. X-ray diffractograms of clay fraction (Glyl) of BC 150-190 cm BST04

HB= hydrobiotite, KK= kaolinite

MontmoriIlonite, in those conditions, occurs only as a transitional phase; under conditions of impeded drainage both montmoriIlonite and halloysite may be formed. Nevertheless, the formation of pedogenic iron oxides (Blue *et al.*, 2002; Simas *et al;* 2006; Simas *et al.*, 2007), hydroxyl-interlayered-smectites in the clay fraction for these soils suggest that chemical weathering has taken place. Graham and Geen, (2009) reported hydroxyl-interlayered minerals, gibbsite, and short range-ordered minerals. According to Birkeland (1999), broad relationships

of soil clay mineralogy are often best correlated with mean annual precipitation, rather than temperature. The amount of precipitation is important because percolating water leaches silica from soils and differentiates the kinds of clays that can form.

Lithiophorite has been identified as the most stable MnO in acid, highly weathered soils (Taylor *et al.,* 1964) and this has been attributed (Golden *et al.,* 1993) to the fact that high Al concentrations are needed for its formation (Table 5). Another possibility is that gibbsite sheets reduce the activation energy for Mn oxides and act as templates for lithiophorite crystallization when Mn oxidation is dissolved from less stable minerals. In the weathering sequence of Mn oxides, Lithiophorite is considered the final weathering product (Dixon, 1988; Parc *et al.*, 1989) and eventually transformed to gibbsite through reductive dissolution (Golden *et al.,* 1993). Indeed, the current study suggests that intense weathering may have caused Mn oxides in BST04 (basaltic parent material) to evolve along a weathering sequence similar to that described by Parc *et al.,* (1989) as follows:




Lepidocrocite (γ-FeooH), a polymorph of goethite (ά-FeooH) was identified with a strong peaks at (6.38 Å, 6.82Å) upon Mg - saturation with glycerol solvation at 100% intensities in BST04-TAHOSS. Vacca *et al.* (2009) reported that Lepidocrocite is a typical alteration product of iron minerals in hydromorphic soils, and can be found in low developed and well drained soils. However, Lepidocrocite might be synthesized through oxidation of Fe

(11) and Fe (I11) from the structure of minerals (e.g., biotite) which could serve as starting material. The immature nature of the soil in the study area Oxic Inceplosols was partially to its formation. Schwertmann and Taylor (1972), in their laboratory studies have thrown more light on the formation and stability of Lepidocrocite. The presence of silicate ions cannot often be held responsible for the inhibition of the conversion to goethite since it interferes only in the nucleation stage of goethite formation (Ibid). The latter has frequently been found associated with lepidocrocite, an indication that nucleation of goethite has already started. The possible effect of Al has not been investigated yet.

Similarly, goethite was detected in the soil; its presence cannot be excluded, as X-ray may not detect it if present in trace amounts. If goethite is present, then inhibited or retarded dissolution of Lepidocrocite could be responsible for its persistence. The absence of anaerobic condition (Table 2) and extreme pH values (Table 5) could act to minimize its dissolution. Furthermore, dissolution of Lepidocrocite rather than nucleation of goethite are the conversion rate determining process at temperatures and pH values prevailing in nature as shown by Schwertmann and Taylor (1972). However, as goethite was absent in BST04 soils, silicate ions may be responsible for the persistence of lepidocrocite through retardation of goethite nucleation. It is possible that retardation of both lepidocrocite dissolution and nucleation of goethite combined might be effective.

Consequently, as hematite was detected in medium rate intensity at a peak of (2.53 Å) in BST04-TAHOSS profile, originated from lepidocrocite, it could be scientifically deduced that conversion of lepidocrocite to hematite. Schwertmann and Taylor (1972) observed that during conversion of lepidocrocite to goethite some hematite formed from poorly crystalline FeOOH at 80°C in M KOH, as well as at lower KOH concentration (0.1M KOH). In the later case, the

super saturation of Fe was much lower for goethite to form while favorable for hematite formation.

On the whole, low permeability of the parent material due to clayey textural class (Table 3) has attenuated mineral weathering and diagenesis (Okusami *et al.,* 1987). The presence of Kaolinite could indicate that some transformation of minerals such as mica, feldspars and vermiculite had taken place. Ojanuga, (1979) opined that the warm soil temperature condition in the subhumid and semi-arid regions (Jos Plateau, subhumid) of Nigeria is believed to cause marked dissociation of soil water leading to a build-up of hydrogen ions, which favours hydrolytic weathering of silicates to Kaolinite.

Further more, chlorite/mixed layer minerals were identified in Profile BST01, and this might be partial chloritization of smectite in the soils as a result of incorporation of Fe, and possibly Al interlayering. The process of partial chloritization implies that exchangeable bases are leached and Al (or Fe) – octahedral sheets are formed at interlayer positions of the smectite by the mechanism referred to as Ferrolysis (Brinkman, 1970, 1978). This chloritization process can be associated with partial dissolution of exchangeable bases and of the Si-Tetrahedral sheet which may lead to formation of Kaolinite – Smectite interstratification or thin intermediate. Olowolafe (1995) work with the volcanic parent materials of the Jos Plateau observed that silicate clay mineral in the Inceptisols, Alfisols and Ultisols is Kaolinite. In a region with a dry season, however, processes are slower, and therefore due to a less severe weathering, kaolinite is accompanied by various amounts of chlorite, vermiculite and illite (Yoothong *et al.,* 1996), while the clay fraction in Entisols is amorphous to X-ray, indicating initial stage of tropical pedogenic processes whereby noncrystalline materials dominate.

In the basaltic parent material, minor quantity of quartz (25%) was observed. Accordingly, Singer (1978) and Singer *et al.* (1994) reported that basaltic parent material is devoid of quartz, many soils developing on basalt contain this mineral as a result of Aeolian deposition of fine silt-sized grains during dry and windy episodes. Thus, the presence of quartz in the most highly weathered horizon (Bt3 88-130 cm) is interpreted to indicate an Aeolian sediment input. Quartz and mica have been reported as constituents of harmattan dust that settles over northern Nigeria, the former sometimes assuming a major proportion (Mob erg *et al;* 1991). In spite of the fact that precipitation was high enough to actively leach carbonate from the soil profile, the presence of aeolian quartz suggests that conditions were intermittently dry.

The surface horizon of the soils developed from granite parent material was predominantly Quartz and interlayered minerals. Profile distribution of the mineral content (Table 9) and X-ray diffractograms of the non-oriented magnesium saturated clay fractions are shown in Figs 5-16. Mica-HIV minerals (12.9Å) and Quartz (3.29 Å) were predominant followed by Jarosite (3.09 Å) and feldspars-plagioclase (6.7Å).

Minor minerals detected were magnetite (5.08Å), goethite (4.17Å). Upon solvation with magnesium-glycolation, M-HIV minerals expanded their band and smectite peak (16.36Å) was observed. Kaolinite (6.99 Å) was also observed as predominant mineral, while silica 26.81Å was medium saturated. On K-saturated heating, there was decrease in the band width of vermiculite and mica-vermiculite (10.6Å) was observed. Similarly, Lepiodocrocite (6.84 Å), Chamosite (ironic) birnessite (7.06 Å) and Geothite (4.15 Å) were also evidence

The subsurface horizon was predominantly occupied with Microcline (3.26 Å) and Halloysite peaks (2.39 Å, 2.36 Å) and Chlorite (2.40 Å) followed by Plagioclase-oligoclase peaks (3.47 Å, 6.61 Å). Other minerals observed were microcline (iron) (3.24 Å) and traces of 2:1 phyllosilicate clay minerals. Upon Mg-glycolation, kaolinite peaks (6.98 Å, 6.96 Å, and 7.00 Å) and lepidocrocite peaks (6.81 Å, 6.83 Å) were predominantly detected. On hating the K-saturated sample, the kaolinite peak disappeared, confirming the presence of kaolin and simultaneously reinforced Al-interlayered vermiculite (10.69 Å), Lithiophorite-vermiculite (9.43 Å) regions. Geothite (4.15 Å, 4.18 Å, and 4.19 Å) and gibbsite (4.36 Å) minerals were detected at higher intensity.

In C horzon of the soils, lepidocrocite peak (6.87 Å), Rutile peak (3.21 Å) and kaolinite (chlorite Fe-rich) peak (3.51 Å) were observed as predominant minerals. Microcline 3.26 Å was dominantly detected. On Mg-glycolation the band width increases the peak regions to interstratifications of mica-vermiculite (20.02 Å). While on heating, the K-saturated sample mica-vermiculite (11.45 Å) was observed with minor kaolinite (6.90 Å). Kretzschmar *et al.* (1997) worked on granitic parent material of North Carolina; USA reported the clay-sized fractions of the A and Bt horizons to contained considerable amounts of hydroxyl- Al-interlayered vermiculite (HIV). The HIV contents were highest near the soil surface and decreased with depth, which is commonly observed in Ultisols of the southeastern United States.

The common minerals found within soils of these settings are products of weathering that are relatively stable in acid, well drained environments (e.g. kaolinite, hydroxy-interlayered vermiculite, gibbsite, goethite, and hematite), resistant minerals (e.g. quartz, and in lesser quantities, Ti-bearing oxides), or weatherable minerals in various stages of

decomposition (e.g. mica and feldspars). Jackson and Sherman (1953) developed a classic weathering/stability sequence that numerically ranked soil mineral stability in oxidized environments. The scheme is based on evaluation of qualitative and quantitative soil mineral data, and is a useful tool for comparing the stability of soil clays. Minerals ranked 10 or above indicate the highest level of stability, and are commonly found in highly weathered soils: i.e. 10 = kaolinite/halloysite, 11 = gibbsite, 12 = hematite/goethite, 13 = anatase/rutile.. Interestingly, in conformity with the present study Qafoku *et al.,* 2004 reported dominate concentration of kaolinite, gibbsite, goethite and hematite in the clay fraction of red soils of advanced stage of weathering and leaching conditions of topical and subtropical regions.

Similarly, Rich (1968) suggested that relatively acid (pH 4.5 to 5.8) — oxidizing conditions in low organic matter environments with seasonal wetting and drying, conditions commonly found in upland, well drained settings of the Southeastern U.S., promote hydroxyinterlayered vermiculite formation. Several studies have noted the enrichment in near-surface horizons and sandy epipedons of hydroxyinterlayered vermiculite, and its relative depletion with corresponding increases in kaolinite either with depth and/or across eluvial/illuvial boundaries (Rich

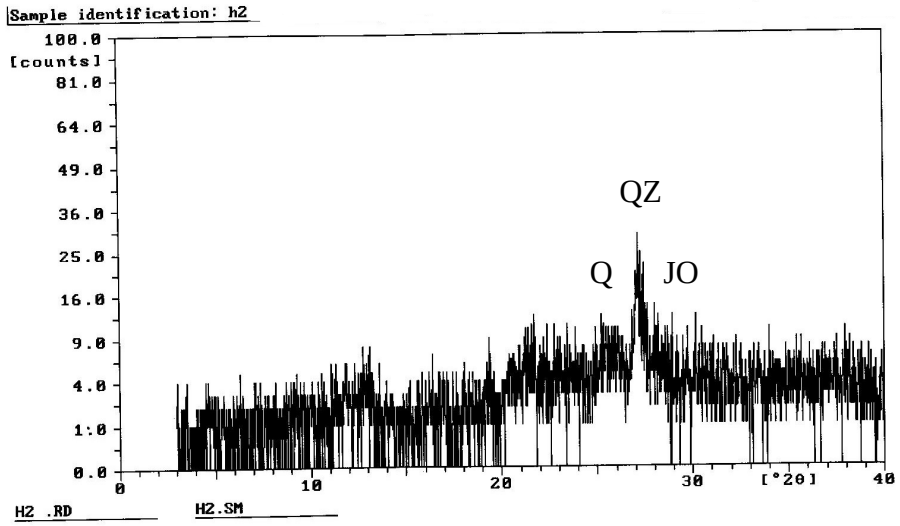



Fig. 6. X-ray diffractogram of clay fraction (Oriented) of Ap 0-25 cm GNT01
QZ= quartz, JO= jarosite

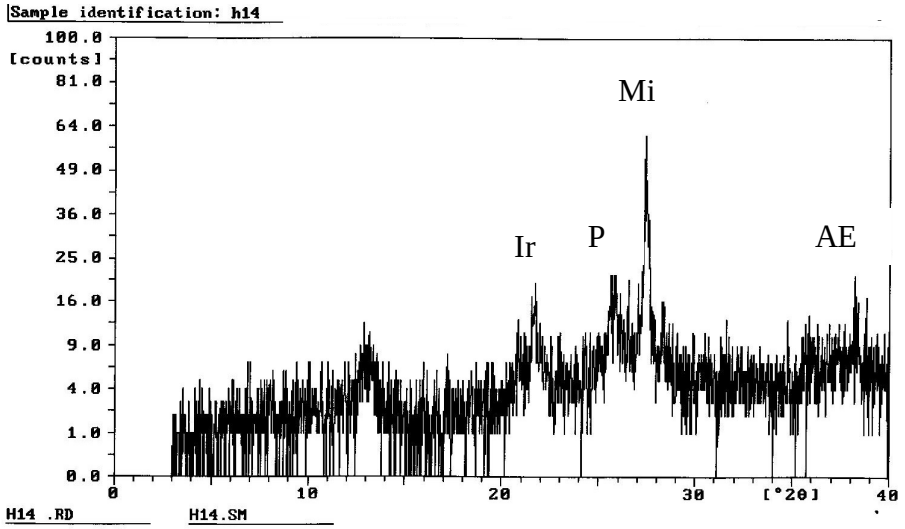



Fig. 7. X-ray diffractogram of clay fraction (Oriented) of B25-60 cm GNT01
Mi= mica, AE= anatase, P= plagioclase, Ir= iron microcline

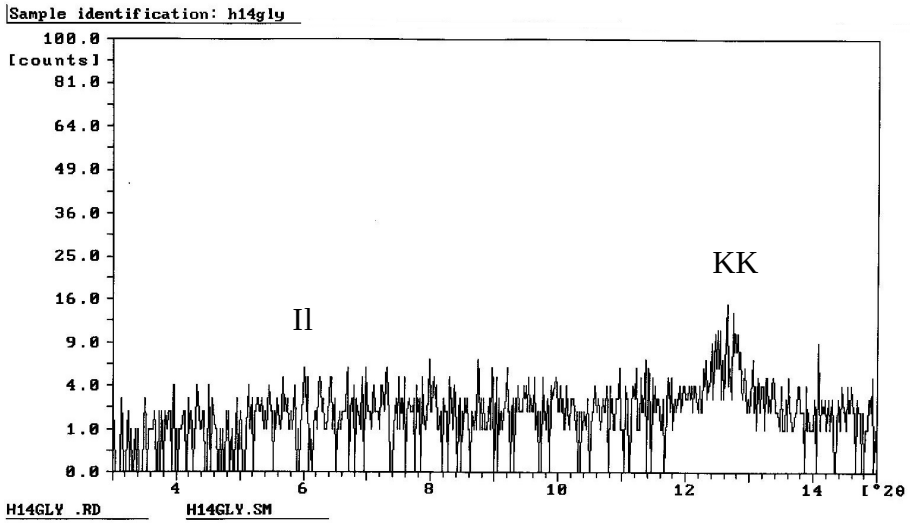



Fig. 8. X-ray diffractogram of clay fraction (Glyl) of B 25-60 cm GNT01

II= illite, KK= kaolinite

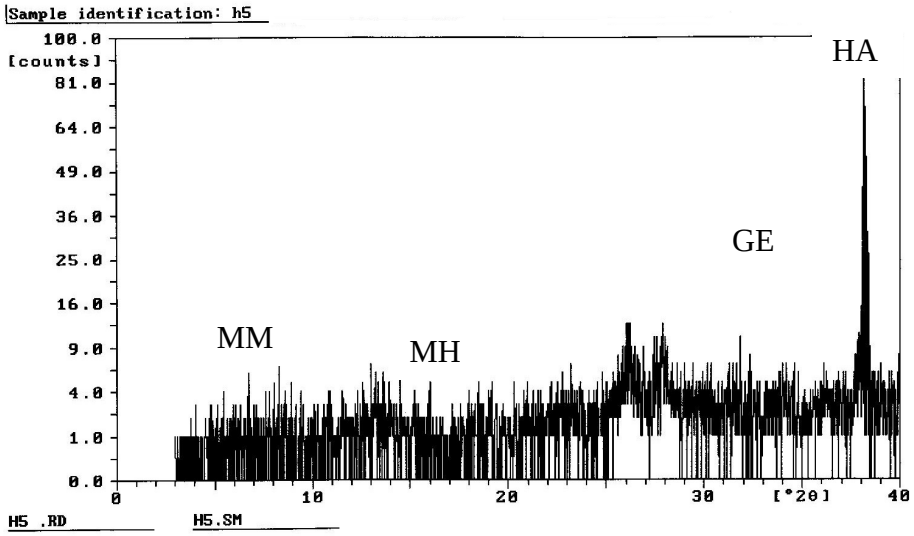



Fig.9. X-ray diffractogram of clay fraction (Oriented) in B 60-100 cm GNT01
MM= montimorillonite-mica, MH= maghemite, GE= goethite, HA= halloysite

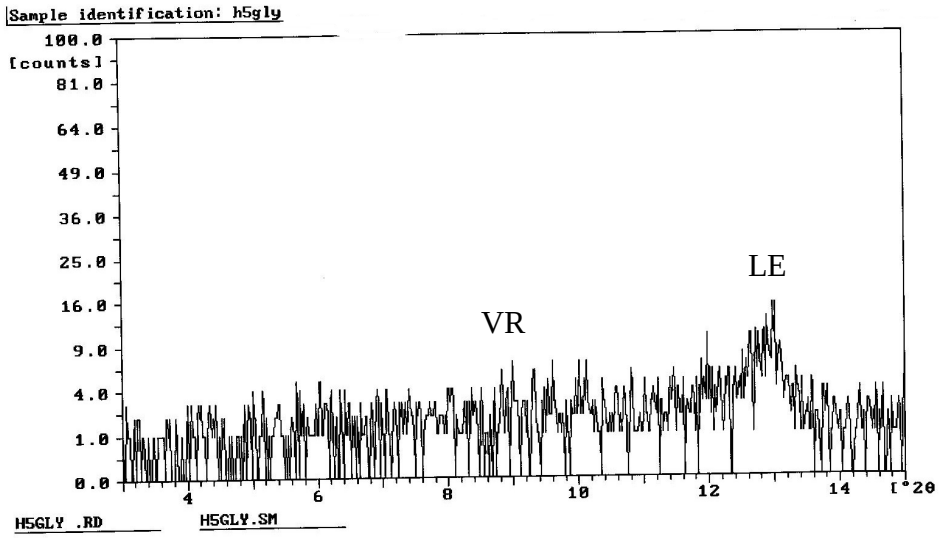



Fig.10. X-ray diffractograms of clay fraction (Glyl) of B 60-100 cm GNT01

VR= vermiculite, LE= lepidocrocite

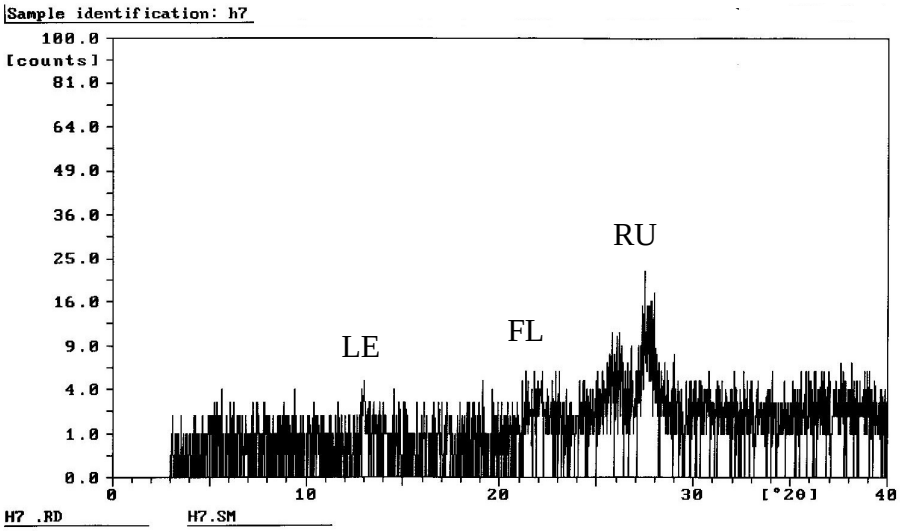



Fig. 11. X-ray diffractogram of clay fraction (Oriented) of C 100-140 cm GNT01
LE= lepidocrocite, RU= rutile

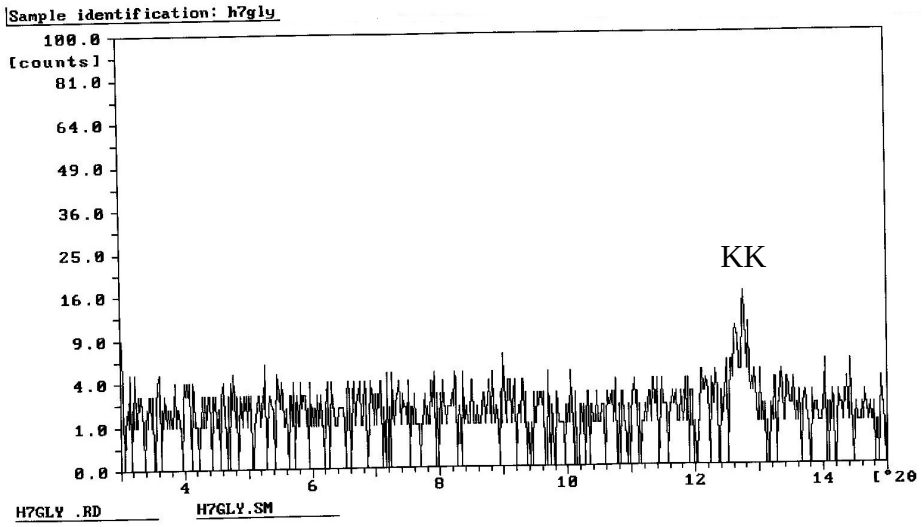



Fig.12. X-ray diffractogram clay fraction (Glyl) of C 100-140 cm GNT01

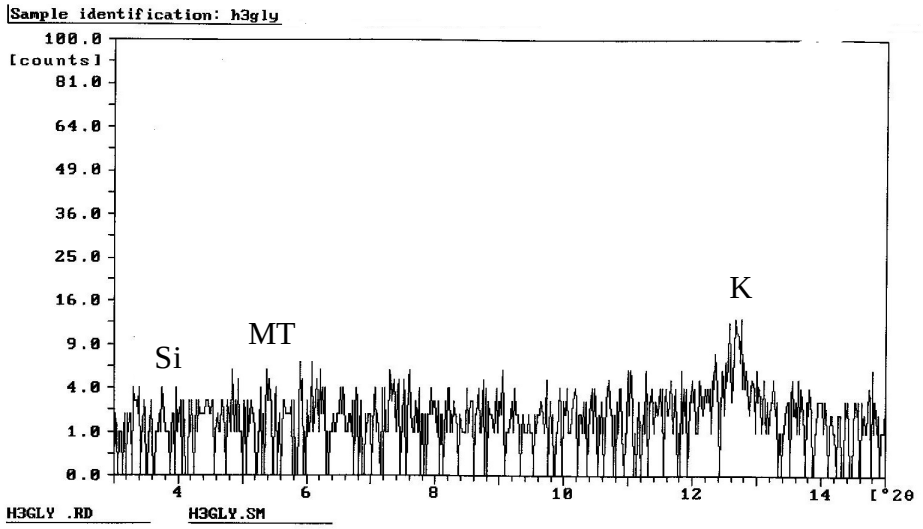



Fig.13. X-ray diffractograms of clay fraction (Glyl) of Ap 0-11 cm GNT04

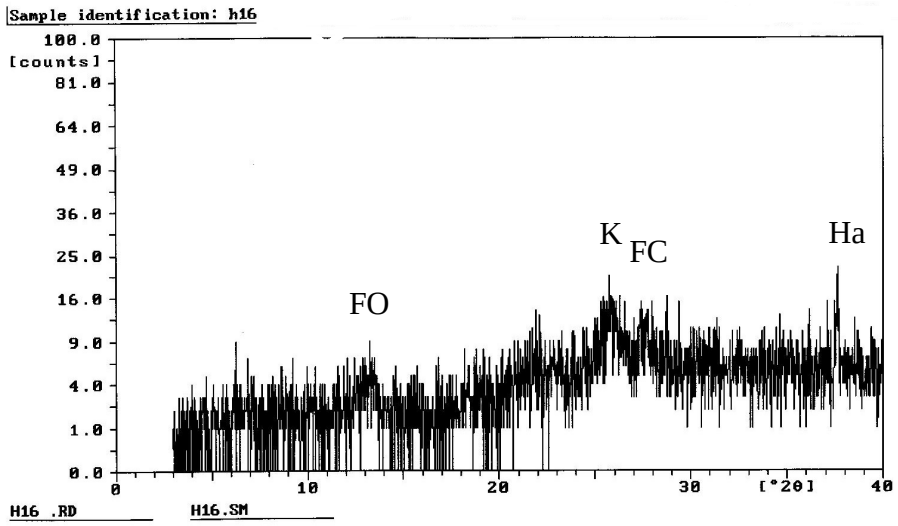



Fig. 14. X-ray diffractogram of clay fraction (oriented) of B 11-38 cm GNT04

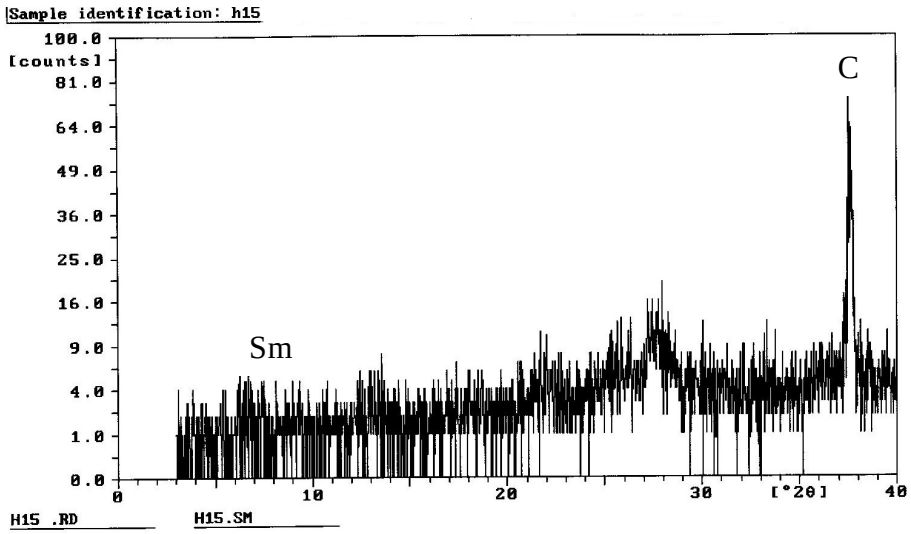



Fig. 15. X-ray diffractogram of clay fraction (Oriented) of Bt1 66-101 cm GNT04

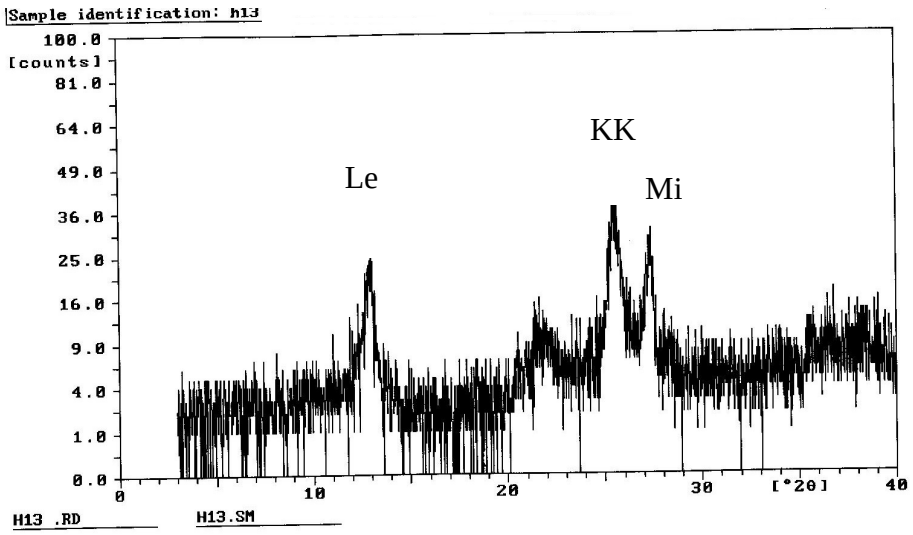



Fig.16 X-ray diffractogram of clay fraction (Oriented) of BC 120-165cm GNT04

and Obenshain, 1955; Harris *et al.*, 1987; Harris *et al.*, 1989; Cabrera-Martinez *et al.*, 1989).

Indeed, mineralogy of the studied soils can be placed into three general categories: (1) inheritance from the parent materials (ii) transformation from primary minerals, and (iii) neoformation (e.g. precipitation from solution). These three categories generally contributed to the clay minerals observed in the study area. Extensive works (Allen and Hajek, 1989; Birkland, 1999; Graham and Geen, 2009) on soils opined that mica, particularly biotite, and chlorite are commonly inherited clay minerals. They are readily transformed to vermiculite, smectite, hydroxyl-interlayered minerals or interstratified minerals. Kaolinite, halloysite, gibbsite, short range-ordered minerals, smectite, and palygorskite are neoformed in various soil environments.

Indeed, the ferruginous soils of Jos Plateau, developed under tropical acid weathering conditions, have been considered as highly weathered soils with dominant proportions of kaolinite and Fe and Al oxide minerals and in significant amounts of weatherable minerals. But the results of the present study indicate the presence of significant amounts (> 10%) of weatherable minerals by the presence of mica-HIV, plagioclase and smectite in the clay faction. The occurrence of M-HIV and mica indicates that mica has been transformed into vermiculite and then to HIV. The $Al^{3+}$ released during tropical weathering is adsorbed in the interlayer of vermiculite to form HIV and further probably to Al-HIV/Kl-HIV. (Pal *et al;* 1989; Bhattacharyya *et al.*, 1993) reported that the hydroxyl- Al-interlayering in the expansible 2:1 layer silicates is a primary reaction towards the interstratifications of 2:1and 1:1 layers and such interstratified minerals are common in the ferruginous soils of India.

## 4.6. Soil Classification

### 4.6.1. Criteria for classification (USDA Soil Taxonomy System)

**a. Soil moisture regime**: The mean annual rainfall in the study area average about 1444.66mm, data collected from Plateau State Agricultural Development Programme (PADP). This amount of rainfall is concentrated within 7-8 months (Table 1). The moisture regime within the study area is therefore, Ustic except a pedon in granitic soils that is Aquic condition (GNT02). All the pedons in basaltic parent material were well drained while the granitic parent material ranged from poorly to imperfectly-drained.

**b. Soil temperature regime:** The mean annual temperature in the study area is 22$^{o}$C or higher. The mean summer and winter soil temperature do not differ by up to 5$^{o}$C at a depth of 30 and 100 cm. Therefore, the difference will be less than 56$^{o}$C at the control section, i.e. 50 cm depth. By implication the soil temperature in this area will be isohyperthermic type (Soil Survey Staff, 1999).

**c. Diagnostic surface horizons (Epipedons)**. The epipedon present in some of the pedons is Umbric (BST03, and GNT01) because the OC is >0.6% and have base saturation (BS) <50% by NH4OAc which is <35% by cation summation. With the high rainfall inferred for the area this lead to leaching of the $Ca^{2+}$ and $Mg^{2+}$ contents. The surface horizons of pedons BST01, BST02, BST04, GNT03, GNT02 and GNT04 all have ochric epipedons because they were too thin, too light in colour, low bivalent cations and low in available.P, to qualify as mollic, anthropic, umbric, histic, melanic or plaggen epipedons. Though, pedons BST04, GNT04 and BST02 have OC >0.6% but with thin layer to be consider as Umbric epipedon.

d. **Diagnostic subsurface horizon (Endopedons)**: The diagnostic B horizons present in the soils were identified as cambic B horizon in pedons BST03 RA-HOSS, BST04 TA-HOSS

and GNT01 because of weakly developed soil structure with little evidence of illuviation clay. It lacks the set of properties diagnostic for a *ferralic, argic, nitric or spodic* horizon and the dark colours, organic matter content and structure of a *histic, folic, mollic or umbric* horizon. Pedons BST01 CHAHA, BST02 NITA, GNT02 and GNT04 all have a kandic B horizon because:

i) The clay increase is >4% within a distance of 20 cm.

ii) A total thickness was more than 30 cm in all the pedons where they occurred.

iii) It has an apparnt CEC of 16 cmol (+) or less per kg clay (by 1N $NH_4OAc$ pH 7) and an apparent ECEC of 12 cmol (+) or less per kg clay in 50 percent or more of its thickness and,

iv) It has a regular decrease in organic carbon content with increasing depth.

e. **Micromorphological related features:** The micromorphological properties of all soils are affected by their parent materials and genesis. The coarser textured soils have compact grain structure while the finer-textured soils have an apedal microstructure. Because of the distinct differences in micromorphological features among these soils, the specific micromorphological features might be employed as diagnostic horizons to differentiate soils while the quantifiable micromorphological features might potentially be selected as diagnostic indices for soil taxonomic classification.

### 4.6.2. Classification

#### a. USDA Soil Taxonomy System

At the order level, pedons BST01, BST02, GNT02, GNT03 and GNT04 could be classified as Ultisols because the BS with kandic horizon <50% (by $NH_4OAc$) and 35 to 90%

less (by sum of cations) throughout or in the major part of the kandic horizon. Pedons BST03, BST04 and GNT01 were classified as Inceptisols due to Cambic B horizon.

At the suborder level, pedons BST01, BST02 and GNT03 were classified as Ustults, pedons BST03, BST04 and GNT01 were classified as Ustepts and pedon GNT02 as Aquults because they have ustic and aquic moisture regimes respectively. At the great group level, pedons BST01, BST02, GNT03 and GNT04 were classified as Kanhaplusults because of the absence of plinthite and the more than 20% decrease in clay content within 100 cm depth while pedon GNT02 is classified as Plinthaquuults because of plinthic horizon within a depth of 150 cm. On the contrary, pedons BST03, BST04 and GNT01 could be classified as Haplustepts due to the absence of duripan or calcic horizon within 100 cm in the mineral soil.

At the subgroup level, pedons BST01, BST02, GNT03, and GNT04 were classified as Typic Haplustults at the subgroup level, because they do not possess any of the special features that distinguish Haplusutlts from other subgroups. Pedon GNT02 is classified as Typic Plinthaquults as it has no any special features that differentiate it from other Plinthaquults in subgroups. However, pedons GNT01 was classified as Oxic Haplustepts because of absence of agrillic or kandic horizons but there is high clay content throughout the profile (Table 3). The weatherable minerals were <10% from the XRD analyses of the soils (Table 6) and the horizons consist mainly of kaolinite and oxides of Fe and Al. Pedons BST03 and BST04 have throughout their horizon a bulk density of <1.0 $MgM^{-3}$ and form from a volcanic rock of basaltic parent material and might probable due to the possess phosphate retention of >85%. Therefore, qualifies to be placed under Andic Haplustepts.

At the family level, pedons BST01 and BST02 have clay content above 35% as the particle size distribution (PSD) in the control section and predominantly characteristic of 2:1

clay minerals (Vermiculite) and isohyperthermic temperature regime. These pedons could be inferred as Typic Haplustults, fine clayey, vermiculitic, isohyperthermic. Similarly, pedons GNT02, GNT03, GNT04 possess clay content of <35% in the control section with a mineralogy of micaceous and isohyperthemic temperature regime. These pedons (GNT03 and GNT04) were classified as Typic Haplustults, fine silty, micaceous, isohyperthermic and GNT02 as Typic Plinthaquults, fine silty, micaceous, isohyperthemic.

Accordingly, pedons BST03 and BST04 possess clayey texture as the predominant PSD in the control section and mineralogy was kaolinite with an isohyperthermic soil temperature regime. Pedon BST03 was classified as Andic Haplustepts, very fine clayey, kaolinitic, isohyperthermic while pedon BST04 was placed as Andic Haplustepts, fine clayey kaolinitic, isohyperthermic. Pedon GNT01 had clay content of 34% and sand >15% in the control section and mineralogy is kaolinitic and oxides of Fe and Al with less weatherable minerals, an isohyperthermic soil temperature regime. This pedon would be best placed as Oxic Haplustepts, fine loamy, kaolinitic, isohypethermic.

**(b). FAO/UNESCO/WRB Map of the World Legend**

Using the World Reference Base for Soil Resources (1998), Pedons BST01, BST02, GNT02, GNT03 and GNT04 were classified as Acrisols. These are soils with argic B horizons which had CEC of clay fractions less than 24 cmol (+) $kg^{-1}$ clay and base saturation (by $NH_4OAc$) of less than 50% in at least, part of the B horizons within 125 cm of the surface. The agric B horizon is a new terminology in the WRB. It is similar to the argillic horizon but had modification of definition to permit easier field identification which was used to be a problem with the argillic horizon. In particular it gives distinct textural differentiation even when clay skin cannot be identified, while clay accumulation which may occur in Ferralsols is excluded

from the argillic B horizons on account of low CEC, low content of water-dispersible clay and low silt-clay ratio (WRB 1998). At the second (lower category) level, Pedons BST01, BST02, and GNT04 were classified as Ferralic because they have ferralic horizon within 100 cm from the soil surface.

Pedons BST03 and BST04 were classified as Cambisols because they have weakly developed soils with a B horizon (cambic horizon). At the second level, BST03 and BST04 were placed on Andic due to andic horizon within 100 cm from the soil surface. While pedon GNT01 was also classified as Cambisols due to cambic horizon. At the second level, GNT01 was inferred as Arenic because it had texture of loamy fine sand throughout the upper 50 cm of the soil.

Table 10: Summary of the soil classification

Table 11: Summary of micromorphological features of the soil profiles

| Profile | Horizon (cm) | | Microstructure | | | Groundmass | | Pedofeatures | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Shape | Pedality | Voids | c/f | b-fabric | Nodules | Coatings | Crystals | |
| | | | | | | **BASALTIC PARENT MATERIAL** | | | | | |
| **BST 01** | Ap 0-10 | PPL | c | w | cp | m | | | | | Weakly spheroi |
| | Ap 10-20 | XPL | | m | | m | C | | | | Monic crystall |
| | Ap 20-30 | PPL | c | | ch | m | | | CR | | Crumb microst clay |
| | Ap 20-30 | XPL | | | | m | P | | HY | | Typic h |
| | Bw1 30-40 | PPL | c | s | ch | op | P | orthic | HY | - | Channe c/f, po impreg |
| | Bw1 30-40 | XPL | c | s | ch | C | C | orthic | HY | - | Strongl chitoni skew p with in infillin modera hydrox |
| | Bw1 40-50 | XPL | | s | v | op | s-g-p | | Micropan | | Vughy related grano-p |
| | Bw1 50-60 | PPL | | m | ch | op | P | | | | Channe c/f, orienta |
| | Bw1 50-60 | XPL | | m | v | op | S | | Loose infil | | Weakly double in comp |

Table 11. Cont'd

| Horizon (cm) | | Microstructure | | | Groundmass | | Pedofeatures | | | Miscell |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Shape | Pedality | Voids | c/f | b-fabric | Nodules | Coatings | Crystals | |
| Bw2 70-80 | XPL | sab | m | | e | S | orthic | HY | - | Subang enaulic orienta coating nodules |
| Bw2 70-80 | PPL | | m | ch | op | P | | Infillings | - | Channe |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | accomm c/f rela infillin |
| Bt1 80-90 | PPL | m | ch | p | P | | Infillings | | Porostr comple |
| Bt1 80-90 | XPL | m | ch | m-p | P | | Infillings | | Monic- microm |
| Bt1 90-100 | XPL | s | ch | p | C | Orthic | Infillings | a | Strongl aggrega microm and pas activity grains colour |
| Bt1 90-100 | PPL | s | ch | p | | Orthic | HY | - | Channe related (cappin nodules |
| Bt1 110-120 | PPL | S | ch | p | | Orthic | HY | | Highly porphy hypo-q grain typic intrape |

Table 11. Cont'd

| Horizon (cm) | | Microstructure | | | Groundmass | | Pedofeatures | | | Miscell |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Shape | Pedalit | Voids | c/f | b-fabric | Nodules | Coatings | Crystals | |
| Bt2 130-140 | XPL | a | S | | m | C | Orthic | Infillings | A | Highly with fi crystall with i coating aggrega ground |
| Bt2 130-140 | PPL | | m | ch | m | | | Crescent | - | Channe hypo-q (cresce |
| Bt2 150-160 | PPL | a | S | | m | P | | Infillings | | Highly with f ground |
| Bt126-36 | PPL | c | M | | P | S | Orthic | HY | | Loose nodul |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Bt1 26-36 | XPL | c | M | Ch | P | S, p | | Hy | - | Porous infillin |
| | Bt1 36-46 | PPL | | W | Ch | op | | t | | - | Free gr |
| | Bt1 36-46 | XPL | | W | Ch | op | S,grano- | t | | - | Dusty v |
| | Bt1 56-66 | XPL | | | | | U | t | Infillings | - | Notice orientat evidenc |
| | Bt1 56-66 | PPL | sab | M | | m | | t | Infillings | - | Comple typic no |
| | Bt2 70-80 | XPL | | M | Ch | Op | g-p | t | Hy | | Free nodules clays. |
| | Bt2 70-80 | PPL | | S | Ch | P | | t | - | - | Dense |
| | Bt2 80-90 | XPL | | M | V | | S,g-p | | | E | Red-br interfer micrma |
| | Bt2 90-100 | XPL | | M | Ve | P | | | | | Vesicul |
| | Bt2 100-110 | XPL | sab | | V | e-p | U | | | | Porostr |

Table 11. Cont'd

| | Horizon (cm) | Microsturcture | | | Groundmass | | Pedofeatures | | | Miscell |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Shape | Pedalit | Voids | c/f | b-fabric | Nodules | Coatings | Crystals | |
| | BC 117-127 | PPL | sab | S | Cp-ch | | Orthic | | | Air bu banded (bottom nodules |
| | BC 117-127 | XPL | | | C | p-g | | | | Poro a microm |
| | BC 127-137 | PPL | sab | S | V | Cp | | | | An ag compos dense i |
| | BC 137-147 | XPL | sab | s | Ve-cp | Cp | U | | | Vesicul fabric t |
| | BC 137-147 | PPL | | S | Cp-v | Cp | | Capping | - | Link microst |
| | BC 152-162 | XPL | | | Cp | c-p | P | | | Fabric crescen |
| | BC 152-162 | PPL | sab | S | V | e-p | | | | Red co |
| BST 03 | Ap 25-35 | PPL | g | M | Cp | | | | | Granula porous discont preferre |
| | Bw1 38-48 | XPL | sab | S | v-ch | | U | c | - | Vughy |
| | Bw1 68-78 | XPL | g | M | v-cp | | | | | Micros |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | related |
| | Bw1 68-78 | PPL | | | V | | u-speckled | | | Undiffe mosail |
| | Bw1 78-88 | PPL | | S | Ch | m | | Orthic | | Orthic t |
| | Bw1 78-88 | XPL | | S | Ch | g | S | | g | Clay co |
| | 2BC1100-110 | PPL | sab | S | | g | | | | Notice |
| | 2BC2110-120 | PPL | sab | M | Ch | | S | | Crescent | Channe with g microm |

Table 11. Cont'd

| Profile | Horizon | Microstructure | | | Groundmass | | Pedofeatures | | | Miscell |
|---|---|---|---|---|---|---|---|---|---|---|
| | (cm) | Shape | Pedalit | Voids | c/f | b-fabric | Nodules | Coatings | Crystals | |
| **BST 04** | Bw1 35-45 | XPL | c | S | Cp | op | C | Orthic | Infillings | - | Porous fabric inclusio volcani intercal (bottom |
| | Bw1 35-45 | PPL | c | S | Cp | op | | Orthic | | | Orthic t |
| | Bw1 55-65 | PPL | sab | s | Ch | | | | HY | - | Crescen |
| | Bw1 55-65 | XPL | sab | M | | P | u-s | | HY | S | Undiffe striated (center) subhedr |
| | Bw1 65-75 | XPL | sab | S | | M | C | Orthic | Infillings | - | Microst interpe infillin orientat |
| | Bw2 120-130 | PPL | | M | Ch | P | P | | Infillings | | Porostr dense i |
| | Bw2 120-130 | XPL | | M | Ch | M | P | | Infillings | | Accom contain porostr |
| | BC 160-170 | PPL | g | M | Cp | | | Orthic | HY | - | Accom contain nodules |
| | BC 180-190 | XPL | sab | s | Ch | C | g-p | | Link capping | | Feldspa fragem volcani orientat capping |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | BC 180-190 | PPL | M | Ch | C | g-p | Orthic | Crust | - | Poro-gr ground typic or |

Table 11. Cont'd.

| Profile No | Horizon (cm) | Microstructure | | | Groundmass | | Pedofeatures | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Shape | Pedality | Voids | c/f | b-fabric | Nodules | Coatings | Crystals | |
| | | | | **Granitic Parent Materials** | | | | | | |
| GNT 01 | AB 25-35 | XPL | c | M | v | c-e | S,p-g | | S | Subhedral crystal to fabric righ infilling co |
| | AB 25-35 | PPL | c | M | v-sp | e | | | | Vughy mi |
| | AB 25-35 | PPL | | M | v | m | | | | Weakly s with vughy |
| | AB 35-45 | XPL | sab | M | | G | S | Orthic | HY | S Subhedral nodule an groundma patterns |
| | AB 45-55 | PPL | | M | cp-p | | | | | A plannar |
| | Bw1 60-70 | XPL | sab | S | | | S | | | S Subangual accommoc clay an porostriate |
| | Bw1 60-70 | PPL | | S | | C | c-s | Orthic | | Highly se orthic typi |
| | Bw1 70-80 | PPL | sab | S | ch | Op | | Orthic | Infillings | - Channel m complete (capping) groundma |
| | Bw1 80-90 | PPL | sab | S | v | Op | | | Infillings | - Vughy infilling co grains (ca hydroxide |
| | Bw1 90-100 | PPL | sab | S | v | Cp | | | infillings | Vughy m fragement coatings in |

Table 11. Cont'd

| Horizon (cm) | | Microstructure | | | Groundmass | | Pedofeatures | | | Miscellane |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Shape | Pedality | Voids | c/f | b-fabric | Nodules | Coatings | Crystals | |
| Bw1 90-100 | XPL | sab | S | v | Cp | C | Orthic | | S | Banded d (brown) o |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | orientation elongated orthic typ dotted bl mineral fr coating of |
| | Bw2 100-110 | PPL | sab | M | v | Op | | Incomplete | - | Incomplet |
| | Bw2 110-120 | PPL | ab | S | ch | Op | | | | Channel m of illuvial intrapedal blank dott |
| | Bw2 120-130 | PPL | sab | S | v | C | orthic | infillings | - | Vughy m hydroxide with interp clay. |
| | Bw2 130-140 | PPL | sab | S | | g-e | | infillings | - | Gefuric-en patterns, interpedal in a fine sa |
| | C 140-150 | PPL | sab | S | ch | Op | orthic | infillings | - | Subangula complete i impregnat (bottom) i |

Table 11. Cont'd

| Profile | Horizon (cm) | | Microstructure Shape | Pedalit | Voids | Groundmass c/f | b-fabric | Pedofeatures Nodules | Coatings | Crystals | Miscellane |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GNT 02 | Ap 0-10 | PPL | c | M | ch | Op | | | crescent | - | Porous s microstruc related dis coating ch brown li capping or |
| | Ap 0-10 | XPL | c | M | | m-p | C | | infillings | - | Monic-por patterns, dotted b complete i |
| | Ap 10-20 | XP | c | M | ch | Op | U | | | A | Porous cr |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | L | | | | | | | | | ahedral cr porostriate undifferen fine organ |
| Ap 10-20 | PPL | c | M | ch | P | | orthic | infillings | | Complete channels, moderatel orthic agg |
| Bt1 20-30 | XPL | Sab | M | | P | g-p | | infillings | A | Weakly s microstruc the finer crystal mi fabric orie |
| Bt1 20-30 | PPL | sab | M | v | P | | orthic | infillings | | Strongly dotted gro of fine coa |

Table 11. Cont'd

| Horizon (cm) | | Microstructure Shape | Pedalit | Voids | Groundmass c/f | b-fabric | Pedofeatures Nodules | Coatings | Crystals | Miscellane |
|---|---|---|---|---|---|---|---|---|---|---|
| Bt1 30-40 | XPL | sab | S | | | | | | S | Subhedral porostriate nodules in |
| Bt1 30-40 | PPL | sab | S | cp | Op | | | | | Quartz gr quartz gra |
| Bt1 40-50 | XPL | sab | S | v | Cp | C | | infillings | | Subangula crystallitic complete voids (cap |
| Bt1 40-50 | PPL | sab | S | v-cp | e-p | | orthic | Typic | | Compound brownish vugh in orthic nod related dis |
| Bt1 58-68 | XPL | sab | S | ch | | C | vascular | infillings | | Subangula infillings b-fabric orientation hydroxide |
| Bt2 68-78 | PPL | sab | S | ch | P | | | infillings | - | Complete |
| Bt2 88-98 | XPL | sab | S | | Op | | anorthic | capping | ahedral | Capping crystal m |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | strongly ir |
| | Bt2 88-98 | PPL | sab | S | v | e-p | | | HY | - | Vughy m accommoc materials. |
| | Bt2 100-110 | PPL | sab | S | ch | Op | | orthic | crescen t | | Subangula microstruc coating cl impregnat groundma |

Table 11. Cont'd

| Horizon (cm) | | Microstructure Shape | Pedalit | Void s | Groundmass c/f | b-fabric | Pedofeatures Nodule s | Coating s | Crystal s | Miscellane |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bt2 100-110 | XP L | sab | S | ch | C | Speckle d | orthic | HY | A | Coalescen excrement enaulic c/ quartz gr quartz gra clay, not related c quaiscoati moderatel |
| | C 120-130 | XP L | sab | S | ch | p-c | C | orthic | infilling s | A | Subangual coating ch with inte crystal mi colour ( groundma black dott |
| GNT 03 | AB 11-21 | XP L | c | S | cp | M | C | orthic | Infillin gs | - | Highly se compound orientation complete c yellow r dispersed and goethi |
| | AB 11-21 | PPL | | S | v | P | | | | | Vughy mi |
| | AB 21-31 | PPL | ab | | sp | C | | | | | Chitonic c grains with |

Table 11. Cont'd

| Horizon (cm) | | Microstructure Shape | Pedalit | Voids | Groundmass c/f | b-fabric | Pedofeatures Nodules | Coatings | Crystals | Miscellane |
|---|---|---|---|---|---|---|---|---|---|---|
| AB 21-31 | XPL | ab | S | sp | C | S | orthic | | | Angular b related d coating accommod porostriate nodules. |
| Bt1 38-48 | PPL | sab | M | v | P | | | | | Vughy mi clays. |
| Bt1 38-48 | XPL | | | | | | | | | |
| Bt1 48-58 | XPL | | | v-ch | P | S | orthic | crescent | a | Vughy w crescent c porostriate crystal evi typic nodu |
| Bt1 48-58 | PPL | | M | ch | Op | | orthic | infillings | - | Completel orientation nodules. |
| Bt2 66-76 | XPL | | M | ch | Op | g-p | orthic | infillings | | Complete porostriate and mod nodules. |
| Bt2 66-76 | PPL | | M | ch | Op | | orthic | Micropan | | Complete (micropan typic nodu |
| Bt3 101-111 | PPL | ab | M | ch | Op | | orthic | infillings | | Channel n c/f relate impregnat complete c |
| Bt3 101-111 | XPL | | M | ch | Oe | | orthic | crescent | | Channel n related di planes quasicoati impregnat |

Table 11. Cont'd

| Horizon (cm) | | Microstructure Shape | Pedalit | Voids | Groundmass c/f | b-fabric | Pedofeatures Nodules | Coatings | Crystals | Miscellane |
|---|---|---|---|---|---|---|---|---|---|---|
| Bt3 111-121 | XPL | | | | | U | orthic | crescent | | Undifferen orientation |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | weakly im |
| | Bt3 | 121-131 | XPL | | M | ch | Op | g-p | | HY | a | Channel m c/f relate porostriate quasicoati coatings. |
| | Bt3 | 121-131 | PPL | | M | ch | Op | | | HY | | Crescent c |
| GNT 04 | Bt1 | 11-21 | PPL | c | M | cp | M | g-p | orthic | Infillings | E | Channel m porostriate dense inf orthic typi |
| | Bt1 | 11-21 | XPL | c | M | sp | M | U | | | E | Crumb mi slide with crystal mi dense free |
| | Bt1 | 21-31 | PPL | | | ch | M | P | Orthic/ anorthic | | - | Lenticular channel orientation |
| | Bt1 | 21-31 | XPL | sab | | | G | G | anorthic | | - | Intra and granostriat orientation anorthic m (bottom). |
| | Bt1 | 31-41 | PPL | sab | W | ch | M | | geodic | Loose infi | - | Finer mon continuous developed microstruc |
| | Bt1 | 31-41 | XPL | | M | v-ch | | g-p | orthic | Crescent | - | Vughy mi coating cla fabric orie |

Table 11. Cont'd

| Horizon (cm) | | Microstructure | | | Groundmass | | Pedofeatures | | | Miscellane |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Shape | Pedalit | Voids | c/f | b-fabric | Nodules | Coatings | Crystals | |
| Bt2 | 48-58 | PPL | | | v | p | p | | | - | Vughy mi fabric orie accommoc nodules. |
| Bt2 | 58-68 | PPL | | M | ch | m | | typic | Infillings | - | Finer mon completely nodules. |
| Bt2 | 58-68 | XPL | | | ch | p | g-p | orthic | Loose inf | - | Porphyric porostriate continuous typic orthi |

# CHAPTER FIVE

## SUMMARY AND CONCLUSIONS

Field and laboratory studies were conducted on two different parent materials in Plateau State ($8^0$ 30' and $10^0$10'N and longitudes $8^0$20' and $9^0$ 30'E).

The main objective of the study was to increase the understanding of soil classification through evaluation of micromorphological and mineralogical properties of soils. With a view to characterize Ultisols physically, chemically and morphologically, Investigating the micromorphological and mineralogical properties of Ultisols derived from basalts and granite-gneiss, and determining if differences in properties could be used in the classification of Ultisols at the lower levels of Soil Taxonomy and WRB. Based on the geological map sheet used to identify different parent materials, eight (8) profiles were dung and described and five distinct soil types were identified and mapped as soil units A, B, C, D and E.

Results obtained revealed morphologically, that the basaltic soils were deep to very deep with some thin Ap horizons (BST02 and BST04). The fine grain sizes in basaltic parent material favors higher weathering. In addition high clay content which complexes humus and thus reduces its ability to move downward in the profiles. Granitic soils were shallow due to restriction from peteroplinthite and the coarse nature of the grains restricts frequent weatherings. The surface and subsoils horizons in basaltic parent material were dominantly dark reddish brown (5YR 3/3; 5YR ¾; 2.5YR ¾). Oxidation-reduction of goethite and hematite could also cause the reddish colour in the soils. On the contrary, granitic soils exhibits dull yellowish brown (10YR 5/3; 7.5YR 4/6) in the surface horizons. The subsoils were grayish yellow to brown (10YR 6/2; 10YR 5/3) due to poor drainage.

Generally, the particle sizes in basaltic soils are dominantly clay fraction with values above 40% and with low sand content. However, granite established coarse-grained soils consisting of significantly highest in sand and silt with lowest clay percentages. Low bulk densitywas evidence in basaltic soils with some profiles (BST03 and BST04) <1.0 $Mgm^{-3}$. Thus, consequence of the development of a porous soil structure arising from the interaction of non-crystalline materials and soil organic matter. The granite soils had the highest bulk density of 1.742 Mgm-3.

The CEC (NH4OAc, ECEC and clay) did not differ significantly among the parent materials. The organic carbon of the surface soils was generally rated low though; basaltic soils are richer than granite soils. The total N and available phosphorus followed the same trend as the organic carbon, suggesting that these nutrients could be derived in the soil from the organic matter.

The soils were found to be very strongly to moderately acid in the Ap horizons with inconsistence vertical variation down the profiles. Exchangeable $Al^{3+}$ constituted the larger proportion of exchangeable acidity, especially in the surface horizons.

The mineralogical composition of the clay fraction indicated dominance of kaolinite especially in granitic soils. However, 2:1 clay types, mixed intestification and chloritilization were in basaltic soils. Hydrous-iron and Al-interlayered oxides minerals such as Maghemite, Microcline, Hematite and Geothite etc were detected in the clay mineralogy.

Micromophologically, old parent materials have porphyric c/f related distribution pattern, low c/f 2u ratios, poor sorting and common infilling and coatings of voids as compared to enaulic c/f related distribution, high c/f 2u ratio in young parent materials. Similarly, self-mulching as a pedofeatures was observed in basaltic soils as opposed to granite parent material.

According to the USDA system of classification, profiles BST01 and BST02 (basaltic PM) and GNT02, GNT03 and GNT04 (granite PM) were classified as Typic Haplustults. The evidence of pedofeatures such as porphyric c/f and typic orthic nodules confirms highly weathered soils. Profiles BST03 and BST04 are classified as Andic Haplustepts and GNT01 as Oxic Haplustepts. In the FAO/WRB system, profiles BST01 and BST02 are classified as Ferralic Acrisols, BST03 and BST04 as Andic Cambisols. While profiles GNT02, GNT03 and GNT04 are classified as Haplic Acrisols, GNT01 as Arenic Cambisols. The micromorphological properties of all soils are affected by their parent materials and genesis. The coarser textured soils have compact grain structure while the finer-textured soils have an apedal microstructure. Because of the distinct differences in micromorphological features among these three soils, the specific micromorphological features might be employed as diagnostic horizons to differentiate soils while the quantifiable micromorphological features might potentially be selected as diagnostic indices for soil taxonomic classification.

I therefore conclude saying that the scope of the work required to fill existing gaps is so diverse that this task should be tackled not only by specialists of micromorphology but also by teams associating researchers from a large range of scientific fields.

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## APPENDIX A

**PROFILE NO: BST 01**

**GENERAL SITE INFORMATION**

| | | |
|---|---|---|
| Location | : | Long. 90° 44.634'N Lat. 08° 47.46' Alt.1260m Chaha Village along Wamco Farm, 150m from the Village |
| Taxonomic Classification | : | |
| USDA | | Typic Haplustults fine clayey vermiculitic isohyperthemic |
| FAO/WRB | | Ferralic Acrisols |
| Parent material | | Basalt |
| Geology | | Igneous rock Nigerian Basement Complex |
| Geomorphology | | Gentle slope |
| Topography | | |
| Local relief | | Upper slope |
| Slope | | Level or nearly level 0.2% Class A |
| Ecological zone | | Northern Guinea Savanna |
| Land Use | | Cultivated with maize and Sorghum Carrot was planted in dry season. |
| Drainage | | Well – drained |
| Erosion hazard | | Sheet |
| Deposition | | Slight |
| Rock out crops | | no bedrock exposed |
| Surface characteristics | | None |
| Estimated depth to water table | | None @ 1780cm |
| Depth to any impenetrable layer | | None @ 1780cm |
| Described by | | B. A. Raji and Hassan, A. M. |
| Date | | 30th April, 2006 |

**HORIZONAL DESCRIPTION**

| Horizon | Depth (cm) | Description |
|---|---|---|
| AP | 0-35 | Dark reddish brown (5YR 3/3) moist; reddish brown (5YR 4/6) dry; clay loam; moderate, medium, SBR structure, plastic, firm, slight hard consistence; many fine-medium roots; common hard fine gravel, common fine tubular pore; few empty fine medium termite/ant holes; gradual smooth boundary. |
| Bw1 | 35 – 60 | Dark reddish brown (2.5YR 3/4) moist, reddish brown (2.5YR 4/6) dry, clayloam, clay cutans along pores; moderate, medium, subangular blocky structure, slightly plastic, firm, slightly hard consistence; few medium roots; many fine hard Mn gravel; few fine tubular pores; clear smooth boundary. |
| Bw2 | 60 – 88 | Dark reddish brown (2.5YR 3/6) moist; reddish brown (2.5YR 4/6) dry; clay thin clayskin on peds; weak, fine subangular blocky structure; plastic, firm, slight hard consistence; few fine-medium roots; irregular common medium hard Fe/Mn concretions; common fine tubular pores; diffuse smooth boundary. |
| Bt1 | 88-130 | Dark reddish brown (2.5YR ¾) moist; dark reddish brown (2.5YR 3/6) dry; clayloam, moderate, medium subangular blocky structure; plastic, firm, slightly hard consistence; few fine-medium roots; irregular common medium hard Fe/Mn concretions; common fine tubular pores; diffuse smooth boundary. |
| Bt2 | 130–178 | Dark, reddish brown (2.5 YR 3/4) moist; dark reddish |

brown (2.5YR 3/6)dry; clayloam; moderate, medium subangular blocky structure; slightly plastic, firm, slightly hard consistence; very few fine roots; common soft to slightly hard Fe/Mn concretions; common very fine pores.

**PROFILE NO: BST 02**

**GENERAL SITE INFORMATION**

| | | |
|---|---|---|
| Location | : | Long. 90° 43.414'N, Lat. 08° 47.47'.072'E Alt. 1271M DSt. 2.26km from BST 01 NITA Farm |
| Taxonomic Classification | : | |
| USDA | | - Typic Haplustults fine clayey vermiculitic isohyperthemic |
| FAO/WRB | | - Ferralic Acrisols |
| Parent material | | Basalt |
| Geology | | Igneous rock |
| Geomorphology | | Gentle slope |
| Topography | | |
| Local relief | | Upper slope |
| Slope | | Level or nearly level 0-2% |
| Ecological zone | | Northern Guinea Savanna |
| Land Use | | Cultivated with maize and Sorghum Vegetable crops-tomato, carrot etc. |
| Drainage | | Well – drained |
| Erosion hazard | | Sheet |
| Deposition | | Slight |
| Rock out crops | | No bedrock exposed |
| Surface characteristics | | None |
| Estimated depth to water table | | None 175cm |
| Depth to any impenetrable layer | | None @ 175cm |
| Described by | | B. A. Raji and Hassan, A. M. |
| Date | | 2nd May, 2006 |

**HORIZONAL DESCRIPTION**

| Horizon | Depth (cm) | Description |
|---|---|---|
| AP | 0-16 | Dark reddish brown (5YR 3/5) moist; clay loam; moderate, medium, subangular blocky structure, plastic, firm, soft consistence; many fine roots; many fine, few-medium, pores; few and nests; clear smooth boundary. |
| Bt1 | 16 – 70 | Dark reddish brown (2.5YR 3/4) moist, dark reddish brown (2.5YR 3/6) dry, clayloam; moderate, medium, subangular blocky structure; plastic, firm, hard consistence; many five root; many fine – medium pores; vertical cracks, many medium ant nest; clear smooth boundary. |
| Bt2 | 70 – 117 | Dark brown (10YR 3/4) moist; clayloam; dark reddish brown (2.5YR 3/6) dry; red (7.5YR 4/8) few, fine, faint mottles; clayloam; moderate medium subangular blocky structure; plastic, firm, hard consistence; many fine roots; many fine pores; few fine Fe/Mn concretions; clear smooth boundary. |
| BC | 117-152 | Dark reddish brown (5YR 3/4) moist; clayloam; moderate, medium subangular blocky structure; sticky, firm, hard consistence; few fine roots; many medium-coarse Fe/Mn concretions; few medium weathered basaltic boulders; clear smooth boundary. |

| | | |
|---|---|---|
| C | 152 – 175 | Dark, reddish brown (5YR 3/4) moist; dark reddish brown , (2.5YR 3/6) many medium-coarse distinct mottles; clayloam; moderate medium subangular blocky structure; plastic, firm, hard consistence; few fine roots; many medium soft Fe/Mn concretions; many medium-coarse partially weathered basaltic parent material. |

**PROFILE NO: BST 03**

**GENERAL SITE INFORMATION**

| | | |
|---|---|---|
| Location | : | Long. 90° 31.136'N Lat. 08° 444'.147'.072'E Alt.1230M DSt. 15km from BST 01 Ra-Hoss Riyom LGC, Near (130m) Assembly of God Church Jos – Abuja Road. |
| Taxonomic Classification | : | |
| USDA | | - Andic Haplustepts, very fine clayey, kaolinitic isohyperthemic |
| FAO/WRB | | - Andic Cambisols |
| Parent material | | Basalt |
| Geology | | Igneous rock Nigerian Basement Complex |
| Geomorphology | | Undulating plain |
| Topography | | |
| Local relief | | Upper slope |
| Slope | | Level or nearly level 0-2% |
| Ecological zone | | Northern Guinea Savanna |
| Land Use | | Cultivated with maize/Potato |
| Drainage | | Well – drained |
| Erosion hazard | | Sheet |
| Deposition | | Slight |
| Rock out crops | | No bedrock exposed |
| Surface characteristics | | None |
| Estimated depth to water table | | None at 190cm |
| Depth to any impenetrable layer | | Hard weathered and basaltic rock at 100cm |
| Described by | | Hassan, A. M. |
| Date | | 4th May, 2006 |

**HORIZONAL DESCRIPTION**

| Horizon | Depth (cm) | Description |
|---|---|---|
| AP | 0-37 | Dark reddish brown (5YR 3/4) moist; clay loam; weak, fine-medium, subangular blocky structure, slightly plastic, firm, soft consistence; many fine-medium roots, many fine-medium pores; common ant and termites nest; clear gradual boundary. |
| Bw | 37–100 | Dark reddish brown (5YR 3/4) moist; clay loam; moderate, medium subangular blocky structure; plastic, firm, hard consistence; many fine pores; few fine soft Fe nodules, clear wavy boundary. |
| 2BC1 | 100-110 | Partially weathered basaltic materials. |
| 2BC2 | 110-143 | Dark reddish brown (5YR 3/4) moist; clay loam; moderate, medium subangular blocky structure, plastic, firm, hard consistence, common medium pores; clear smooth boundary. |
| 2Cr | 143-190 | Dark reddish brown (5YR 3/4) moist; clay loam; moderate, medium subangular blocky structure; plastic, firm, hard consistence, many coarse partially weathered basaltic materials. |

**PROFILE NO: BST04**

## GENERAL SITE INFORMATION

| | | |
|---|---|---|
| Location | : | Long. 90° 35.673'N Lat.08° 42.030'E<br>Alt.1134m DSt. 19km from BST 01 Ta-Hoss Riyom LGC, Land Resources Farm Jos-Abuja Road. |
| Taxonomic Classification | : | |
| USDA | | - Andic Haplustepts, fine clayey kaolinitic isohyperthemic |
| FAO/WRB | | - Andic Cambisols |
| Parent material | | Basalt |
| Geology | | Igneous rock |
| Geomorphology | | Gentle slope |
| Topography | | |
| Local relief | | Middle slope |
| Slope | | Nearly level 0-2% |
| Ecological zone | | Northern Guinea Savanna |
| Land Use | | Cultivated with maize Farm |
| Drainage | | Well – drained |
| Erosion hazard | | Sheet |
| Deposition | | Slight |
| Rock out crops | | No bedrock exposed |
| Surface characteristics | | None |
| Estimated depth to water table | | None at 190cm |
| Depth to any impenetrable layer | | None at 190cm |
| Described by | | Hassan, A. M. |
| Date | | 4th May, 2006 |

**HORIZONAL DESCRIPTION**

| Horizon | Depth (cm) | Description |
|---|---|---|
| AP | 0-15 | Dark reddish brown (5YR 3/3) moist; clayloam; weak, fine, subangular blocky structure; plastic, very friable and soft consistence; many fine-medium roots; many fine pores; few termites and nest; clear smooth boundary. |
| Bw1 | 15 – 110 | Dark reddish brown (5YR 3/4) moist; yellowish red (5YR 4/6) dry, clayloam; moderate medium coarse subangular blocky structure; plastic, firm, hard consistence; many fine roots; many fine-common pores; many medium concretions; few termite nest; diffuse smooth boundary. |
| Bw2 | 110-156 | Dark reddish brown (5YR ¾) moist; yellowish red (5YR 4/6) dry; clayloam; moderate medium-coarse subangular blocky structure; plastic, firm, hard consistence; many fine pores; few medium-coarse Fe/Mn concretion; partially weathered basaltic boulder; many medium-coarse parent materials; clear gradual boundary. |
| BC | 156-190 | Dark reddish brown (5YR 3/4) moist; gravel clayloam; moderate, medium-coarse subangular blocky structure; plastic, firm, hard consistence; many medium-coarse Fe/Mn concretions; many coarse partially weathered basaltic parent materials. |

**PROFILE NO: GNT 01**

## GENERAL SITE INFORMATION

| | | |
|---|---|---|
| Location | : | Kuru, Land Resource Farm |
| Taxonomic Classification | : | |
| USDA | | - Oxic Haplustepts, fine loamy, kaolinitic isohyperthemic |
| FAO/WRB | | - Arenic Cambisols |
| Parent material | | Granite |
| Geology | | Igneous rock |
| Geomorphology | | Gentle slope, nearly level to slightly undulating |
| Topography | | |
| Local relief | | Middle slope |
| Slope | | Nearly level 0-2% |
| Ecological zone | | Northern Guinea Savanna |
| Land Use | | Cultivated with maize farm |
| Drainage | | Poorly drainage |
| Erosion hazard | | Sheet |
| Deposition | | Slight |
| Rock out crops | | No bedrock exposed |
| Surface characteristics | | Gravelly |
| Estimated depth to water table | | None at 195cm |
| Depth to any impenetrable layer | | None @ 195cm |
| Described by | | Hassan, A. M. |
| Date | | 3rd May, 2006 |

**HORIZONAL DESCRIPTION**

| Horizon | Depth (cm) | Description |
|---|---|---|
| AP | 0–25 | Dull yellowish brown (10YR 5/3) moist; brown (7.5 YR 4/6) few, fine faint mottles; clayloam; moderate, fine/medium subangular blocky structure; plastic, firm, soft consistence; many fine-medium pore; many fine roots; many fine quartz grain gravel; many termite and ant nest; clear smooth boundary. |
| AB | 25– 60 | Dull yellowish brown (10YR 5/3) moist; dull yellowish orange (10YR 6/3) dry; bright yellowish brown (10YR 6/3) many medium/coarse distinct mottles; clayloam; moderate, medium/coarse subangular blocky structure; plastic, firm, hard consistence; few fine roots, many fine pores; few ant nest; many fine quartz grains gravel; diffuse smooth boundary. |
| Bw1 | 60–100 | Grayish yellow brown (10YR 6/2) moist; brown (7.5YR 4/6) many medium distinct mottles; clay loam; moderate/strong subangular blocky structure; sticky firm, hard consistence; many fine pores; few medium ant nest; common fine Fe nodules; diffuse smooth boundary. |
| Bw2 | 100-140 | Grayish yellow brown (10YR 6/2) moist; brown (7.5YR 4/6) many Medium/coarse distinct mottles; clay loam; moderate medium/coarse subangular blocky structure; sticky, firm, hard consistence; many fine/medium pores; many fine medium quartz grain gravel; few ant nest; diffuse wavy boundary. |
| C | 140-195 | Grayish yellow brown (10YR 6/2); bright brown |

(7.5YR 5/8) many, medium/coarse prominent mottles; clay loam; moderate/strong, medium/coarse subangular blocky structure; very sticky, very firm, very hard consistence, few fine pores; many fine quartz grains gravel.

**PROFILE NO: GNT 02**

**GENERAL SITE INFORMATION**

| | | |
|---|---|---|
| Location | : | Kuru, Land Resource Farm |
| Taxonomic Classification | : | |
| USDA | | - Typic Plinthaquults, fine silty, micaceous, isohyperthemic |
| FAO/WRB | | - Haplic Acrisols |
| Parent material | | Granite |
| Geology | | Igneous rock |
| Geomorphology | | Gentle slope, gently undulating |
| Topography | | |
| Local relief | | Lower slope |
| Slope | | Gently Slope 2 - 4% Class B |
| Ecological zone | | Northern Guinea Savanna |
| Land Use | | Cultivated with maize |
| Drainage | | Imperfectly drainage |
| Erosion hazard | | Sheet |
| Deposition | | Slight |
| Rock out crops | | No bedrock exposed |
| Surface characteristics | | Gravelly |
| Estimated depth to water table | | None at 130cm |
| Depth to any impenetrable layer | | None @ 130cm |
| Described by | | Dr. Raji, B.A and Hassan, A. M. |
| Date | | 2nd May, 2006 |

**HORIZONAL DESCRIPTION**

| Horizon | Depth (cm) | Description |
|---|---|---|
| AP | 0–20 | Brown (10YR 4/4) moist; orange (7.5YR 6/8) few, fine, faint mottles; clayloam; moderate medium subangular blocky structure; plastic, firm, soft consistence; common fine roots; few medium quartz grains gravel; fine many pores; many coarse animal ant nest; clear smooth boundary. |
| Bt1 | 20 – 60 | Dull yellowish brown (10YR 5/3) moist; dark brown (7.5YR 3/4) common fine, distinct mottle; clay loam; moderate medium subangular blocky structure; plastic, firm, hard consistence; few coarse pores; few coarse pores; few coarse animal holes; few, fine/medium quartz grains gravel; clear smooth boundary. |
| Bt2 | 60–90 | Dull yellowish brown (10YR 5/3) moist; reddish brown (2.5YR 4/6) common medium distinct mottle; clayloam; moderate medium subangular blocky structure; plastic, firm, hard consistence; many fine pores; few medium ant nest; common fine Fe nodules; diffuse smooth boundary. |
| BC | 90-130 | Grayish yellow brown (10YR 5/2) moist; reddish brown (5YR 4/6) many medium/coarse prominent mottles; clayloam; moderate medium subangular blocky structure; slightly sticky, firm, slightly hard consistence; few fine quartz grain gravel; common, medium coarse Fe nodules; very few fine pores; few animal activities; diffuse wavy boundary. |

| | | |
|---|---|---|
| C | 130 - | Bright yellowish brown (10YR 6/4) moist; dull yellow orange (10YR 7/2) dry; gravelly; weak, fine/medium granular structure; non sticky, loose, loose consistence; few fine quartz grains gravel; many medium/coarse Fe/Mn concretions, weathered granitic material. |

**PROFILE NO: GNT 03**

**GENERAL SITE INFORMATION**

| | |
|---|---|
| Location | : Long. 90° 38.329'N Lat.08° 45.935'E Alt. 1208m DSt. 11.9km from BST 01 Riyom NYSC Farm, near Jos-Abuja Road |
| Taxonomic Classification | : |
| USDA | - Typic Haplustults, fine silty, micaceous, isohyperthemic |
| FAO/WRB | - Haplic Acrisols |
| Parent material | Granite |
| Geology | Igneous rock |
| Geomorphology | Gentle slope, nearly level to slightly undulating |
| Topography | |
| Local relief | Middle slope |
| Slope | Nearly level 0-2% class A |
| Ecological zone | Northern Guinea Savanna |
| Land Use | Cultivated with maize/Potato |
| Drainage | Imperfectly drainage |
| Erosion hazard | Sheet |
| Deposition | Slight |
| Rock out crops | No bedrock exposed |
| Surface characteristics | Gravelly |
| Estimated depth to water table | None at 148cm |
| Depth to any impenetrable layer | None @ 148cn |
| Described by | Hassan, A. M. |
| Date | 4th May, 2006 |

**HORIZONAL DESCRIPTION**

| Horizon | Depth (cm) | Description |
|---|---|---|
| AP | 0–11 | Brown (7.5YR 4/6) moist; sandyloam; weak, fine subangular blocky structure; slightly plastic, very friable, loose consistence; many fine roots; many fine/medium pores; many termites and ant nests; many fine/medium quartz grains gravel; clear smooth boundary. |
| BA | 11–38 | Bright brown (7.5YR 5/8) moist; clayloam; moderate fine/medium subangular blocky structure; plastic, firm, hard consistence; many few fine/coarse pores; many medium/coarse quartz grain gravel; clear smooth boundary. |
| Bt1 | 38–66 | Bright brown (7.5YR 5/8) moist; yellow orange (10YR 7/8) few fine faint mottles; clayloam; moderate medium subangular blocky structure; plastic, firm, hard consistence; many fine pores; many fine/medium quartz grains gravel; clear wavy boundary. |
| Bt2 | 66-101 | Light yellow orange (10YR 8/4) moist; bright brown (7.5YR 5/8) few fine faint mottles; clayloam; moderate medium subangular blocky structure; plastic, firm, hard consistence; many fine pores; many fine-medium quartz grains gravel; clear smooth boundary. |
| Bt3 | 101-148 | Light brownish gray (7.5YR 7/2) moist; bright brown |

(7.5YR 5/8) common medium distinct mottles; clayloam; moderate medium subangular blocky structure; plastic, firm, hard consistence; few fine pores; few fine guartz grains gravel.

**PROFILE NO: GNT 04**

**GENERAL SITE INFORMATION**

| | | |
|---|---|---|
| Location | : | Long. 09° 38.425'N Lat. 08° 46.146'E Alt. 1208m DSt. 11.7km from BST 01 Riyom, off NYSC Farm, along Jos-Abuja Road |
| Taxonomic Classification | : | |
| USDA | | - Typic Haplustults, fine silty, micaceous, isohyperthemic |
| FAO/WRB | | - Haplic Acrisols |
| Parent material | | Granite |
| Geology | | Igneous rock |
| Geomorphology | | Gentle slope |
| Topography | | |
| Local relief | | Upper slope |
| Slope | | Nearly level 0-2% |
| Ecological zone | | Northern Guinea Savanna |
| Land Use | | Cultivated with maize farm |
| Drainage | | Imperfectly drainage |
| Erosion hazard | | Sheet |
| Deposition | | Slight |
| Rock out crops | | No bedrock exposed |
| Surface characteristics | | Gravelly |
| Estimated depth to water table | | None at 165cm |
| Depth to any impenetrable layer | | None @ 165cn |
| Described by | | Hassan, A. M. |

Date 4th May, 2006

**HORIZONAL DESCRIPTION**

| Horizon | Depth (cm) | Description |
|---|---|---|
| AP | 0-11 | Brown (7.5YR 4/6) mosit; clayloam; weak, fine subangular blocky structure; slightly plastic, frable, soft consistence; many fine roots; many fine pores; many fine quartz grains gravels; common ant cast; clear smooth boundary. |
| Bt1 | 11 –48 | Bright brown (7.5YR 5/8) moist; dark reddish brown (2.5YR 3/6) common, medium distinct mottles; clayloam; moderate medium subangular blocky structure; slightly plastic friable, hard consistence; few fine roots; common fine pores; few fine quartz grains gravel; clear smooth boundary. |
| Bt2 | 48-120 | Grayish yellow brown (10YR 6/2) moist, bright reddish brown (5YR 5/8) common medium distinct mottles; sandyloam; moderate medium subangualr structure; slightly plastic, friable, soft consistence; few fine pores; many medium-coarse quartz grains gravel; clear smooth boundary. |
| BC | 120-165 | Brown (7.5YR 4/4) moist, dark reddish brown (2.5YR |

3/6) many medium-coarse prominent mottles; sandyloam; moderate medium subangular blocky structure; plastic, firm, hard consistence; common fine pores; many fine-medium quartz grains gravel.

## APPENDIX B

**Table 11: Summary of micromorphological features of the soil profiles**

Table 11: Summary of micromorphological features of the soil profiles

| Profile | Horizon (cm) | | Microstructure | | | Groundmass | | Pedofeatures | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Shape | Pedality | Voids | c/f | b-fabric | Nodules | Coatings | Crystals | |
| | | | | | | **BASALTIC PARENT MATERIAL** | | | | | |
| **BST 01** | Ap 0-10 | PPL | c | w | cp | m | | | | | Weakly spheroi |
| | Ap 10-20 | XPL | | m | | m | C | | | | Monic crystall |
| | Ap 20-30 | PPL | c | | ch | m | | | CR | | Crumb microst clay |
| | Ap 20-30 | XPL | | | | m | P | | HY | | Typic h |
| | Bw1 30-40 | PPL | c | s | ch | op | P | orthic | HY | - | Channe c/f, po impreg |
| | Bw1 30-40 | XPL | c | s | ch | C | C | orthic | HY | - | Strongl chitoni skew p with in |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | infillin |
| | | | | | | | | modera |
| | | | | | | | | hydrox |
| Bw1 40-50 | XPL | s | v | op | s-g-p | | Micropa n | Vughy related grano-p |
| Bw1 50-60 | PPL | m | ch | op | P | | | Channe c/f, orienta |
| Bw1 50-60 | XPL | m | v | op | S | | Loose infil | Weakly double in comp |

Table 11. Cont'd

| Horizon (cm) | | Microstructure Shape | Pedalit | Void s | Groundmass c/f | b-fabric | Pedofeatures Nodule s | Coatings | Crystal s | Miscell |
|---|---|---|---|---|---|---|---|---|---|---|
| Bw2 70-80 | XPL | sab | m | | e | S | orthic | HY | - | Subang enaulic orienta coating nodules |
| Bw2 70-80 | PPL | | m | ch | op | P | | Infillings | - | Channe accomm c/f rela infillin |
| Bt1 80-90 | PPL | | m | ch | p | P | | Infillings | | Porostr comple |
| Bt1 80-90 | XPL | | m | ch | m-p | P | | Infillings | | Monic- microm |
| Bt1 90-100 | XPL | | s | ch | p | C | Orthic | Infillings | a | Strongl aggrega microm and pas activity grains colour |
| Bt1 90-100 | PPL | | s | ch | p | | Orthic | HY | - | Channe related (cappin nodules |
| Bt1 110-120 | PPL | | S | ch | p | | Orthic | HY | | Highly porphy hypo-q |

grain (
typic
intrape

Table 11. Cont'd

| Horizon (cm) | | Microstructure Shape | Pedalit | Voids | Groundmass c/f | b-fabric | Pedofeatures Nodules | Coatings | Crystals | Miscell |
|---|---|---|---|---|---|---|---|---|---|---|
| Bt2 130-140 | XPL | a | S | | m | C | Orthic | Infillings | A | Highly with fi crystall with i coating aggrega ground |
| Bt2 130-140 | PPL | | m | ch | m | | | Crescent | - | Channe hypo-q (cresce |
| Bt2 150-160 | PPL | a | S | | m | P | | Infillings | | Highly with f ground |
| Bt126-36 | PPL | c | M | | P | S | Orthic | HY | | Loose nodul |
| Bt1 26-36 | XPL | c | M | Ch | P | S, p | | Hy | - | Porous infillin |
| Bt1 36-46 | PPL | | W | Ch | op | | t | | - | Free gr |
| Bt1 36-46 | XPL | | W | Ch | op | S,grano- | t | | - | Dusty v |
| Bt1 56-66 | XPL | | | | | U | t | Infillings | - | Notice orientat evidenc |
| Bt1 56-66 | PPL | sab | M | | m | | t | Infillings | - | Comple typic no |
| Bt2 70-80 | XPL | | M | Ch | Op | g-p | t | Hy | | Free c nodules clays. |
| Bt2 70-80 | PPL | | S | Ch | P | | t | - | - | Dense c |
| Bt2 80-90 | XPL | | M | V | | S,g-p | | | E | Red-br interfer micrma |
| Bt2 90-100 | XPL | | M | Ve | P | | | | | Vesicul |
| Bt2 100-110 | XPL | sab | | V | e-p | U | | | | Porostr |

Table 11. Cont'd

| | Horizon (cm) | | Microsturcture Shape | Pedalit | Voids | Groundmass c/f | b-fabric | Pedofeatures Nodules | Coatings | Crystals | Miscell |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | BC 117-127 | PPL | sab | S | Cp-ch | | | Orthic | | | Air bu banded (bottom nodules |
| | BC 117-127 | XPL | | | | C | p-g | | | | Poro a microm |
| | BC 127-137 | PPL | sab | S | V | Cp | | | | | An ag compos dense i |
| | BC 137-147 | XPL | sab | s | Ve-cp | Cp | U | | | | Vesicul fabric t |
| | BC 137-147 | PPL | | S | Cp-v | Cp | | | Capping | - | Link microst |
| | BC 152-162 | XPL | | | Cp | c-p | P | | | | Fabric crescen |
| | BC 152-162 | PPL | sab | S | V | e-p | | | | | Red co |
| BST 03 | Ap 25-35 | PPL | g | M | Cp | | | | | | Granula porous discont preferre |
| | Bw1 38-48 | XPL | sab | S | v-ch | | U | | c | - | Vughy |
| | Bw1 68-78 | XPL | g | M | v-cp | | | | | | Microst related |
| | Bw1 68-78 | PPL | | | V | | u-speckled | | | | Undiffe mosail |
| | Bw1 78-88 | PPL | | S | Ch | m | | Orthic | | | Orthic t |
| | Bw1 78-88 | XPL | | S | Ch | g | S | | g | | Clay co |
| | 2BC1100-110 | PPL | sab | S | | g | | | | | Notice |
| | 2BC2110-120 | PPL | sab | M | Ch | | S | | Crescent | | Channe with g microm |

Table 11. Cont'd

| Profile | Horizon (cm) | | Microstructure Shape | Pedalit | Voids | Groundmass c/f | b-fabric | Pedofeatures Nodules | Coatings | Crystals | Miscell |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **BST 04** | Bw1 35-45 | XPL | c | S | Cp | op | C | Orthic | Infillings | - | Porous fabric inclusio volcani |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | intercal (bottom |
| | Bw1 35-45 | PPL | c | S | Cp | op | | Orthic | | Orthic t |
| | Bw1 55-65 | PPL | sab | s | Ch | | | | HY | - Crescer |
| | Bw1 55-65 | XPL | sab | M | | P | u-s | | HY | S Undiffe striated (center) subhedi |
| | Bw1 65-75 | XPL | sab | S | | M | C | Orthic | Infillings | - Microst interpe infillin orienta |
| | Bw2 120-130 | PPL | | M | Ch | P | P | | Infillings | Porostr dense i |
| | Bw2 120-130 | XPL | | M | Ch | M | P | | Infillings | Accom contain porostr |
| | BC 160-170 | PPL | g | M | Cp | | | Orthic | HY | - Accom contain nodules |
| | BC 180-190 | XPL | sab | s | Ch | C | g-p | | Link capping | Feldspa fragem volcani orienta cappin |
| | BC 180-190 | PPL | | M | Ch | C | g-p | Orthic | Crust | - Poro-gr ground typic or |

Table 11. Cont'd.

| Profile No | Horizon (cm) | Microstructure | | | Groundmass | | Pedofeatures | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Shape | Pedality | Voids | c/f | b-fabric | Nodules | Coatings | Crystals | |
| | | | | | **Granitic Parent Materials** | | | | | |
| GNT 01 | AB 25-35 | XPL | c | M | v | c-e | S,p-g | | | S Subhedral crystal to fabric righ infilling co |
| | AB 25-35 | PPL | c | M | v-sp | e | | | | Vughy mi |
| | AB 25-35 | PPL | | M | v | m | | | | Weakly s with vugh |
| | AB 35-45 | XPL | sab | M | | G | S | Orthic | HY | S Subhedral nodule an groundma patterns |
| | AB 45-55 | PPL | | M | cp-p | | | | | A plannar |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Bw1 60-70 | XPL | sab | S | | | S | | | S | Subangual accommoc clay an porostriate |
| Bw1 60-70 | PPL | | S | | C | c-s | Orthic | | | Highly se orthic typi |
| Bw1 70-80 | PPL | sab | S | ch | Op | | Orthic | Infillings | - | Channel n complete (capping) groundma |
| Bw1 80-90 | PPL | sab | S | v | Op | | | Infillings | - | Vughy infilling c grains (ca hydroxide |
| Bw1 90-100 | PPL | sab | S | v | Cp | | | infillings | | Vughy m fragement coatings ir |

Table 11. Cont'd

| Horizon (cm) | | Microstructure Shape | Pedalit | Voids | Groundmass c/f | b-fabric | Pedofeatures Nodules | Coatings | Crystals | Miscellane |
|---|---|---|---|---|---|---|---|---|---|---|
| Bw1 90-100 | XPL | sab | S | v | Cp | C | Orthic | | S | Banded d (brown) o orientation elongated orthic typ dotted bl mineral fr coating of |
| Bw2 100-110 | PPL | sab | M | v | Op | | | Incomplete | - | Incomplet |
| Bw2 110-120 | PPL | ab | S | ch | Op | | | | | Channel n of illuvial intrapedal blank dott |
| Bw2 120-130 | PPL | sab | S | v | C | | orthic | infillings | - | Vughy m hydroxide with inter clay. |
| Bw2 130-140 | PPL | sab | S | | g-e | | | infillings | - | Gefuric-en patterns, interpedal in a fine sa |
| C 140-150 | PPL | sab | S | ch | Op | | orthic | infilling | - | Subangula |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | s | | complete i impregnat (bottom) i |

Table 11. Cont'd

| Profile | Horizon (cm) | | Microstructure Shape | Pedalit | Voids | Groundmass c/f | b-fabric | Pedofeatures Nodules | Coatings | Crystals | Miscellane |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GNT 02 | Ap 0-10 | PPL | c | M | ch | Op | | | crescent | - | Porous s microstruc related dis coating ch brown li capping or |
| | Ap 0-10 | XPL | c | M | | m-p | C | | infillings | - | Monic-por patterns, dotted b complete i |
| | Ap 10-20 | XPL | c | M | ch | Op | U | | | A | Porous cr ahedral cr porostriate undifferen fine organ |
| | Ap 10-20 | PPL | c | M | ch | P | | orthic | infillings | | Complete channels, moderatel orthic agg |
| | Bt1 20-30 | XPL | Sab | M | | P | g-p | | infillings | A | Weakly s microstruc the finer crystal mi fabric orie |
| | Bt1 20-30 | PPL | sab | M | v | P | | orthic | infillings | | Strongly dotted gro of fine coa |

Table 11. Cont'd

| Horizon | Microstructure | Groundmass | Pedofeatures | Miscellane |
|---|---|---|---|---|

| (cm) | | Shape | Pedalit | Voids | c/f | b-fabric | Nodules | Coatings | Crystals | |
|---|---|---|---|---|---|---|---|---|---|---|
| Bt1 30-40 | XPL | sab | S | | | | | | S | Subhedral porostriate nodules in |
| Bt1 30-40 | PPL | sab | S | cp | Op | | | | | Quartz gr quartz gra |
| Bt1 40-50 | XPL | sab | S | v | Cp | C | | infillings | | Subangula crystallitic complete voids (cap |
| Bt1 40-50 | PPL | sab | S | v-cp | e-p | | orthic | Typic | | Compound brownish vugh in orthic nod related dis |
| Bt1 58-68 | XPL | sab | S | ch | | C | vascular | infillings | | Subangula infillings b-fabric orientation hydroxide |
| Bt2 68-78 | PPL | sab | S | ch | P | | | infillings | - | Complete |
| Bt2 88-98 | XPL | sab | S | | Op | | anorthic | capping | ahedral | Capping crystal m strongly in |
| Bt2 88-98 | PPL | sab | S | v | e-p | | | HY | - | Vughy m accommod materials. |
| Bt2 100-110 | PPL | sab | S | ch | Op | | orthic | crescent | | Subangula microstruc coating cl impregnat groundma |

Table 11. Cont'd

| Horizon (cm) | | Microstructure Shape | Pedalit | Voids | Groundmass c/f | b-fabric | Pedofeatures Nodules | Coatings | Crystals | Miscellane |
|---|---|---|---|---|---|---|---|---|---|---|
| Bt2 100-110 | XPL | sab | S | ch | C | Speckled | orthic | HY | A | Coalescen excrement enaulic c/ quartz gr quartz gra |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | clay, not related c quaiscoati moderatel |
| | C 120-130 | XPL | sab | S | ch | p-c | C | orthic | infillings | A | Subangual coating ch with inte crystal mi colour ( groundma black dott |
| GNT 03 | AB 11-21 | XPL | c | S | cp | M | C | orthic | Infillings | - | Highly se compound orientation complete c yellow r dispersed and goethi |
| | AB 11-21 | PPL | | S | v sp | P C | | | | | Vughy mi |
| | AB 21-31 | PPL | ab | | | | | | | | Chitonic c grains wit |

Table 11. Cont'd

| Horizon (cm) | | Microstructure Shape | Pedalit | Voids | Groundmass c/f | b-fabric | Pedofeatures Nodules | Coatings | Crystals | Miscellane |
|---|---|---|---|---|---|---|---|---|---|---|
| AB 21-31 | XPL | ab | S | sp | C | S | orthic | | | Angular b related c coating accommoc porostriate nodules. |
| Bt1 38-48 | PPL | sab | M | v | P | | | | | Vughy mi clays. |
| Bt1 38-48 | XPL | | | | | | | | | |
| Bt1 48-58 | XPL | | | v-ch | P | S | orthic | crescent | a | Vughy w crescent c porostriate crystal evi typic nodu |
| Bt1 48-58 | PPL | | M | ch | Op | | orthic | infillings | - | Completel orientation |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | nodules. |
| | Bt2 66-76 | XPL | | M | ch | Op | g-p | orthic | infillings | Complete porostriate and mod nodules. |
| | Bt2 66-76 | PPL | | M | ch | Op | | orthic | Micropan | Complete (micropan typic nodu |
| | Bt3 101-111 | PPL | ab | M | ch | Op | | orthic | infillings | Channel n c/f relate impregnat complete c |
| | Bt3 101-111 | XPL | | M | ch | Oe | | orthic | crescent | Channel n related di planes quasicoati impregnat |

Table 11. Cont'd

| Horizon (cm) | | Microstructure Shape | Pedalit | Voids | Groundmass c/f | b-fabric | Pedofeatures Nodules | Coatings | Crystals | Miscellane |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bt3 111-121 | XPL | | | | U | orthic | crescent | | Undifferen orientation weakly im |
| | Bt3 121-131 | XPL | | M | ch | Op | g-p | | HY | a Channel n c/f relate porostriate quasicoati coatings. |
| | Bt3 121-131 | PPL | | M | ch | Op | | | HY | Crescent c |
| GNT 04 | Bt1 11-21 | PPL | c | M | cp | M | g-p | orthic | Infillings | E Channel n porostriate dense inf orthic typi |
| | Bt1 11-21 | XPL | c | M | sp | M | U | | | E Crumb m slide with crystal mi dense free |
| | Bt1 21-31 | PPL | | | ch | M | P | Orthic/ anorthic | | - Lenticular channel orientation |
| | Bt1 21-31 | XPL | sab | | | G | G | anorthic | | - Intra and granostriat orientation |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | anorthic m (bottom). |
| Bt1 31-41 | PPL | sab | W | ch | M | | geodic | Loose infi | - | Finer mon continuous developed microstruc |
| Bt1 31-41 | XPL | | M | v-ch | | g-p | orthic | Crescent | - | Vughy mi coating cla fabric orie |

Table 11. Cont'd

| Horizon (cm) | | Microstructure | | | Groundmass | | Pedofeatures | | | Miscellane |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Shape | Pedalit | Voids | c/f | b-fabric | Nodules | Coatings | Crystals | |
| Bt2 48-58 | PPL | | | v | p | p | | | - | Vughy mi fabric orie accommod nodules. |
| Bt2 58-68 | PPL | | M | ch | m | | typic | Infillings | - | Finer mon completely nodules. |
| Bt2 58-68 | XPL | | | ch | p | g-p | orthic | Loose inf | - | Porphyric porostriate continuous typic orthi |

Table 4: Comparism of some physical properties based on parent materials

| Parameter | Mean/CV (%) | Basalts | Granite | Grand mean | SED | LSD (T-test) |
|---|---|---|---|---|---|---|
| Bulk density | X | 0.942 | 1.505 | 1.216 | 0.0598 | *** |
| | CV | 22 | 10 | | | |
| Clay | X | 52.00 | 32.00 | 42.3 | 3.18 | *** |
| | CV | 21 | 26 | | | |
| Sand | X | 24.11 | 40.17 | 31.9 | 4.35 | *** |
| | CV | 44 | 39 | | | |
| Silt | X | 24.32 | 26.33 | 25.3 | 2.80 | NS |
| | CV | 17 | 44 | | | |

*** Significant at P<0.001, NS = Not Significant



Table 6: Comparism of some chemical properties based on parent materials

| **Parameter** | **Mean/CV (%)** | **Basalts** | **Granite** | **GM** | **SED** | **LSD (T-test)** |
|---|---|---|---|---|---|---|
| Exchangeable acidity | X | 1.763 | 4.67 | 3.18 | 0.466 | ** |
| | CV | 42 | 40 | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| $H^+$ | X | 0.61 | 1.594 | 1.089 | 0.148 | *** |
| | CV | 54 | 34 | | | |
| CEC | X | 10.25 | 6.094 | 8.23 | 0.90 | *** |
| | CV | 34 | 27 | | | |
| CEC-clay | X | 16.71 | 14.85 | 15.8 | 2.57 | NS |
| | CV | 53 | 44 | | | |
| Base saturation | X | 20.37 | 27.67 | 23.9 | 3.32 | *** |
| | CV | 46 | 39 | | | |
| $Ca^{2+}$ | X | 1.62 | 1.312 | 1.47 | 0.25 | * |
| | CV | 55 | 45 | | | |
| $Mg^{2+}$ | X | 0.16 | 0.19 | 0.174 | 0.043 | NS |



Table 6 Cont'd

| **Parameter** | **Mean/CV (%)** | **Basalts** | **Granite** | **GM** | **SED** | **LSD (T-test)** |
|---|---|---|---|---|---|---|
| | CV | 86 | 65 | | | |
| $K^+$ | X | 0.195 | 0.185 | 0.19 | 0.029 | NS |
| | CV | 44 | 49 | | | |
| $Na^+$ | X | 0.061 | 0.074 | 0.067 | 0.010 | * |
| | CV | 41 | 44 | | | |
| ECEC | X | 3.813 | 6.325 | 5.04 | 0.601 | *** |
| | CV | 36 | 35 | | | |
| Organic C | X | 0.541 | 0.47 | 0.508 | 0.075 | NS |
| | CV | 46 | 42 | | | |

NS = Not significant, * P< 0.05, ** P < 0.01, *** P< 0.001, X = Arithmetic mean GM = Grand mean, SED = Standard error of difference.



Table 5: Soil chemical properties of the pedons

| Horizon | Depth (cm) | pH ($H_2O$) | pH $CaCl_2$ | Exch Acidity $Al^+ + H^+$ | Exch Acidity $H^+$ | OC % | Exchangeable bases Cmol(+)$kg^{-1}$ Ca | Mg | K | Na | bases | C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | BASALTIC PARENT MATERIAL BST01 | | | | | | |
| Ap | 0-35 | 5.3 | 4.9 | 2.3 | 1.0 | 0.54 | 0.90 | 0.026 | 0.266 | 0.045 | 1.237 | 1 |
| Bw1 | 35-60 | 5.2 | 4.6 | 1.2 | 0.4 | 0.66 | 1.53 | 0.324 | 0.296 | 0.071 | 2.221 | 8 |
| Bw2 | 60-88 | 4.6 | 4.2 | 2.2 | 0.8 | 0.68 | 1.26 | 0.501 | 0.197 | 0.039 | 1.997 | 4 |
| Bt1 | 88-130 | 5.4 | 4.6 | 0.8 | 0.4 | 0.24 | 1.46 | 0.063 | 0.297 | 0.036 | 1.856 | 7 |
| Bt2 | 130-170+ | 5.4 | 4.6 | 0.9 | 0.4 | 0.41 | 0.89 | 0.097 | 0.164 | 0.055 | 1.206 | 9 |
| | | | | | | BST02 NITA | | | | | | |
| Ap | 0-16 | 5.0 | 4.5 | 1.3 | 0.3 | 0.68 | 1.57 | 0.247 | 0.230 | 0.030 | 2.077 | 1 |
| Bt1 | 16-70 | 5.4 | 4.8 | 1.6 | 0.5 | 0.60 | 1.42 | 0.314 | 0.294 | 0.082 | 2.110 | 1 |
| Bt2 | 70-117 | 5.6 | 4.5 | 2.8 | 0.5 | 0.39 | 1.53 | 0.339 | 0.114 | 0.050 | 2.033 | 1 |
| BC | 117-152 | 5.3 | 4.7 | 3.2 | 1.2 | 0.40 | ND | 0.195 | 0.228 | 0.066 | 0.489 | 1 |
| C | 152-175+ | 5.2 | 5.0 | 3.3 | 1.2 | 0.41 | 2.68 | 0.287 | 0.147 | 0.084 | 3.198 | 1 |
| | | | | | | BST03 RA-HOSS | | | | | | |
| Ap | 0-37 | 5.2 | 4.6 | 2.1 | 0.6 | 1.08 | 1.47 | 0.002 | 0.049 | 0.042 | 1.563 | 1 |
| Bw1 | 37-100 | 5.2 | 4.2 | 1.3 | 0.4 | 0.33 | 1.35 | 0.028 | 0.068 | 0.124 | 1.570 | 9 |
| 2BC1 | 100-110 | 4.6 | 4.2 | 1.1 | 0.2 | 0.55 | 1.50 | 0.028 | 0.188 | 0.077 | 1.793 | 9 |
| 2BC2 | 110-143 | 4.9 | 4.5 | 2.2 | 0.7 | 0.51 | 1.30 | 0.176 | 0.246 | 0.032 | 1.754 | 9 |
| 2Cr | 143-190 | 5.0 | 4.6 | 3.8 | 1.5 | 0.42 | 4.83 | 0.029 | 0.278 | 0.062 | 5.199 | 1 |
| | | | | | | BST04 TA-HOSS | | | | | | |
| Ap | 0-15 | 5.5 | 5.4 | 1.4 | 0.6 | 1.23 | 1.19 | 0.152 | 0.181 | 0.045 | 1.568 | 8 |
| Bw1 | 15-110 | 5.3 | 5.0 | 1.3 | 0.4 | 0.43 | 1.60 | 0.026 | 0.242 | 0.046 | 1.914 | 9 |
| Bw2 | 110-156 | 4.8 | 4.7 | 1.7 | 0.8 | 0.31 | 1.22 | 0.115 | ND | 0.071 | 1.406 | 8 |
| BC | 156-190 | 5.6 | 5.2 | 1.2 | 0.2 | 0.41 | 1.48 | 0.152 | 0.027 | 0.102 | 1.761 | 5 |
| | | | | | | GRANITIC PARENT MATERIAL GNT01 | | | | | | |
| Ap | 0-25 | 4.6 | 3.6 | 5.9 | 2.1 | 0.76 | 1.39 | 0.379 | 0.213 | 0.043 | 2.025 | 7 |
| AB | 25-60 | 4.8 | 4.1 | 5.9 | 2.1 | 0.30 | 0.66 | 0.128 | 0.279 | 0.098 | 1.165 | 5 |

Table 5.Cont'd

| | Depth | pH | | Exch Acidity | | OC | Exchangeable bases Cmol(+)kg$^{-1}$ | | | | | C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Horizon | (cm) | ($H_2O$) | $CaCl_2$ | $Al^+$+$H^+$ | $H^+$ | % | Ca | Mg | K | Na | □bases | |
| Bw1 | 60-100 | 4.2 | 3.9 | 4.0 | 1.4 | 0.31 | 1.60 | 0.067 | 0.280 | 0.048 | 1.995 | 4 |
| Bw2 | 100-140 | 4.5 | 3.6 | 1.9 | 0.4 | 0.43 | ND | 0.132 | 0.062 | 0.139 | 0.333 | 4 |
| C | 140-195 | 4.6 | 3.8 | 3.0 | 1.5 | 0.58 | 0.84 | 0.175 | 0.125 | 0.110 | 1.250 | 5 |
| | | | | | | | | GNT02 | | | | |
| Ap | 0-20 | 5.2 | 4.7 | 7.9 | 1.9 | 0.69 | 1.24 | 0.131 | ND | 0.052 | 1.423 | 8 |
| Bt1 | 20-78 | 4.4 | 3.5 | 3.7 | 1.4 | 0.26 | 1.48 | 0.020 | 0.128 | 0.116 | 1.744 | 5 |
| Bt2 | 78-115 | 4.5 | 3.3 | 1.2 | 0.9 | 0.27 | 1.45 | 0.107 | 0.153 | 0.120 | 1.830 | 8 |
| C | 115-130 | 4.6 | 3.6 | 2.3 | 0.8 | 0.35 | 1.55 | 0.315 | 0.231 | 0.061 | 2.157 | 8 |
| | | | | | | | | GNT03 | | | | |
| Ap | 0-11 | 5.4 | 4.6 | 3.2 | 1.4 | 0.54 | 0.85 | ND | 0.289 | 0.062 | 1.201 | 6 |
| Bt1 | 11-38 | 4.7 | 3.9 | 6.6 | 2.2 | 0.79 | 3.05 | 0.124 | 0.243 | 0.058 | 3.475 | 8 |
| Bt2 | 38-66 | 4.2 | 3.4 | 6.4 | 2.3 | 0.49 | 1.41 | ND | 0.140 | 0.056 | 1.606 | 5 |
| Bt3 | 66-101 | 4.3 | 3.3 | 5.4 | 1.6 | 0.31 | 1.58 | 0.208 | 0.033 | 0.031 | 1.852 | 4 |
| Bt4 | 101-148 | 4.5 | 3.8 | 4.0 | 1.2 | 0.43 | 0.58 | 0.142 | 0.108 | 0.056 | 0.886 | 5 |
| | | | | | | | | GNT04 | | | | |
| Ap | 0-11 | 5.2 | 4.3 | 6.9 | 2.4 | 0.83 | 1.50 | 0.435 | 0.080 | 0.062 | 2.077 | 4 |
| Bt1 | 11-48 | 4.4 | 4.2 | 6.2 | 1.9 | 0.42 | 1.59 | 0.183 | 0.334 | 0.108 | 2.215 | 7 |
| Bt2 | 48-120 | 4.4 | 3.6 | 4.8 | 1.4 | 0.59 | 0.47 | 0.352 | 0.279 | 0.072 | 1.173 | 5 |
| BC | 120-165 | 4.2 | 3.8 | 4.8 | 1.8 | 0.15 | 1.07 | 0.071 | 0.165 | 0.036 | 1.342 | 4 |



Table 10: Summaries of the soil classification

| Pedon | USDA System | WRB System |
|---|---|---|
| BST01 | Typic Haplustults fine clayey, vermiculite, isohyperthemic | Ferralic Acrisols |
| BST02 | Typic Haplustults fine clayey, vermiculite, isohyperthemic | Ferralic Acrisols |
| BST03 | Andic Haplustepts, very fine clayey, kaolinite isohyperthemic | Andic Cambisols |
| BST04 | Andic Haplustepts, very fine clayey, kaolinite isohyperthemic | Andic Cambisols |
| GNT01 | Oxic Haplustepts, fine loamy, kaolinitic isohyperthemic | Arenic Cambisols |
| GNT02 | Typic Plinthaquults, fine silty, micaeous, isohyperthemic | Plinthic Acrisols |
| GNT03 | Typic Haplustults, fine silty, micaeous, | Haplic Acrisols |

| | | |
|---|---|---|
| | isohyperthemic | |
| GNT04 | Typic Haplustults, fine silty, micaeous, isohyperthemic | Haplic Acrisols |

Table 7. Micromorphological features of the modal soil profiles for basaltic and granite parent materials

| Horizon (cm) | | Microsturcture Shape | Pedalit | Voids | Groundmass c/f | b-fabric | Pedofeatures Nodules | Coatings | Crystals | Miscellane |
|---|---|---|---|---|---|---|---|---|---|---|
| Bt126-36 | PPL | c | M | | P | S | Orthic | HY | | Loose con |
| Bt1 26-36 | XPL | c | M | Ch | P | S, p | | Hy | - | Porous sp infillings. |
| Bt1 36-46 | PPL | | W | Ch | op | | t | | - | Free grain |
| Bt1 36-46 | XPL | | W | Ch | op | S,grano- | t | | - | Dusty volc |
| Bt1 56-66 | XPL | | | | | U | t | Infillings | - | Notice o orientation of extincti |
| Bt1 56-66 | PPL | sab | M | | m | | t | Infillings | - | Complete nodules in |
| Bt2 70-80 | XPL | | M | Ch | Op | g-p | t | Hy | | Free quart complete c |
| Bt2 70-80 | PPL | | S | Ch | P | | t | - | - | Dense con |
| Bt2 80-90 | XPL | | M | V | | S,g-p | | | E | Red-brow blue colou |
| Bt2 90-100 | XPL | | M | Ve | P | | | | | Vesicular |
| Bt2 100-110 | XPL | sab | | V | e-p | U | | | | Porostriate |
| BC 117-127 | PPL | sab | S | Cp-ch | | | Orthic | | | Air bubble oriented in moderately |
| BC 117-127 | XPL | | | | C | p-g | | | | Poro and micromass |
| BC 127-137 | PPL | sab | S | V | Cp | | | | | An aggreg of fresh c coating cla |
| BC 137-147 | XPL | sab | s | Ve-cp | Cp | U | | | | Vesicular top-right, |
| BC 137-147 | PPL | | S | Cp-v | Cp | | | Capping | - | Link ca microstruc |
| BC 152-162 | XPL | | | Cp | c-p | P | | | | Fabric pe crescent fa |

Table 7. Cont'd

| Horizon (cm) | | Microsturcture Shape | Pedalit | Voids | Groundmass c/f | b-fabric | Pedofeatures Nodules | Coatings | Crystals | Miscellane |
|---|---|---|---|---|---|---|---|---|---|---|
| **Granitic Parent Materials** | | | | | | | | | | |
| AB 25-35 | XPL | C | M | v | c-e | S,p-g | | S | Subhedral muscov crystal top and bo fabric right and upp infilling coatings cla | |
| AB 25-35 | PPL | C | M | v-sp | e | | | | Vughy microstructur | |
| AB 25-35 | PPL | | M | v | m | | | | Weakly separated ( with vughy microstr | |
| AB 35-45 | XP | Sab | M | | G | S | Orthic | HY | S | Subhedral crystal ( |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | L | | | | | | | | | nodule and internal groundmass, gefuric patterns |
| AB 45-55 | PPL | | M | cp-p | | | | | | A plannar void accor |
| Bw1 60-70 | XP L | Sab | S | | | S | | | S | Subangualar blo accommodating pla clay and intrap porostriated b-fabric |
| Bw1 60-70 | PPL | | S | | C | c-s | Orthic | | | Highly separated wi orthic typic nodules. |
| Bw1 70-80 | PPL | Sab | S | ch | Op | | Orthic | Infillings | - | Channel microstruct complete dense (capping) with groundmass. |
| Bw1 80-90 | PPL | Sab | S | v | Op | | | Infillings | - | Vughy microstruc infilling coatings on grains (capping), b hydroxides nodules. |
| Bw1 90-100 | PPL | Sab | S | v | Cp | | | infillings | | Vughy microstructu fragement at the bo coatings in banded p |

Table 7. Cont'd

| Horizon (cm) | | Microstructure Shape | Pedalit | Voids | Groundmass c/f | b-fabric | Pedofeatures Nodules | Coatings | Crystals | Miscellaneous |
|---|---|---|---|---|---|---|---|---|---|---|
| Bw1 90-100 | XP L | Sab | S | v | Cp | C | Orthic | | S | Banded distribution (brown) organic frag orientation (both elongated particles orthic typic iron h dotted black limpi mineral fraction on coating of fine clay r |
| Bw2 100-110 | PPL | Sab | M | v | Op | | | Incomplete | - | Incomplete infillings |
| Bw2 110-120 | PPL | Ab | S | ch | Op | | | | | Channel microstruct of illuvial clays, ac intrapedal channel r blank dotted limpidit |
| Bw2 120-130 | PPL | Sab | S | v | C | | orthic | infillings | - | Vughy microstruct hydroxides nodules with interpedal infil clay. |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Bw2 130-140 | PPL | Sab | S | | g-e | | infillings | - | Gefuric-enaulic c/ patterns, accomm interpedal complete in a fine sand size te |
| C 140-150 | PPL | Sab | S | ch | Op | orthic | infillings | - | Subangular with complete infilling of impregnated orthic (bottom) in groundm |

Table 8. Profile distribution of the mineral contents

| Horizon | Depth (cm) | Treatment | Mineral | Horizon | Depth (cm) | Treatment | Mi |
|---|---|---|---|---|---|---|---|
| **BST01 CHAHA** | | **BASALTIC PARENT MATERIAL** | | **BST04 TA-HOSS** | | | |
| Ap | 0-35 | Mg-sat | Mica-vermiculite | Ap | 0-15 | Mg-sat | Ka |
| | | Glyl | Hydroxy-interlayered vermiculite | | | | Mr |
| | | Heated | Hydroxyaluminium interlayered vermiculite | | | | Bir |
| | | | Mixed layer (Maghemite) | | | | Po |
| Bw2 | 60-88 | Mg-sat | Kaolinite | | | Glyl | Le |
| | | | Geothite | | | Heated | Hy |
| | | Glyl | Kaolinite | Bw1 | 15-110 | Mg-sat | Sil |
| | | Heated | Maghemite | | | | Ka |
| Bt1 | 88-130 | Mg-sat | Kaolinite | | | | Ve |
| | | | Sepiolite | | | | He |
| | | | Gibbsite | | | | Qu |
| | | | Mica-vermiculite | | | Glyl | Ka |
| | | Glyl | Sepiolite | | | Heated | Pla |
| | | Heated | Maghemite | | | | Mi |
| | | | Microcline silica | Bw2 | 110-156 | Mg-sat | Sm |
| Bt2 | 130-170 | Mg-sat | Kaolinite | | | | Ka |
| | | | Chlorite | | | | Ch |
| | | | Plagioclase feldspars | | | | Sil |
| | | Glyl | Hydromica | | | Glyl | Le |
| | | | Kaolinite | | | Heated | Sa |
| | | | Microcline | | | | Illi |
| | | Heated | Maghemite | | | | Pla |
| | | | Sillica | | | Mg-sat | Ma |
| | | | | | | | Lit |
| | | | | | | Glyl | Ka |
| | | | | | | Heated | Mi |



Table 9. Profile distribution of the mineral contents (granite parent material)

| Horizon | Depth (cm) | Treatment | Mineral | Horizon | Depth (cm) | Treatment | Mi |
|---|---|---|---|---|---|---|---|
| **GNT01** | | **GRANITE PARENT** | | **GNT04** | | | |
| **MATERIAL** | | | | | | | |
| Ap | 0-25 | Mg-sat | Quartz | Ap | 0-11 | Mg-sat | Mi |
| | | | Jarosite | | | | He |
| | | Glyl | Kaolinite | | | Glyl | Sm |
| | | | Lepidocrocite | | | | Ka |
| | | Heated | Chamosite (ironic)birnessite | | | | Sil |
| | | | Geothite | | | Heated | Ve |
| AB | 25-60 | Mg-sat | Microcline | Bt1 | 11-38 | Mg-sat | Ha |
| | | | Iron microcline-low form | | | | Ka |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | Plagioclase(oligoclase) | | | | Sm |
| | | | Anatse | | | | Pla |
| | | Glyl | Kaolinite | | | | Mi |
| | | | Trace 2:1 phyllosillicate | | | Glyl | Ka |
| | | Heated | Geothite | | | Heated | Ge |
| | | | Lithiophorite (Mn-rich) | | | | Al- |
| Bw1 | 60-100 | Mg-sat | Halloysite (-$H_2O$) | Bt2 | 66-101 | Mg-sat | Ch |
| | | | Lepidocrocite | | | Glyl | Le |
| | | | Vermiculite | | | Heated | Lit |
| | | Heated | Mica-plagioclase | | | | Ge |
| Bw2 | 100-140 | Mg-sat | Rutile | | | | Ka |
| | | | Lepidocrocite | | | | Mi |
| | | Glyl | Kaolinite | BC | 120-165 | Mg-sat | Le |
| | | Heated | Smectite | | | | Ka |
| | | | Tridymite (quartz) | | | | Mi |
| | | | Geothite | | | Glyl | Int |
| | | | | | | Heated | Int |

**** Interpretation of symbols used in describing micromorphological features of the pedons in Table 11.**

**Optical Techniques**

PPL = Plane Polarize Light

XPL = Crossed Polarize Light

**Microstructure:**

**Shape**

C = Crumb

Sab = Subangular blocky

**Pedality**

W = Weak

M = Moderately

S = Strongly

**Voids**

CP = Compound packing voids

Ch = Channel

V = Vughs

Cham = Chamber

P = Planes

**S-Matrix (ground mass):**

**Coarse: Fine Ratio (c/f)**

M = Monic

P = Porphyric

OP = Open Porphyric

C = Chitonic

E = Enaulic

G = Gefuric

**b-fabric**

C = Crystallitic

S = Striated

P = Porostriated

G = Grano

**Pedofeatures:**

**Nodules**

O = Orthic

T = Typic

An = Anorthic

**Coatings**

HY = Hypocoatings

CR = Crescent coatings

MI = Micropan

**Cryatals**

E = Euhedral

SE = SubEuhedral

A = Anhedral

## APPENDIX C

## MICROMORPHOLOGICAL INTERPRETATION

**PROFILE NO: BST01**

**Ap 0-10cm PPL:** moderately developed, but weakly separated crumb with porous spheroidal microstructure and compound packing voids, fine monic c/f related distribution pattern;

**Ap 10-20cm XPL:** moderately developed, but weakly separated crumb microstructure; monic c/f related distribution pattern; crystallitic sequioxide nodules.

**Ap 20-30cm PPL:** moderately developed crumb microstructure superposed to channel microstructure, fine monic c/f related distribution pattern, strained with prostrated b-fabric micromass orientation, free grain crescent infillings of coating clay.

**Ap 20-30cm XPL:** moderately separated crumb microstructure with porouspheroidal aggregates, fine monic c/f related distribution pattern, porostriated b-fabric micromass orientation. Hypo-quasicoating (Typic).

**Bw1 30-40cm XPL:** Highly developed and separated crumb microstructure with chitonic c/f related distribution pattern. Meta-skew planes orthovoids. Accommodating planes with interpedal voids contain dense complete infillings or intercalation of black sediments. Crystallitic b-fabric orientation and porostriated. Hypo-quasicotaing clay (Tyic). Moderately impregnated orthic aggregate iron hydroxide nodules.

**Bw1 30-40cm XPL:** Highly separated channel microstructure with open porphytic c/f related distribution pattern Porostriated b-fabric orientation groundmass. Hypo-quasicoatings (micropan). Highly impregnated orthic typic nodules.

**Bw1 40-50cm XPL:** Highly separated vughy microstructure with open porphyric c/f related distribution pattern. Striated with grano-porostriated b-fabric orientation groundmass; complete dense infillings coatings of voids, hypoquasicoating (micropan).

**Bw1 50-60cm PPL:** Moderately developed channel microstructure with open porphyric c/f related distribution pattern. Porostriated b-fabric orientation micromass.

**Bw1 50-60cm XPL:** Moderately developed, but weakly separated vughy microstructure with double spaced to open porphyric c/f related distribution pattern. Striated with porostriated b-fabric groundmass orientation. Loosed and in complete infillings coatings clay.

**Bw2 70–80cm XPL:** Moderately separated sub-angular blocky microstructure with open enaulic c/f related distribution. Striated with grano-porostriated b-fabric ground mass orientation. Hypo-quasicoating (crescent coatings). Crytallitic sequioxides b-fabric orientation middle and right – sided slide. Strongly impregnated orthic typic nodules.

**Bw2 70–80cm PPL:** Moderately separated channel microstructure, interpedal voids accommodating channel with open porphyric c/f related distribution. Porostriated b-fabric orientation. Complete dense infillings or coating clay parallel to the voids.

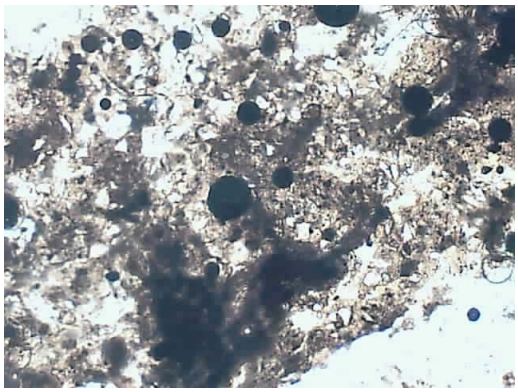
**Bw2 80–90cm PPL:** Moderately separated channel microstructure with porphyric c/f related distribution. Porostriated b-fabric micromass orientation. Complete dense infillings

**Bw2 80 – 90cm XPL:** Moderately separated channel microstructure with monic c/f related distribution. Complete dense infilling coating clay. Porostriated b-fabric micromass in banded orientations.

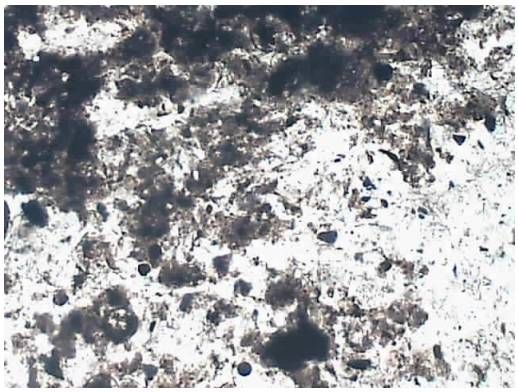
**BST 01 CHAHA**

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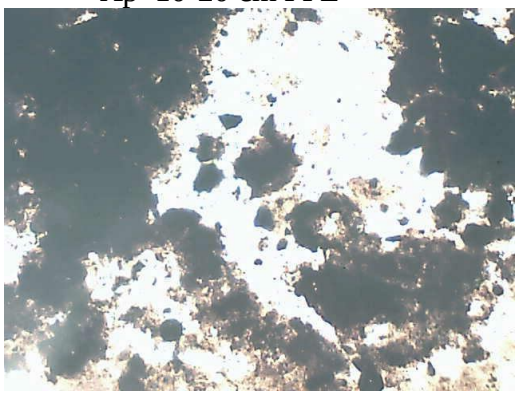
Ap 10-20 cm XPL



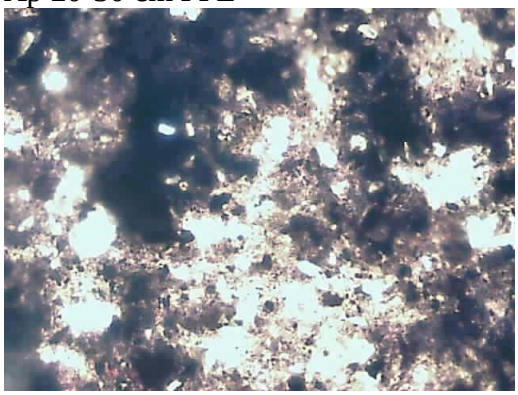
Ap 10-20 cm PPL



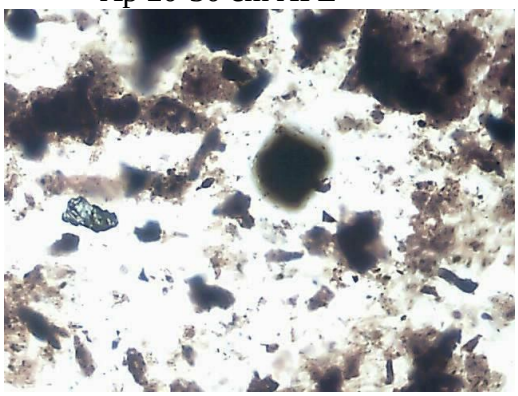
Ap 20-30 cm PPL



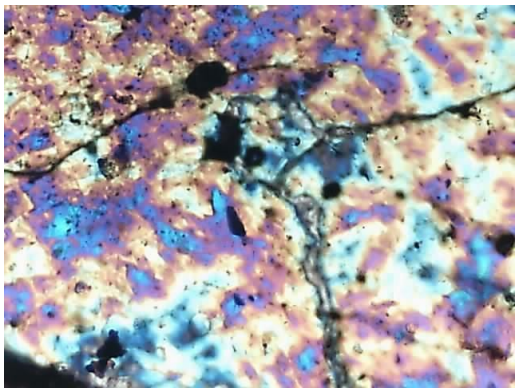
Ap 20-30 cm XPL



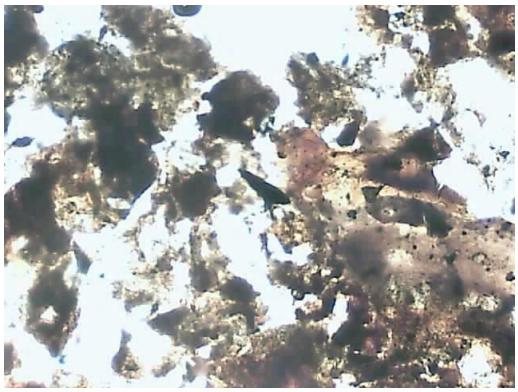
Bt1 30-40 cm XPL

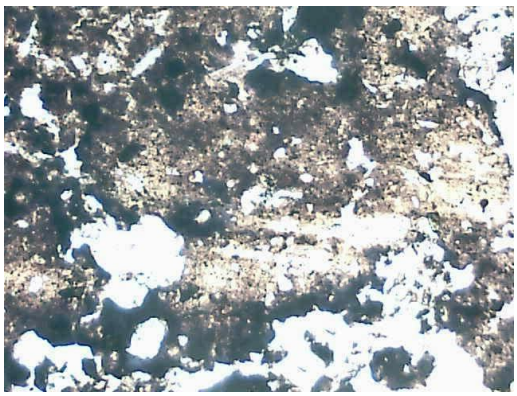


Bt1 30-40 cm PPL



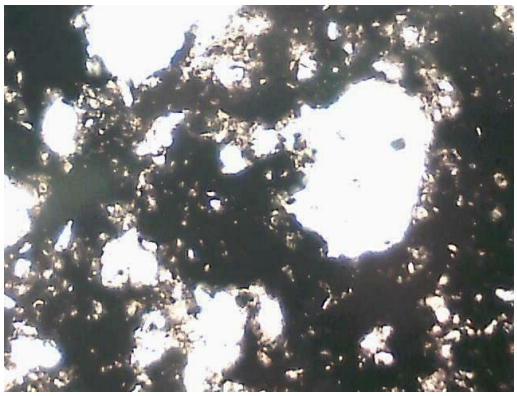
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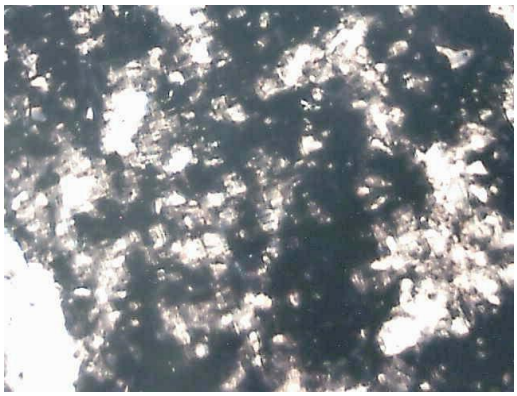


Thin-sections from the depth of 0-50cm in Profile BST01

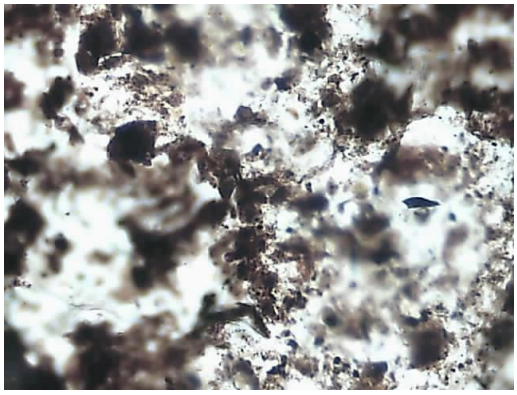
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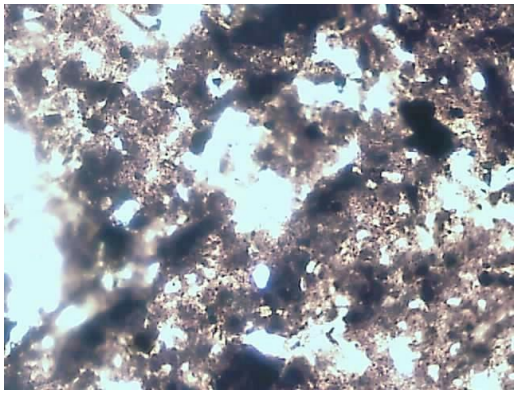
Bt1 50-60 cm XPL



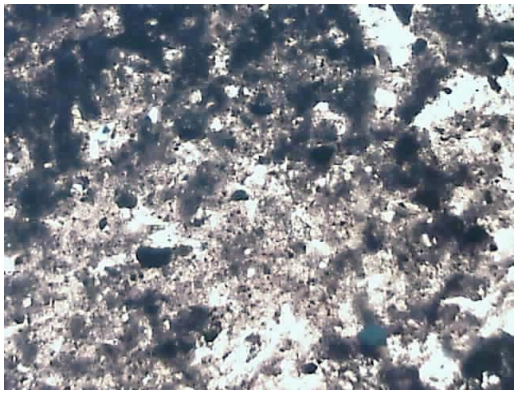
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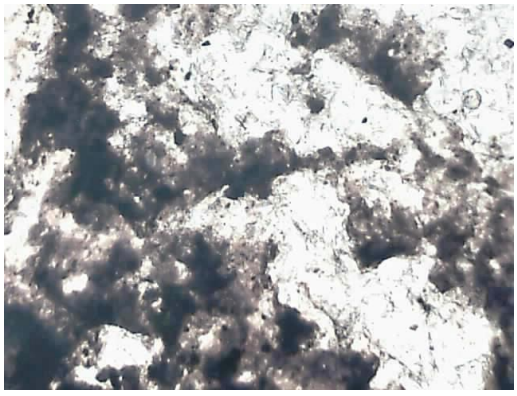
Bt3 70-80 cm PPL



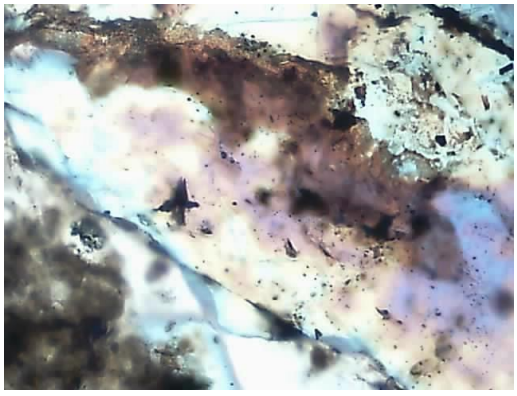
Bt3 80-90 cm PPL



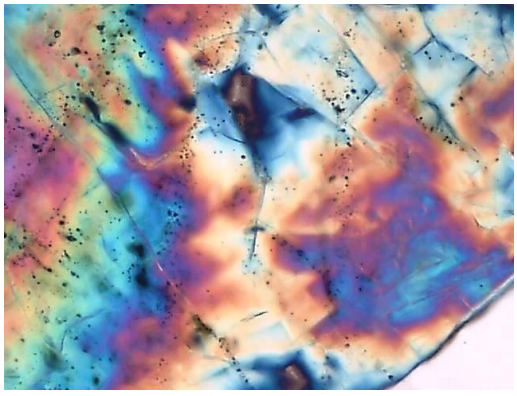
Bt3 80-90 cm XPL



Bt3 90-100 cm XPL

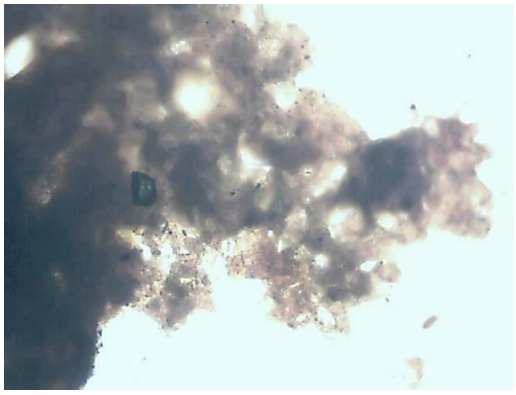


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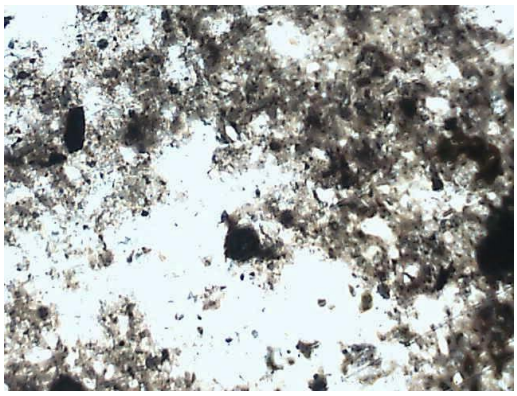


Thin-sections from the depth of 50-100cm in Profile BST01

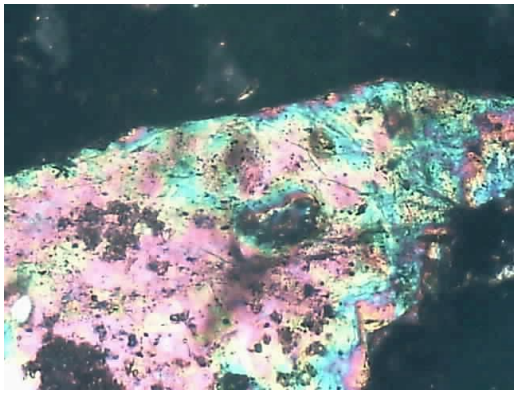
Bt3 90-100 cm PPL



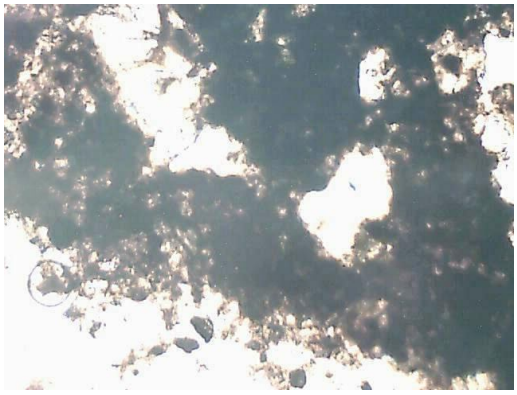
Bt3 110-120 cm PPL



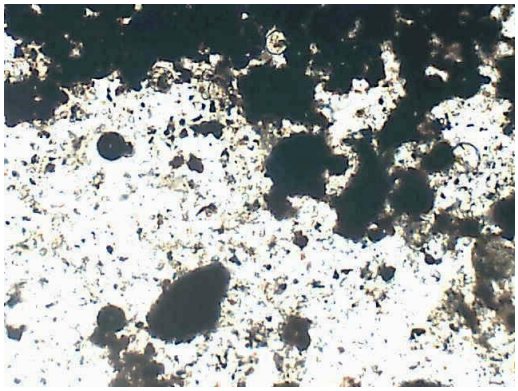
Bt4 130-140 cm XPL



Bt4 130-140 cm PPL



Bt4 150-160 cm



Thin-sections from the depth of 90-160cm in profile BST01

**90–100cm XPL:** Strongly impregnated orthic typic and aggregates nodules. Crystallitic b-fabric micromass orientation several infillings and passage features pointing to a high biological activity (micropan).

**90 – 100cm XPL:** Notice angular mineral grains with cleavage streak and interference color limpid clay coatings. Crystallitic sequioxids b-fabric micromass.

**90 – 100cm PPL:** Weakly separated channel microstructure with porphyric c/f related distribution. Hypo-quasicoating (capping). Moderately impregnated orthic typic nodules.

**110 – 120cm PPL:** Highly separated channel microstructure with porphyric c/f related distribution. Hypo-quasicoating on top of free or embedded grain (capping); strongly impregnated orthic typic nodules. Interpedal voids connecting intrapedal.

**130 – 140cm XPL:** Highly separated angular blocky microstructure with fine monic c/f related distribution. Crystallitic sequioxide b-fabric micromass with interference limpid color infillings coating clay. Moderately impregnated orthic aggregated nodules. Undifferentiated b-fabric groundmass on top and right-sided slide.

**130-140cm PPL:** Moderately separated channel microstructure with fine monic c/f related distribution. Hypo-quasicoating infilling channel/voids (crescent coating).

**150 – 160cm PPL:** Highly separated angular blocky microstructure with fine monic c/f related distribution. Porostriated b-fabric groundmass. Infillings coatings channel voids

**PROFILE NO: BSTO2**

**16-26cm PPL:** Medium separated vughy microstructure. Open porphyric c/f related distribution pattern. Complete infillings coatings clay.

**26-36cm XPL:** Moderately developed crumb with porous spheroidal aggregates microstructure with interpedal accommodating channels. Porphyric c/f related distribution. Striated with porostriated b-fabric orientation; internal crescent hypocoatings clay and infillings.

**26 – 36cm PPL:** Fine monic c/f related distribution. Loose continuous coatings clay; complete infilling clay in the plannarvoids. Striated b-fabric orientation. Typic orthic nodules.

**36 – 46cm XPL:** Weakly developed and separated channel microstructure (dusty volcanic ash). Open porphyric c/f related distribution. Striated with grano-porostriated b-fabric orientation. Typic microxides nodules.

**36-46cm PPL:** Weakly separated channel microstructure. Open porphyric c/f related distribution pattern. Typic nodules and free grain coatings clays.

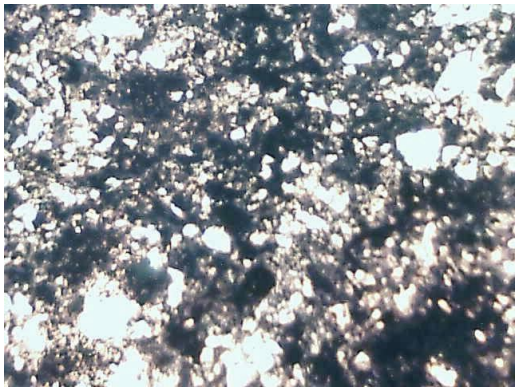
**56 – 66cm XPL:** Notice interlamellar deposits of parallel orientation and high interference color. Undifferentiated b-fabric orientation. Evidence of extinction mineral cleavage. Typic nodules and infillings coatings clay.

**56-66cm PPL:** Moderately developed, but weakly separated sub-angular blocky microstructure. Monic c/f related distribution. Complete dense infillings coating clay and typic nodules in groundmass.

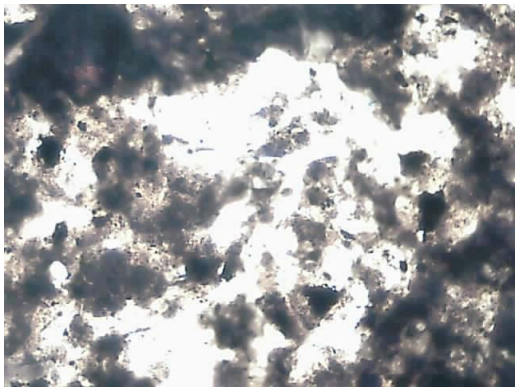
**70-80cm XPL:** Moderately developed channel microstructure. Free quarts grains. Open porphyric c/f related distribution. Grano-porostriated b-fabric orientation. Typic and aggregated nodules, hypocoatings clay and complete dense infillings coatings clay.

**BST02 NITA VOM**

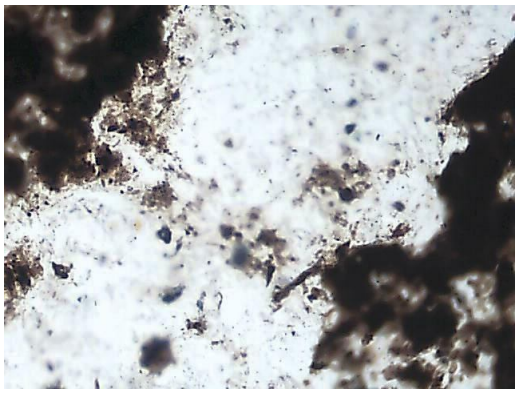
Bt1 16-26 cm PPL



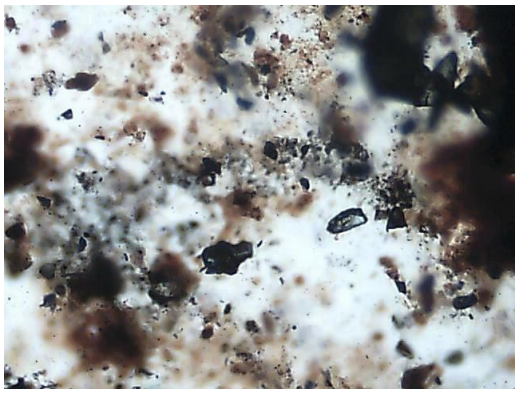
Bt1 26-36 cm XPL



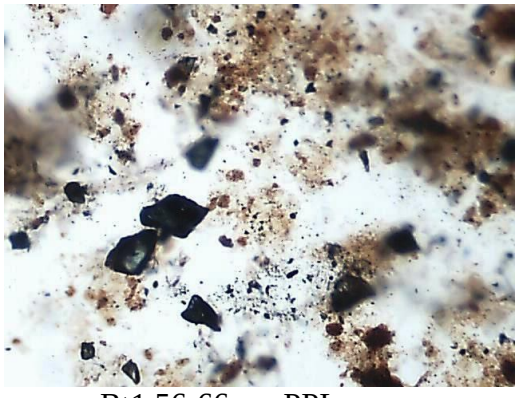
Bt1 26-36 cm PPL



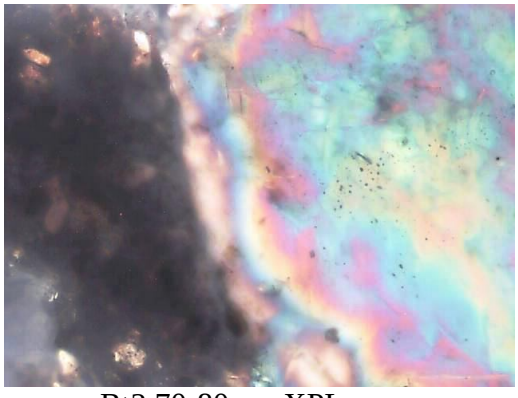
Bt1 36-46 cm XPL



Bt1 36-46 cm PPL

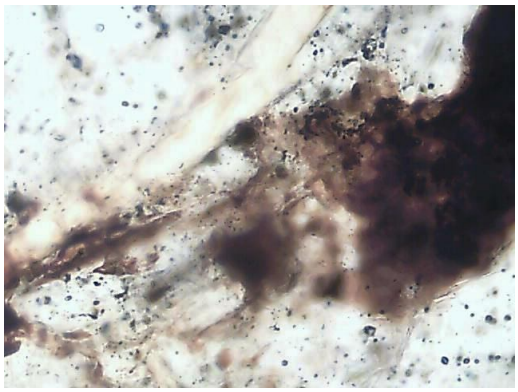
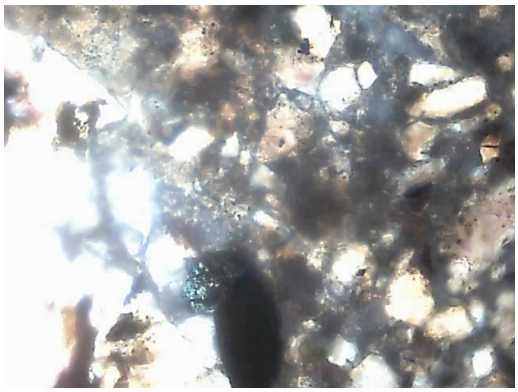


Bt1 56-66 cm XPL



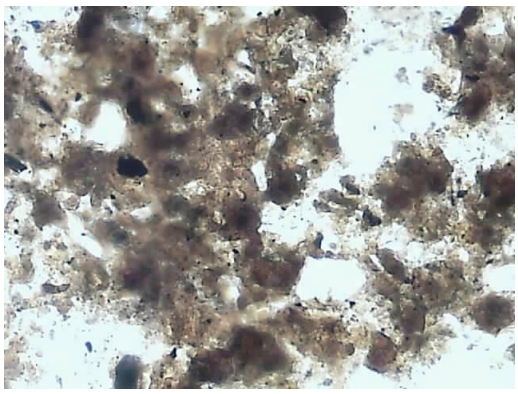
Bt1 56-66 cm PPL

Bt2 70-80 cm XPL

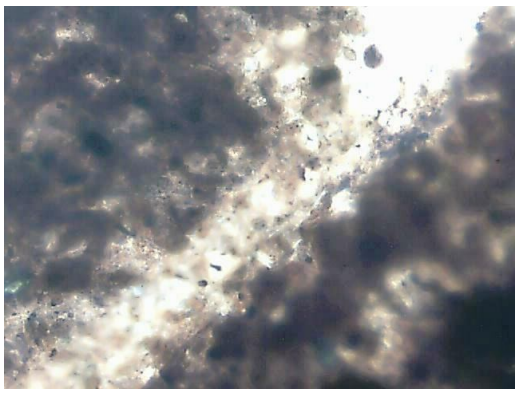



Thin-sections from the depth of 16-80cm in profile BST02

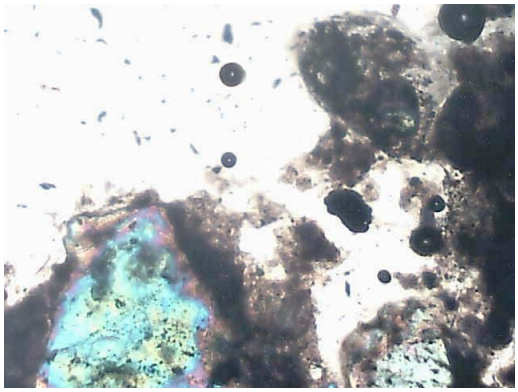
Bt2 70-80 cm PPL



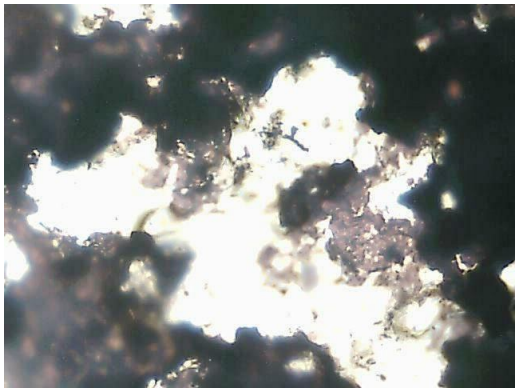
Bt2 70-80 cm XPL



Bt2 80-90 cm XPL

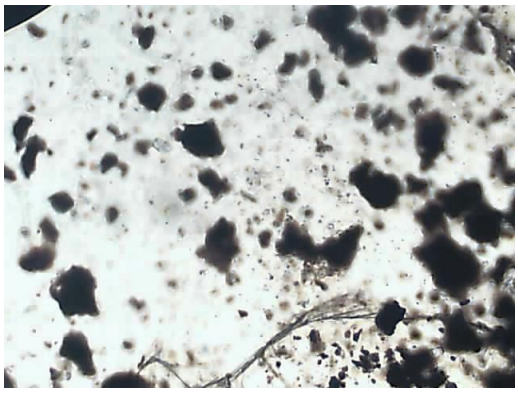


Bt2 90-100 cm XPL

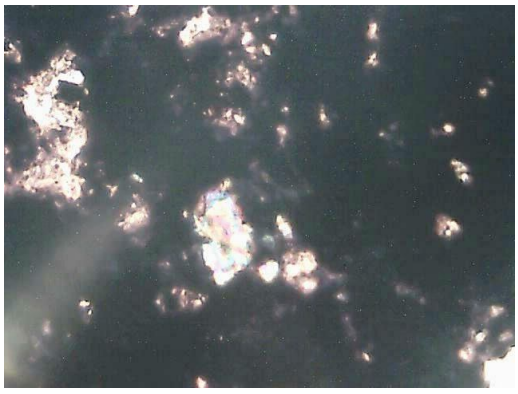


Bt2 100-110 cm PPL

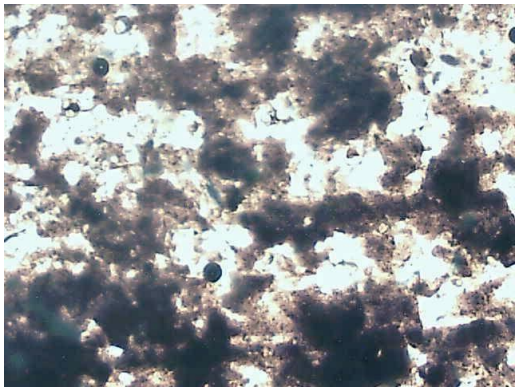
Bt2 100-110 cm XPL

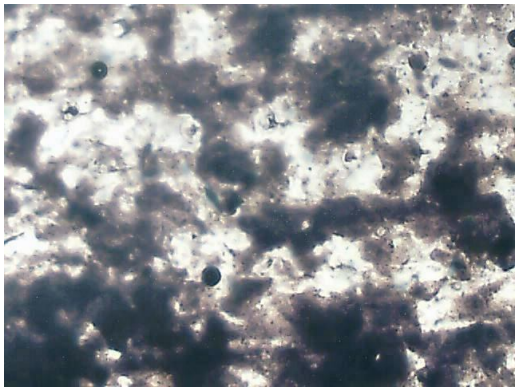


BC 117-127 cm PPL



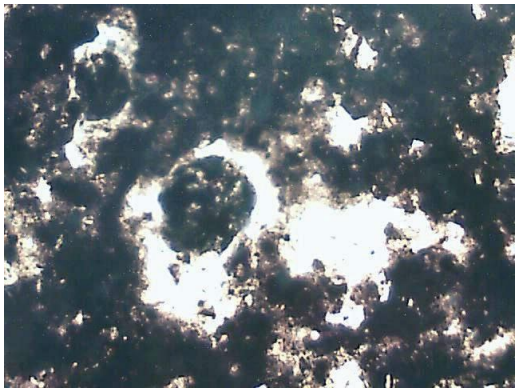
BC 117-127 cm XPL





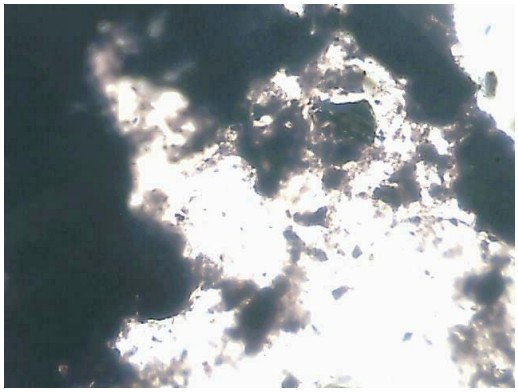
Thin-sections from the depth of 70-127cm in profile BST02

BC 127-137 cm PPL

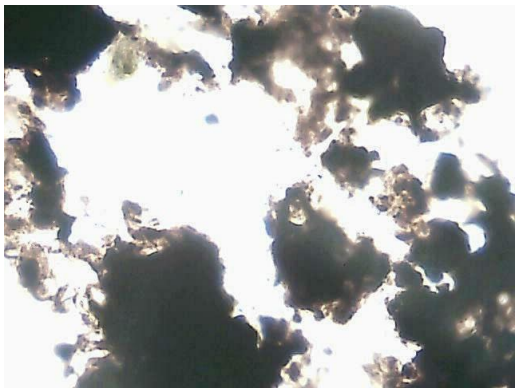


C 137-147 cm PPL

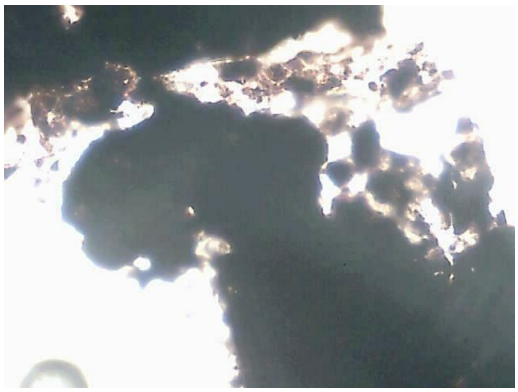
C 137-147 cm XPL



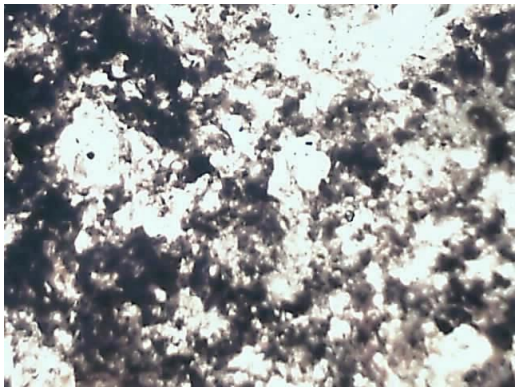
C137-147 cm PPL



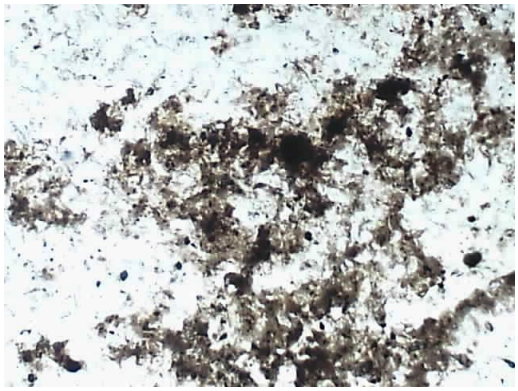
C 152-162 cm PPL



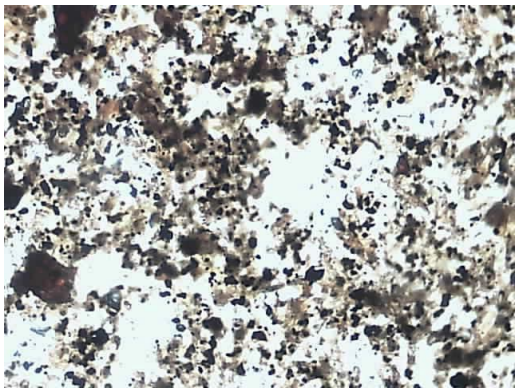
C152-162 cm XPL

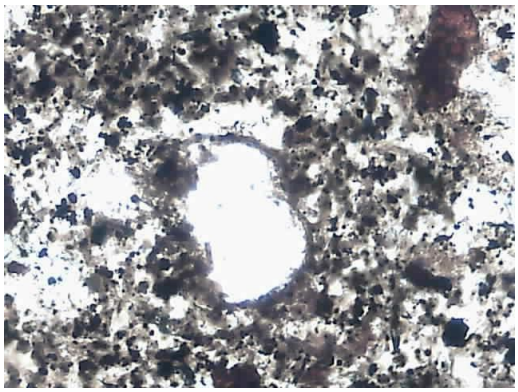


C 162-172 cm PPL



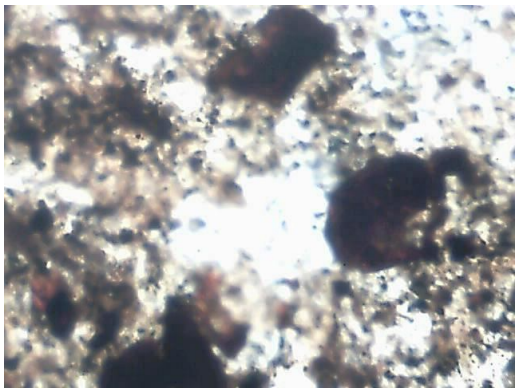
C 162-172 cm XPL





Thin-sections from the depth of 127-172cm in profile BST02

C 162-172 cm XPL



Thin-sections from the depth of 162-172 in profile BST02

**70-80cm PPL:** strongly developed channel microstructure porphyric c/f related distribution. Dense complete infillings of coatings clay. Typic nodules.

**70-80cm XPL:** Weakly separated channel microstructure. Chitonic c/f related distribution. Undifferentiated b-fabric orientation except in the center slide. Striated with porostriate and typic orthic nodules.

**80-90cm XPL:** Moderately developed vughy microstructure. Euhedral mineral crystals (bottom) slide. Striated with grano-porostriated b-fabric orientation. Air bubbles will hollow.

**80-90cm XPL:** Euhedral mineral crystal grain with interference blue color and dotted black micromass. Red-brown color enmass the grain.

**90-100cm XPL:** Moderately developed with vesicular crust (centre) microstructure. Close porphyric c/f related distribution pattern left bottom slide.

**100-110cm PPL:** Strongly developed angular blocky microstructure compound packing voids.

**100-110cm XPL:** Moderately developed with weak separated sub-angular blocky vughy microstructure. Undifferentiated b-fabric orientation. Enaulic-porphyric c/f related distribution pattern. Porostriated on the voids.

**117-127cm PPL:** Strongly developed and moderately separated sub angular blocky microstructure. Compound packing voids. Air bubble with hollow on top and bottom slide. Banded oriented infilling coating of the channel (bottom). Moderately impregnated orthic nodules.

**117-127cm XPL:** Poro and granostriated b-fabric orientation. Chitonic c/f relataed distribution pattern.

**127-137cm PPL:** Highly developed and moderately separated sub-bamgular blocky with vughy microstructure. The aggregate in the centre is an excrement composed of fresh cell fragments. Close-porphyric c/f related distribution pattern. Completed dense infilling coating clay of voids.

**137-147cm XPL:** Strongly developed sub-angular blocky vesicular microstructure. Compound packing voids. Undifferentiated b-fabric orientation top – right slide. Close porphyric c/f related distribution pattern. Porostriated b-fabric (center) orientation.

**137-147cm PPL:** Highly separated with compound packing voids, vughy microstructure. Link capping over voids (top). Close porphyric c/f related distribution pattern.

**152-162cm XPL:** Fabric pedofeature, passage feature visible by crescent fabric in grayish groundmass with chitonic-porphyric c/f related distribution pattern. Compound packing voids. Porostriated b-fabric orientations.

**162-172cm PPL:** Highly separated sub-angular blocky vughy microstructure. Enaulic porphyric c/f fabric related distribution pattern. Red color indicating hematite mineral.

**162-172cm XPL:** Highly separated sub-angular blocky vughy microstructure. Compound packing voids. Aggregate nodule micromass, Crystallitic b-fabric micromass. Complete dense infilling coating in banded distribution. Porostriated b-fabric orientation.

**162-172cm XPL:** Highly separated sub-angular voids. Interpedal accommodating plannes with infilling coating channel/vughy voids. Moderately impregnated anorthic nodules. Gefuric c/f fabric related distribution pattern (top left). Notice red interference color mineral grain (hematite). Chitonic – porphyric c/f related distribution over the slide.

**PROFILE NO: BST03**

**25-35cm PPL:** Moderately developed, but weakly separated crumb microstructure characterized by porous spheroidal aggregates. Compound packing voids, loose discontinuous infillings coating clay in banded preferred distribution.

**38-48cm XPL:** Vughy microstructure with some channels and crescent coatings clay. Undifferentiated b-fabric. Medium developed but weakly separated sub angular blocky microstructure.

**48-58cm XPL:** Strongly developed and separated sub angular blocky microstructure in the right-sided of the slide crytallitic b-fabric micromass. Notice of rock fragment, enualic c/f related distribution. Grano-porostriated in the bottom right section.

**48-58cm PPL:** Dense complete infillings and porostriated b-fabric orientation.

**58-68cm PPL:** Strongly developed separated sub-angular microstructure.

**58-68cm XPL:** Vughy microstructure with grano-striated b-fabric.

**68-78cm XPL:** Moderately separated granular to vughy microstructure with star stiaped vughy. Banded related distribution with compound packing voids.

**68-78cm XPL:** Weakly separatd with vughy microstructure. Undifferentiated b-fabric on top and right bottom slide. Mosail speckled b-fabric (center), granostriated.

**78-88cm PPL:** Strongly developed and separated channel microstructure. Monic c/f related, distribution. Orthic typic nodules.

**78-88cm XPL:** Strongly developed with moderate separated channel microstructure. Gefuric c/f relalteld distribution. Clay coating with striated b-fabric granostriated.

**100-110cm PPL:** Gefuric c/f related distribution. Notice of the rock fragment.

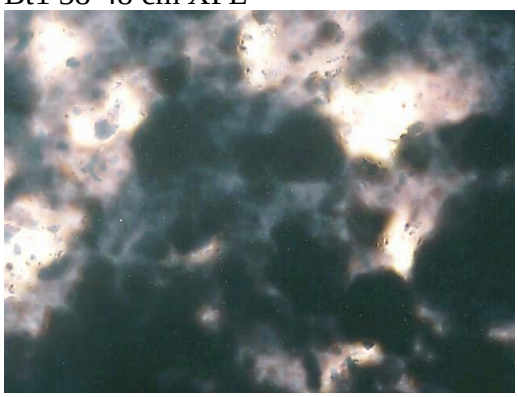
**100-110cm XPL:** Strongly developed with moderate separated sub-angular blocky microstructure. Crystallitic b-fabric and granostriated.

**BST 03**

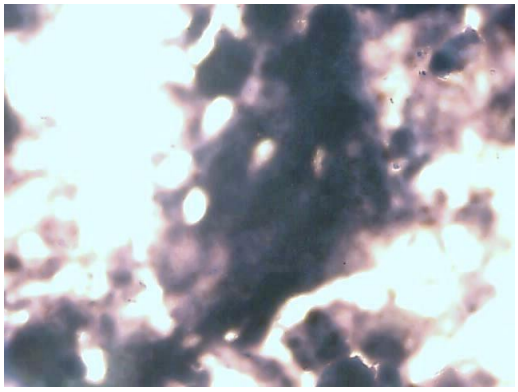
Ap 25-35 cm PPL



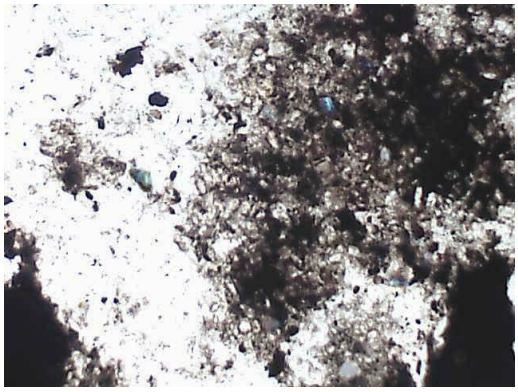
Bt1 38-48 cm XPL



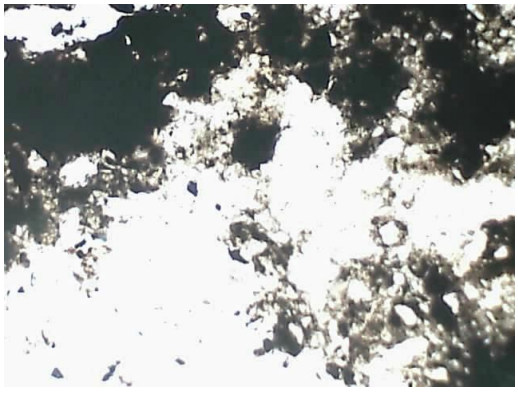
Bt1 38-48 cm PPL



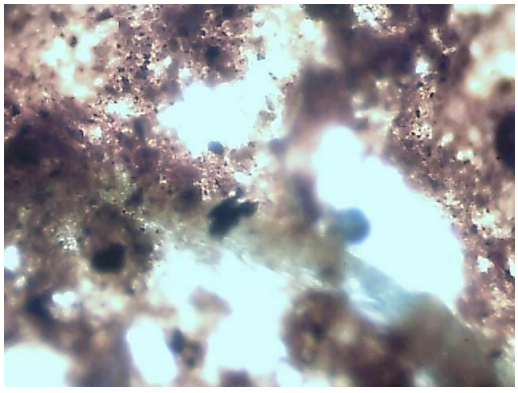
Bt1 48-58 cm XPL



Bt1 48-58 cm PPL

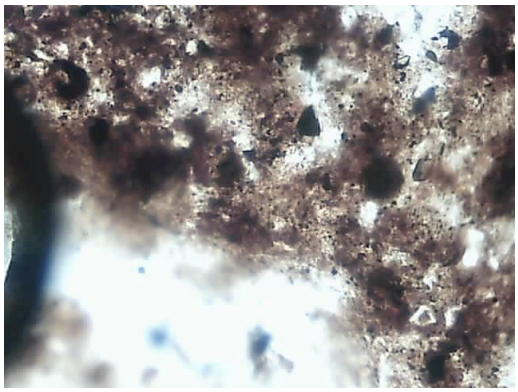


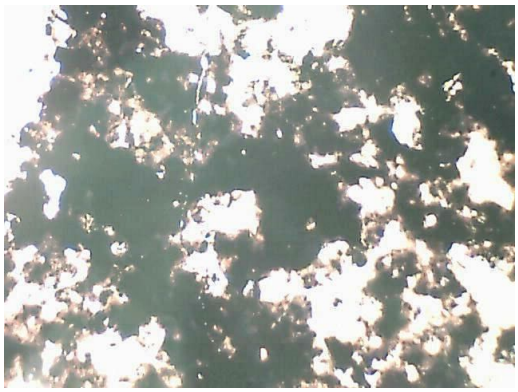
Bt1 58-68 cm PPL



Bt1 58-68 cm XPL

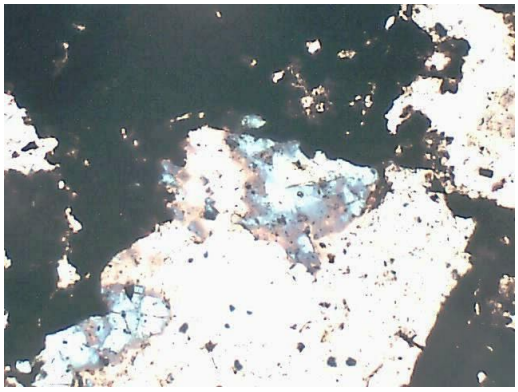
Bt1 68-78 cm PPL



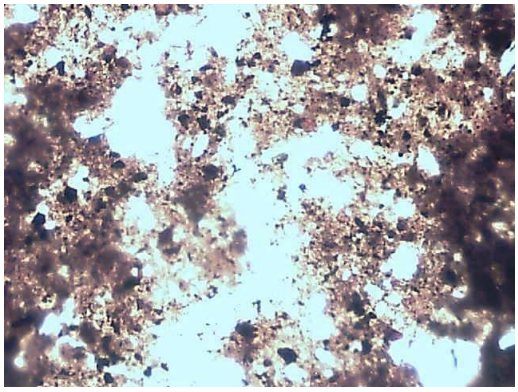


Thin-sections from the depth of 25-88cm in profile BST03

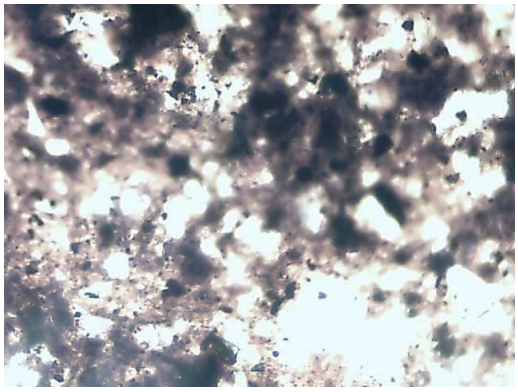
Bt1 68-78 cm XPL



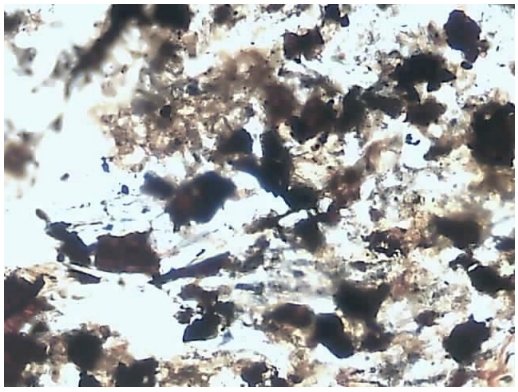
Bt1 78-88 cm PPL



Bt1 78-88 cm XPL



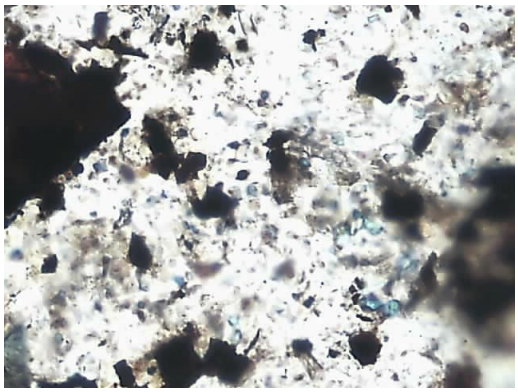
LD 100-110 cm PPL



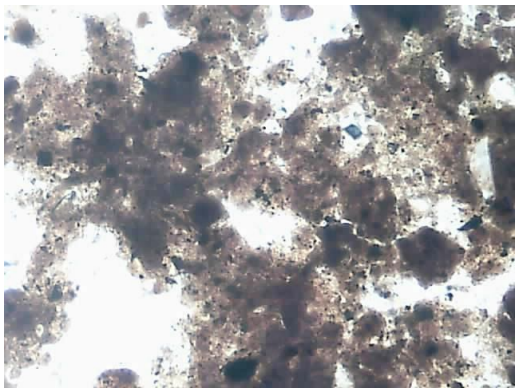
LD 100-110 cm XPL



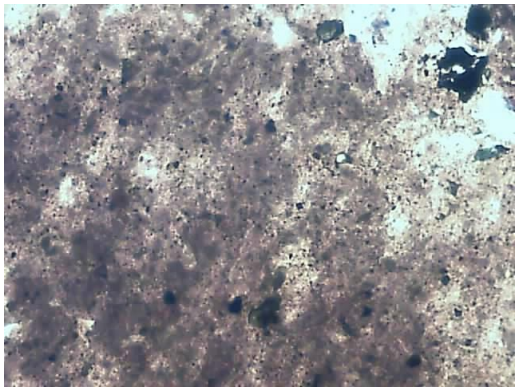
BC 110-120 cm XPL

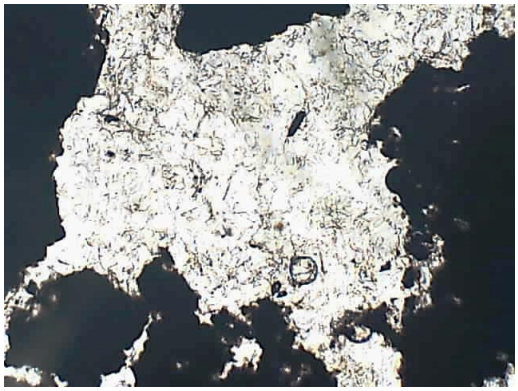


BC110-120 cm PPL



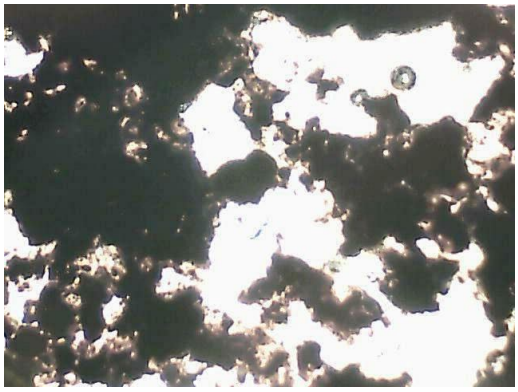
BC 120-130 cm PPL





Thin-sections from the depth of 68-130cm in profile BST03

BC 120-130 cm PPL

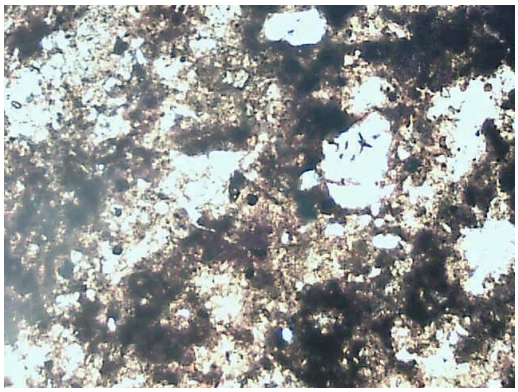


Cr 143-153 cm PPL

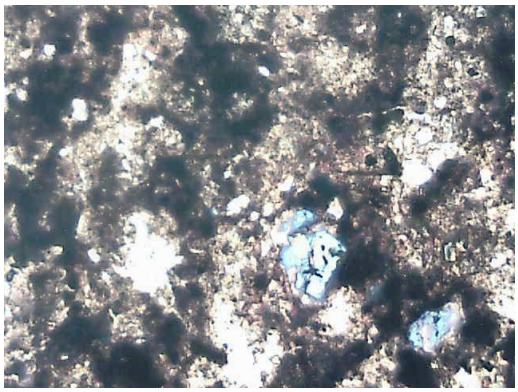
BC 130-140 cm XPL



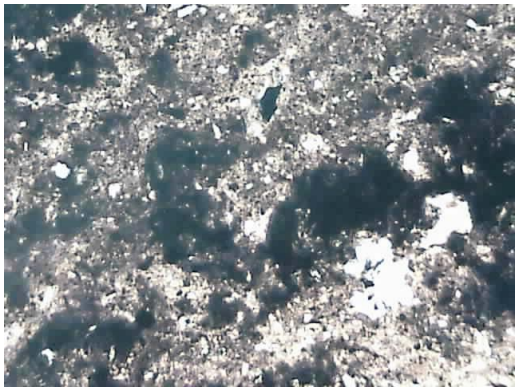
Cr 143-153 cm XPL



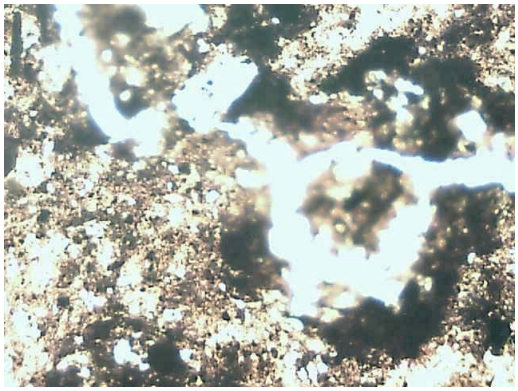
Cr 153-163 cm XPL



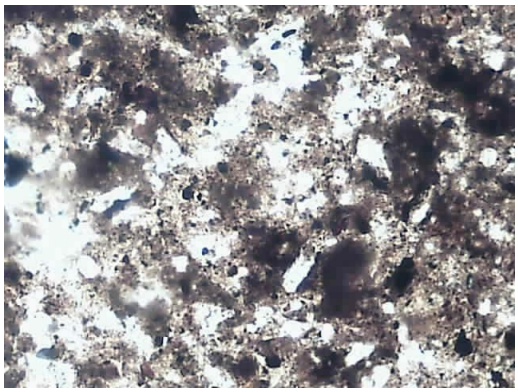
Cr 153-163 cm PPL

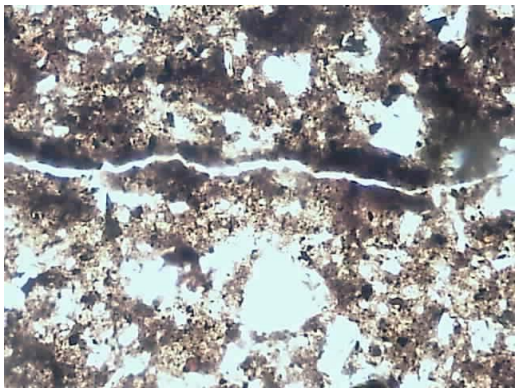


Cr 163-173 cm XPL



Cr 163-173 cm PPL





Thin-sections from the depth of 120-173cm in profile BST03

**110-120cm PPL:** Moderately developed and separated sub-angular blocky microstructure with compound packing voids. Channels with crescent coatings clay. Striated with grano-porostriated b-faabric orientation micromass.

**110-120cm PPL:** Moderated developed vughy microstructure monic c/f related distribution. Loose complete infilling coating clay.

**PROFILE NO: BSTO4**

**Bw1 35-45cm XPL:** Moderately separated crumb with porous spheroidal microstructure. Open porphyric c/f related distribution crystallitic b-fabric micromass. Feldspar grains with inclusion of basaltic glass (bottom) pointing to a volcanic origin. Complete dense infillings or intercalation coatings clay. Orthic typic and aggregates (bottom) nodules.

**Bw1 35-45cm PPL:** Moderately separated crumb with porous spheroidal microstructure with compound packing void. Open porphyric c/f related distribution. Orthic typic nodules micromass.

**Bw1 55-65cm PPL:** Moderately separated sub angular blocky microstructure and channel microstructure with hypo-quasicoating (crescent coatings)

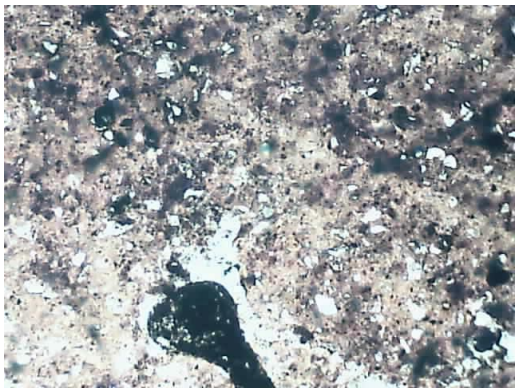
**Bw1 55-65cm XPL:** Moderately developed sub-angular blocky microstructure c/f related distribution. Undifferentiated b-fabric except central part of the slide. Striated with grano-porostriated b-fabric (center). Hypo-quasicoatings (link capping). Subhedral crystal grain (center).

**Bw1 55-65cm XPL:** Moderately separated sub-angular blocky microstructure porphyric c/f related distribution. Hypo-quasicoatings (link capping). Subhedral crystal grain (left center).

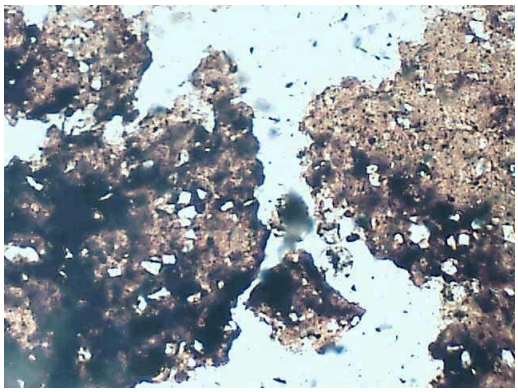
**Bw1 65-75cm XPL:** Highly developed sub-angular blocky microstructure with accommodating planes and interpedal and intrapedal voids contain dense complete infillings. Fine monic c/f related distribution. Crystallitic nodules micromass. Granostriated b-fabric orientation. Complete dense infillings coatings clay. Typic orthic nodules.

**BST 04**

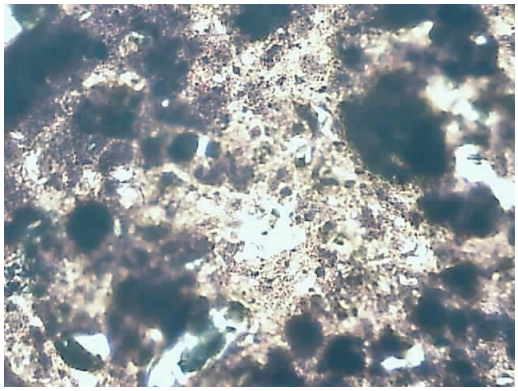
Bt1 35-45 cm XPL Bt1 35-45 cm PPL



Bt1 55-65 cm PPL



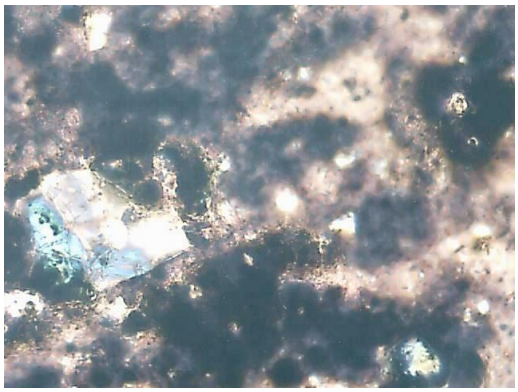
Bt155-65 cm XPL



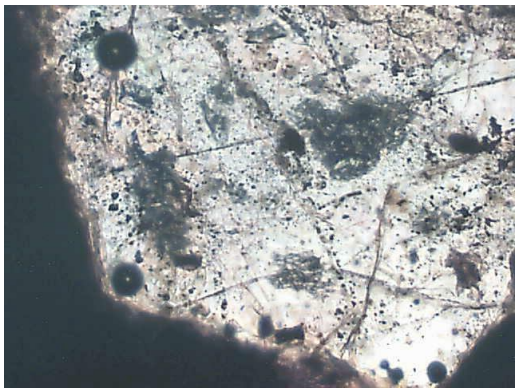
Bt1 55-65 cm XPL



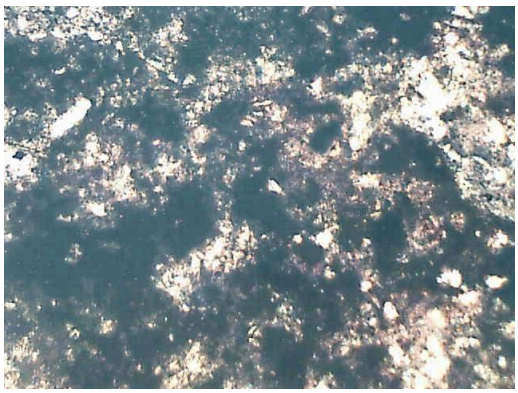
Bt1 65-75 cm XPL



Bw2 120-130 cm PPL



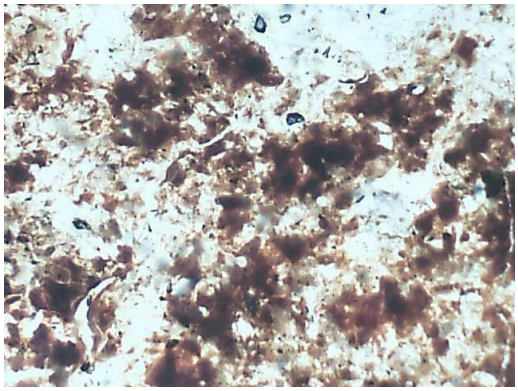
Bw2 120-130 cm XPL



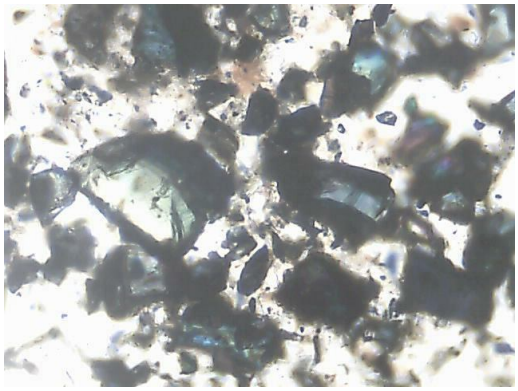


Thin-sections from the depth of 35-130cm in profile BST04

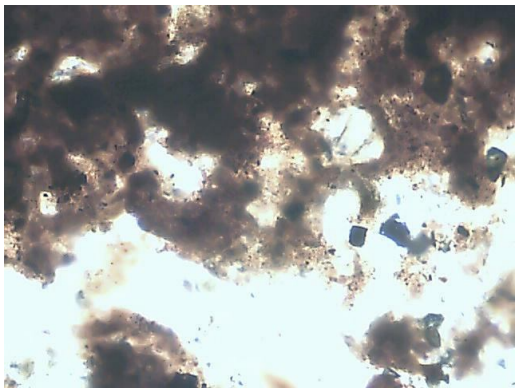
BC 160-170 cm PPL



BC 180-190 cmXPL



BC 180-190 cm PPL



Thin-sections from the depth of 160-190cm in profile BST04

**Bw2 120-130cm PPL:** Moderately developed channel microstructure with porphyric c/f related distribution. Porostriated b-fabric orientation. Complete dense infillings coatings channels.

**Bw2 120-130cm XPL:** Moderately developed but weakly separated channel microstructure with fine monic c/f related distribution. Accommodating planes with interpedal voids contain dense. Complete infillings of yellowish coatings clay. Porostriated b-fabric orientations

**BC 160-170cm PPL:** Moderately separated granular microstructure with compound packing voids. Accommodating plans and interpedal voids contain dense complete infilling. Orthic typic nodules. Hypo-quasicoating capping.

**BC 180-190cm XPL:** Highly developed and separated sub-angular blocky microstructure with chitonic c/f related distribution. Feldspar grains with inclusion of rock fragment of basaltic glass pointing to a volcanic origin. Granino-porostriated b-fabric orientation. Hypo-quasicoating (link capping).

**BC 180-190cm PPL:** Moderately separated channel microstructure with chitonic c/f distribution pattern. Poro-gran-striated b-fabric orientation groundmass. Hypo-quasicoating clay (crust). Typic orthic nodules.

**PROFILE NO: GNT01**

**AB 25-35cm XPL:** Moderately developed and separated crumb vughy microstructure. Subhedral miscuvite, feldspar-microcline crystals on top and bottom of the section. Striated b-fabric with poro-granostriated. Undifferentiated b-fabric in the right and upper left section loose incomplete infillings coatings clay. Close enualic c/f related distribution.

**AB 25-35cm PPL:** Moderately, but weakly separated crumb with vughy microstructure; simple packing voids. Gefuric c/f related distribution.

**AB 35-45cm PPL:** Moderately developed but weakly separated (center and right) section with vughy microstructure. Monic c/f relateld distribution.

**AB 35-45cm XPL:** Moderately developed subangular blocky microstructure. Subhedral crystal (right) with orthic typic nodule and internal hypo-coatings yellowish groundmass. Striated b-fabric orientation. Gefuric c/f related distribution pattern.

**AB 45-55cm PPL:** Moderately developed, with compound packing voids. A plannar void accommodating.

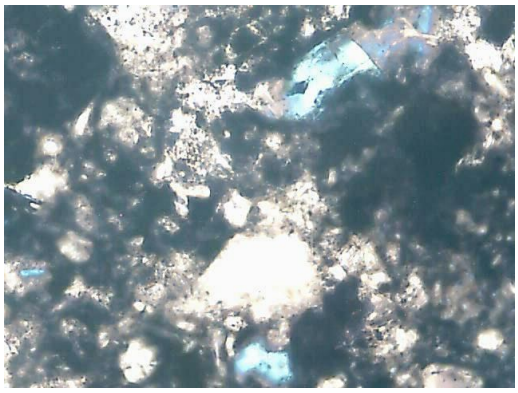
**Bw1 60-70cm XPL:** A striated orientation of clay domain parallel to the voids surfaces in responsible for a porostriated b- fabric (center) crystallitic b-fabric (left) of the section. Fe/Mn hydroxide nodules.

**Bw1 60-70cm XPL:** Highly separated sub angular blocky microstructure with mainly accommodating planners, interpedal coatings clay and intrapedal nodule. Euhedral crystals, grano-porostriated b-fabric orientation.

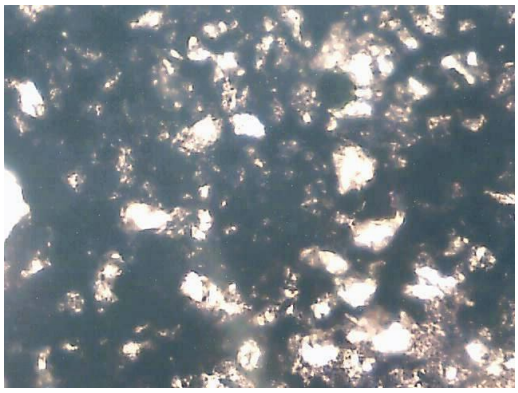
**Bw1 60-70cm PPL:** Highly separated with quartz grains (center), orthic typic nodules. Chitonic c/f related distribution pattern.

**GNT 01**

B 25-35 cm XPL



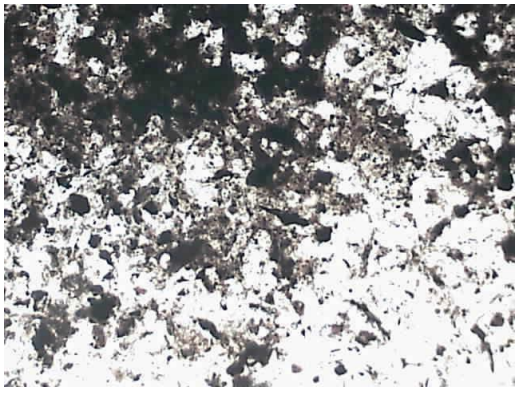
B 25-35 cm PPL



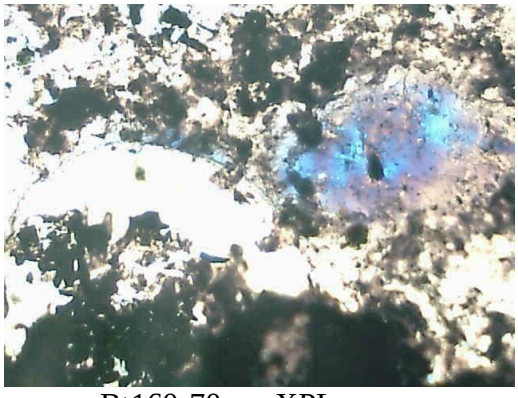
B35-45cm PPL



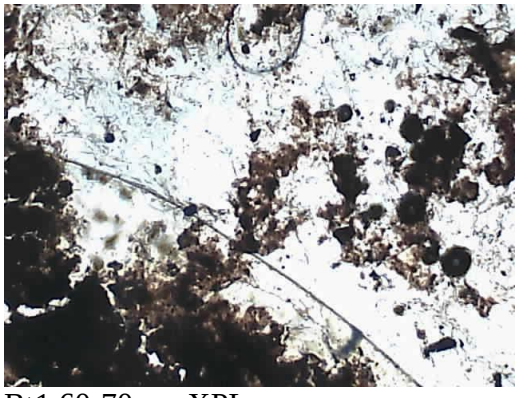
B35-45 cm



B45-55cm XPL

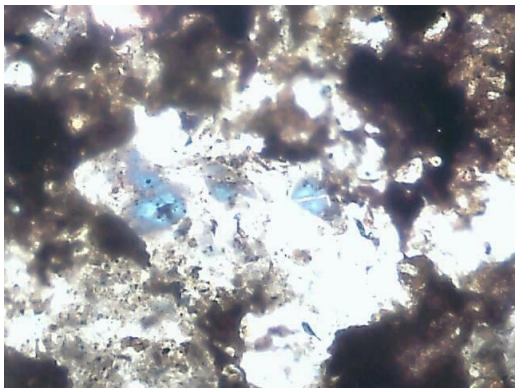


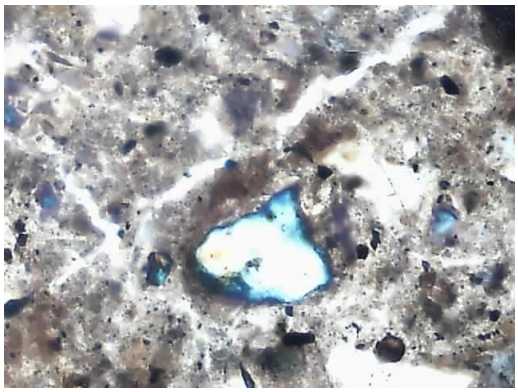
B45-55 cm PPL



Bt160-70 cm XPL

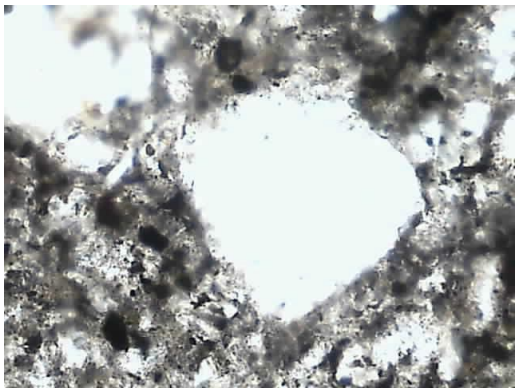
Bt1 60-70 cm XPL



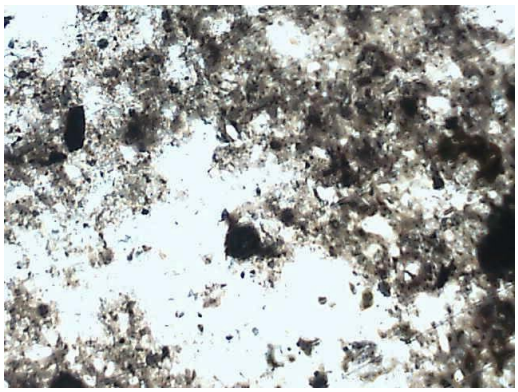


Thin-sections from the depth of 25-70cm in profile GNT01

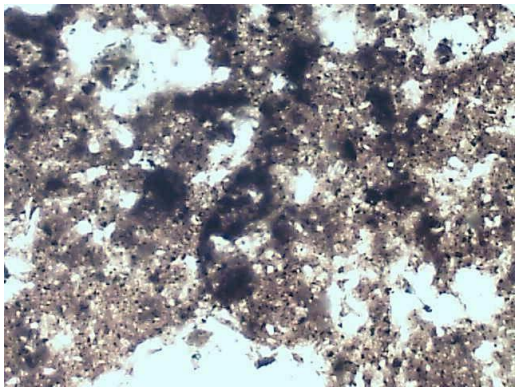
Bt1 60-70 cm PPL



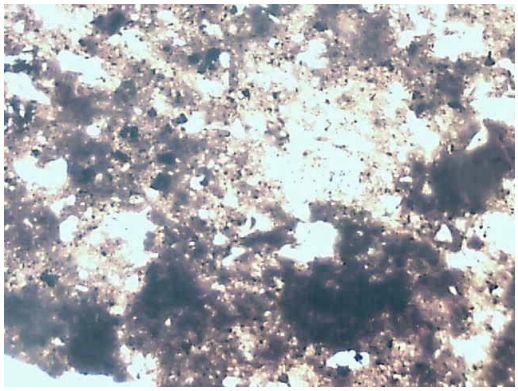
Bt1 70-8 cm PPL



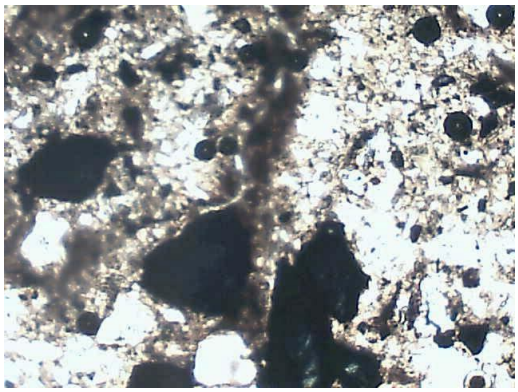
Bt1 80-90 cm PPL

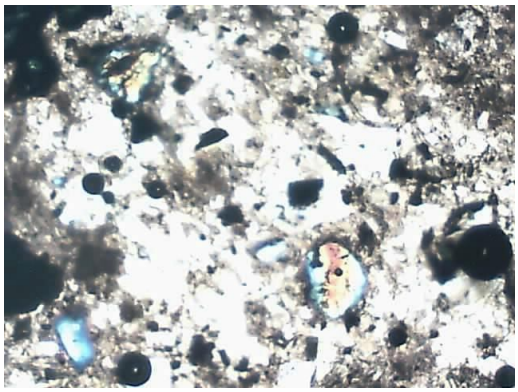


Bt1 80-90 cm PPL



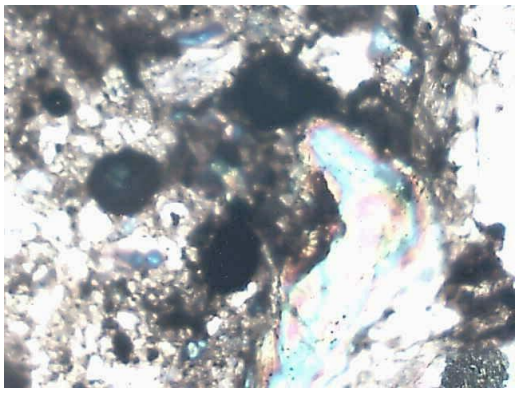
Bt1 90-100 cm XPL

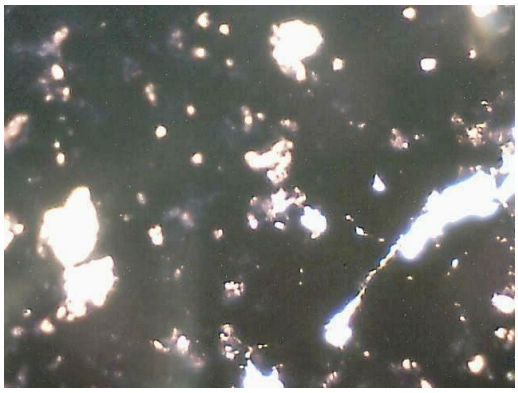




Bt1

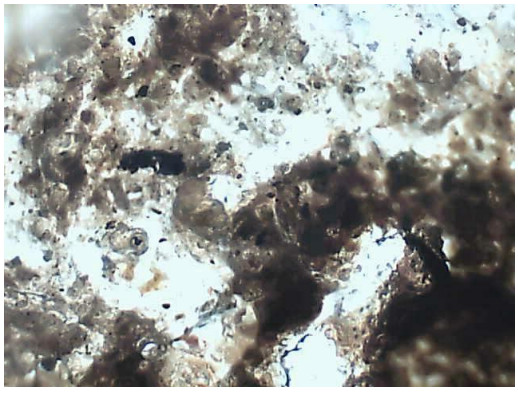
90-100 cm XPL BC 100-110 cm PPL

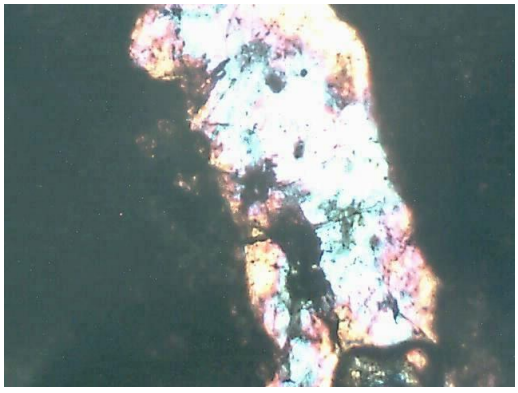




Thin-sections from the depth of 60-110cm in profile GNT01

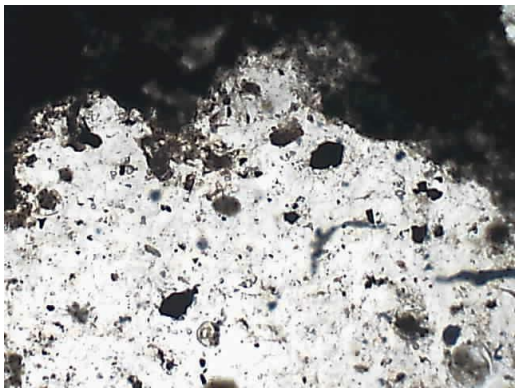
BC 110-120 cm PPL BC 120-130 cm XPL

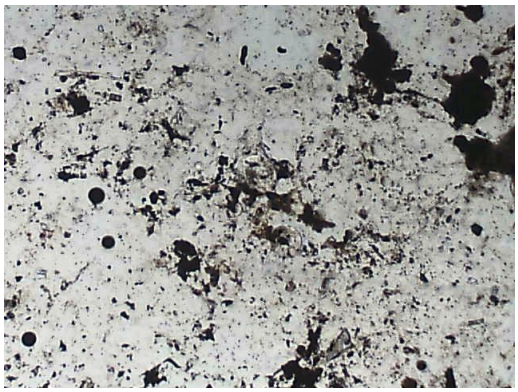




BC

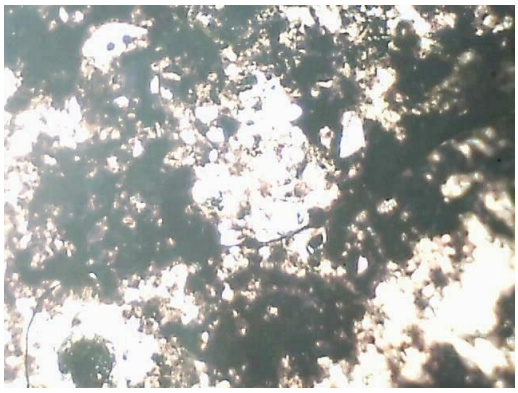
120-130 cm PPL BC 130-140 cm PPL





C

140-150 cm PPL



Thin-sections from the depth of 110-150cm in profile GNT01

**Bw1 70-80cm PPL:** Moderately developed and highly separated sub-angular blocky microstructure with channel microstructure orthic typic nodules, open porphyric c/f related distribution pattern. Complete dense infillings coating clay (capping) with black dotted nodules groundmass.

**Bw1 80-90cm PPL:** Strongly developed sub angular blocky vughy microstructure. Open porphyric c/f related distribution pattern. Complete dense infilling coatings on top of a free or embedded grains (capping). Black dotted coarse iron hydroxides nodules.

**Bw1 90-100cm PPL:** Strongly developed and separated sub-angular vughy microstructure. Close porphyric c/related distribution pattern. Vescicle or quartz fragment at the bottom. Dense infilling clay coatings in banded parallel to voids.

**Bw1 90-100cm XPL:** Strongly developed and separated sub-angular blocky with vughy microstructure. Close porphyric c/f related distribution pattern. Banded distribution of sand grains and fine (brown) organic fragment with weak parallel orientation (both basic and referred) of elongated particles. Strongly impregnated orthic typic iron hydroxides nodules with dotted black limpidity b-fabric orientation. Euhedral mineral fraction on top and bottom of the slide. Crescent coating of fine clay material.

**Bw1 80-90cm PPL:** Strongly developed and separated sub-angular blocky vughy microstructure. Open porphyric and close porphyric at the (right top) c/f related distribution pattern. Complete infilling coarse clay coatings (Crescent coating) parallel to voids or grains. Black dotted in brown limpidity micromass. Strongly impregnated orthic typic iron hydroxide nodules.

**Bw1 90-100cm XPL:** Strongly developed and separated sub-angular blocky vughy microstructure. Close porphyric c/f related distribution pattern. Strongly impregnated orthic iron hydroxide nodules. Poro-granostriated b-fabric orientations.

**Bw2 100-110cm PPL:** Moderately separated and weakly developed sub angular with vughy microstructure. Open porphyric c/f related distribution pattern. Incomplete infillings of the coatings clay.

**Bw2 110-120cm PPL:** Strongly developed and separated angular blocky with channel microstructure, coatings and infillings of illuvial clays. Accommodating plannes and intrapedal channel microstructure. Open porphyric c/f related distribution pattern. Aggregated black dotted limpidity micromass.

**Bw2 120-130cm PPL:** Strongly developed and separated sub-angular blocky vughy microstructure. Chitonic c/f related distribution pattern. Orthic typic iron hydroxide nodules. Accommodating plannes with interpedal infillings channels voids with clay.

**Bw2 130-140cm PPL:** Strongly developed and separated sub-angular blocky microstructure. Gefuric – enualic c/f related distribution pattern. Accommodating plannes with interpedal completely infillings brown voids in a fine sand size texture.

**C 140-150cm PPL:** Highly developed and separated sub-angular blocky with channel microstructure. Open porphyric c/f related distribution pattern. Complete infilling of the voids by the clay. Weakly impregnated orthic iron hydroxide nodules (bottom) in groundmass.

**PROFILE NO: GNT02**

**Ap 0-10cm PPL:** Moderately developed and separated porous spheroidal crumb with channel microstructure. Open spaced porphyric c/f related distribution pattern. Crescent infillings coating of the channel voids, black dotted in the brown limpidity groundmass orientation capping on embedded grains.

**Ap 0-10cm XPL:** Moderately developed and separated porous crumb microstructure. Monic – porphyric c/f related distribution pattern. Crystallitic sequioxide with black dotted b-fabric micromass orientation. Complete infilling coatings of time clay.

**Ap 10-20cm XPL:** Moderately developed and separated porous crumb with channel. Microstructure open porphyric c/f related distribution pattern . Euhedral crystal mineral with greenwish color, porostriated b-fabric orientation (top left). Undifferentiated (over 50%) of the slide with time organic materials.

**Ap 10-20cm PPL:** Moderately developed and separated porous crumb channel microstructure. Close porphyric c/f related distribution pattern. Complete infillings coating clay of the channels, black dotted nodules groundmass, moderately impregnated orthic nodule (top), orthic aggregate iron hydroxide nodules (bottom left).

**Bt1 20-30cm XPL:** Moderately developed and weakly separated porous spheroidal crumb microstructure. Monic c/f related distribution pattern. Dense complete infilling of the timer coating clay on top of the Euhedral crystal mineral grain. Grano porostriated b-fabric orientation.

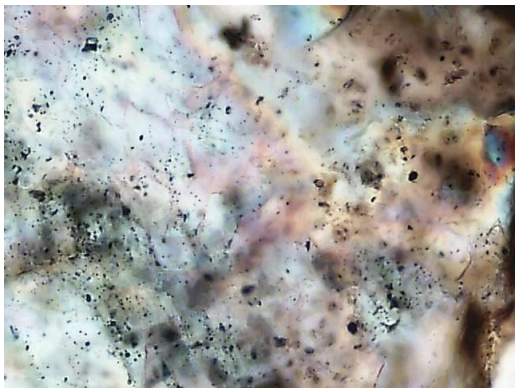
**Bt1 20-30cm XPL:** Strongly developed and moderately separated porous crumb with channel microstructure. Open porphyric c/f related distribution pattern. Loose continuous infilling of the channel voids. Crystallitic sequioxides nodules in dotted micromass.

**GNT 02**

Ap 0-10 cm PPL

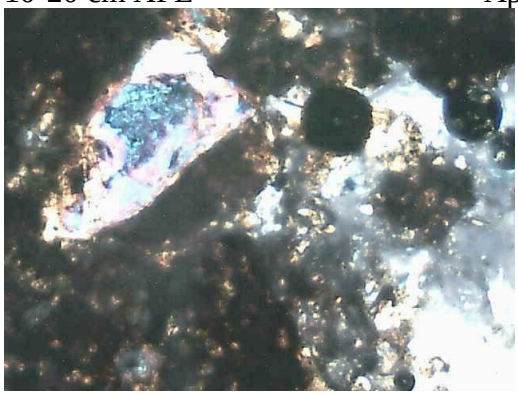
Ap 0-10 cm XPL

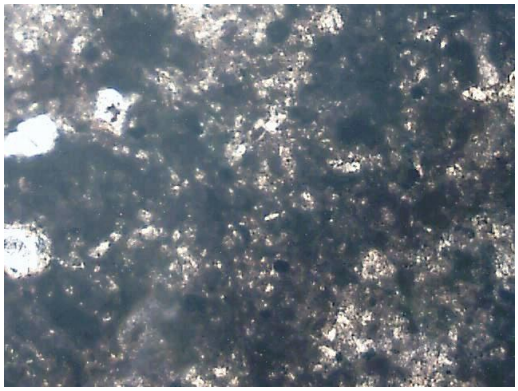




Ap

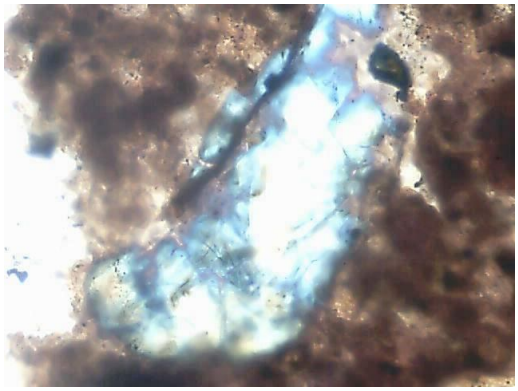
10-20 cm XPL Ap 10-20 cm PPL

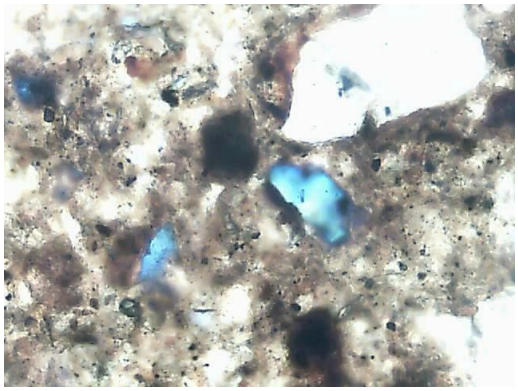




Bt1

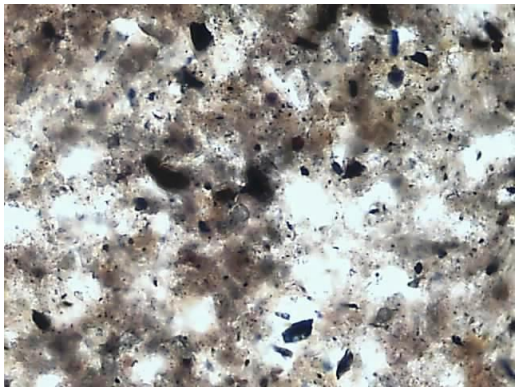
20-30 cm XPL Bt1 20-30 cm XPL



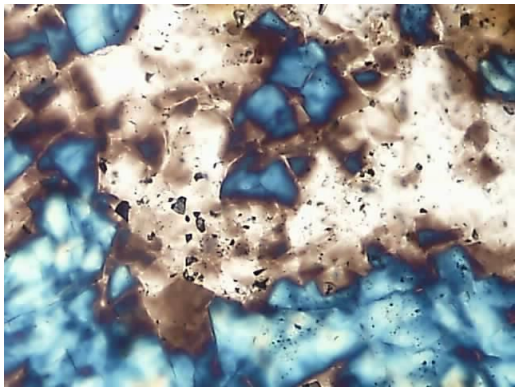


Thin-sections from the depth of 0-30cm in profile GNT02

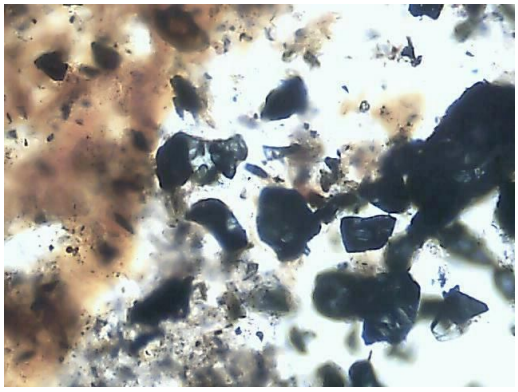
Bt1 20-30 cm PPL



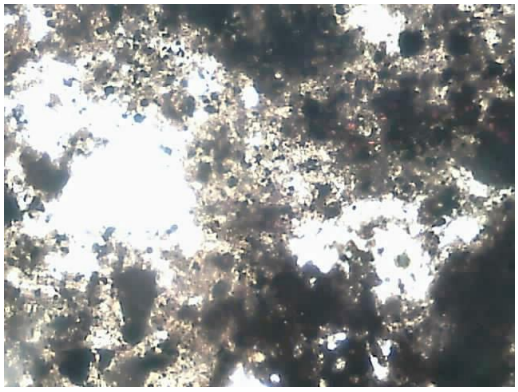
Bt1 30-40 cm XPL



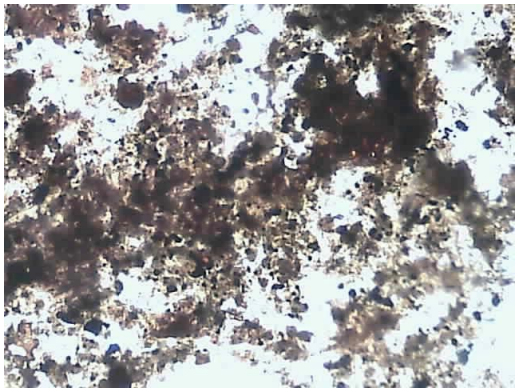
Bt1 30-40 cm PPL



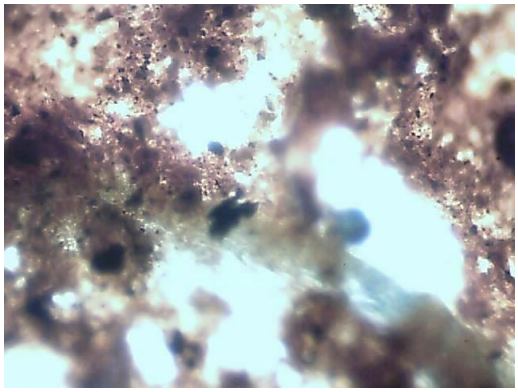
Bt1 40-50 cm XPL



Bt140-50 cm PPL

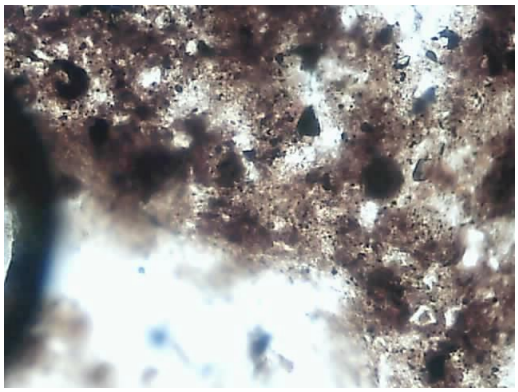


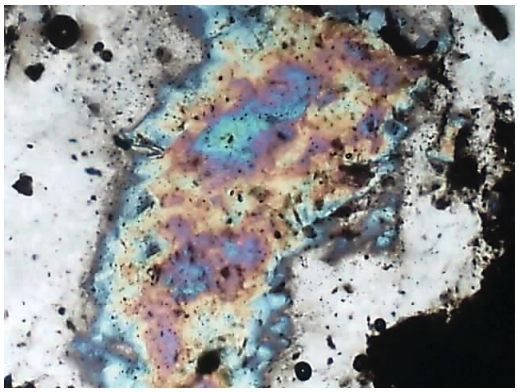
58-68 cm PPL



B 58-68 cm XPL

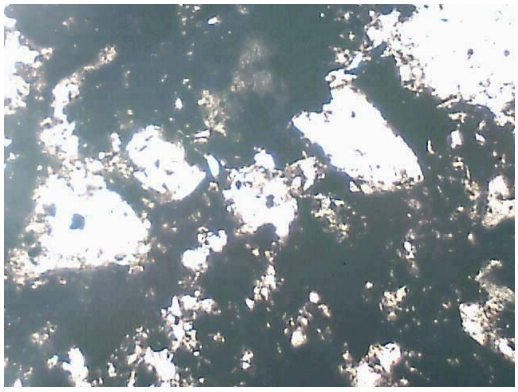
B68-78 cm XPL



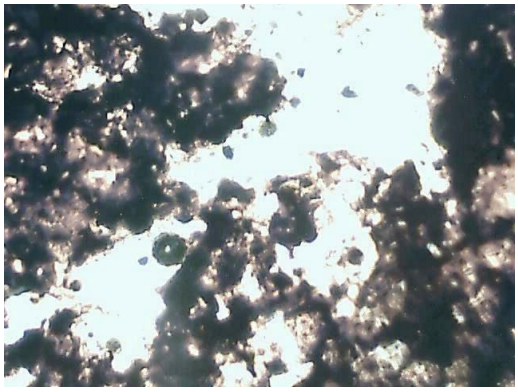


Thin-sections from the depth of 20-78cm in profile GNT02

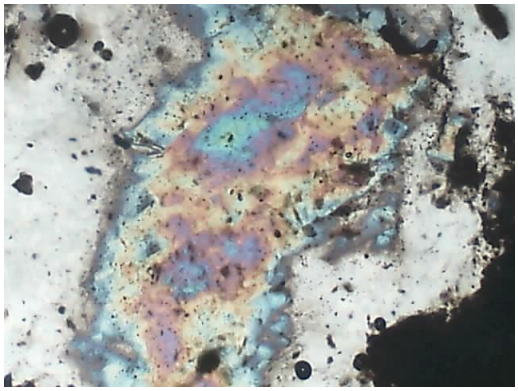
B 68-78 cm PPL



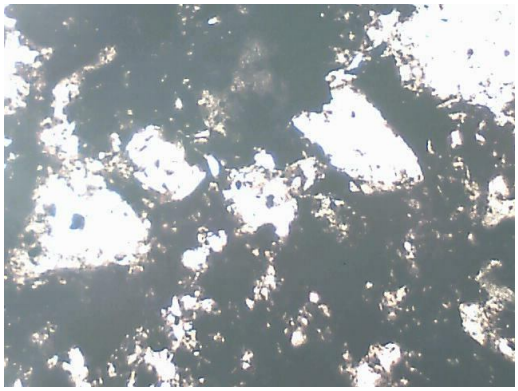
Bt2 78-88 cm PPL



Bt2 88-98 cm XPL



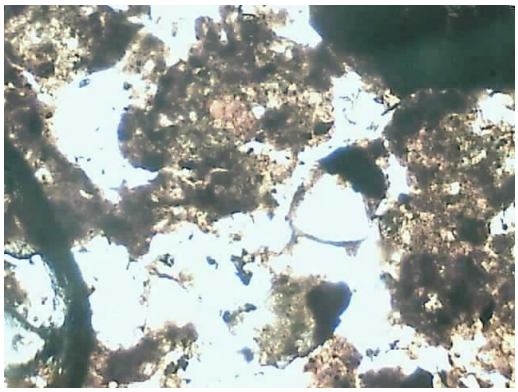
Bt2 88-98 cm PPL



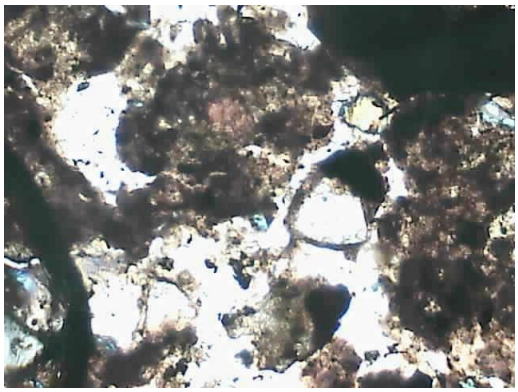
BC 100-110 cm PPL



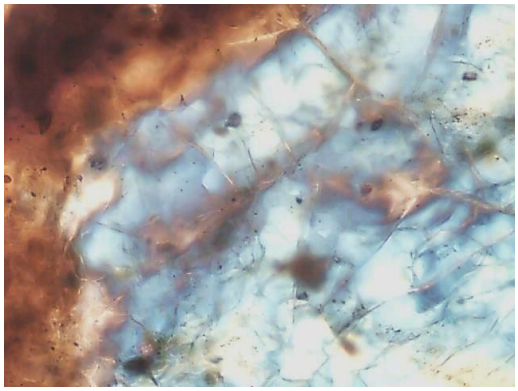
BC 100-110 cm XPL

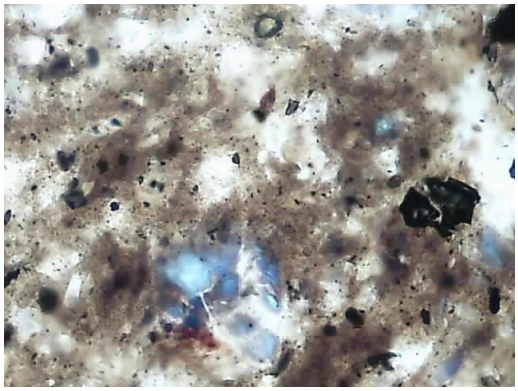


C 120-130 cm XPL



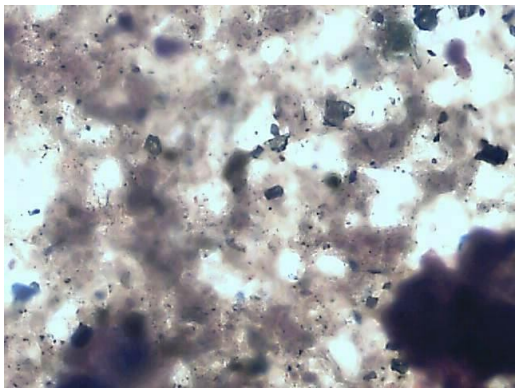
C 120-130 cm XPL





Thin-sections from the depth of 68-130cm in profile GNT02

C 120-130 cm PPL



Thin-sections from the depth of 120-130cm in profile GNT02

Moderately impregnated orthic nodules, nucleic nodules. Complete dense infilling of time coating, clay. Strongly impregnated orthic nodule and dotted groundmass orientation. Open porphyric c/f related distribution pattern.

**Bt1 30-40cm XPL:** Strongly developed and separated sub angular blocky microstructure. Euhedral crystal of olivine mineral. Grano-porostriated b-fabric orientation. Black dotted nodules in micromass. Close porphyric c/f related distribution pattern.

**Bt1 30-40cm PPL:** Strongly developed and moderately separated sub-angular blocky with compound packing voids. Open porphyric c/f related distribution pattern. Quartz grains embedded covered parallel to quartz grain in form of caping".

**Bt1 40-50cm XPL:** Strongly developed but moderately separated sub-angular blocky vugh microstructure. Crystallitic nodules b-fabric orientation close porphyric c/f related distribution pattern. Complete dense infilling coating top of the voids (capping).

**Bt1 40-50cm PPL:** Strongly developed and separated sub-angular blocky compound packing voids. Compound pedofeature. Typic coating of brownish limpid, strongly oriented clay on vugh in the centre strongly impregnated orthic nodules in the bottom. Eunalic – porphyric c/f related distribution pattern.

**Bt1 58-68cm XPL:** Strongly developed and medium separated sub-angular blocky with complete dense infilling channel microstructure. Crystallitic b-fabric micromass and grano-porostriated b-fabric orientation. Notice the vascular iron hydroxide nodules.

**Bt2 78-98cm XPL:** Strongly developed and separated sub-angular blocky microstructure. Monic – chitonic c/f related distribution pattern. Capping fine organic materials on Euhedral crystal mineral grains. Black dotted and strongly impregnated orthic nodules in groundmass. Hypo and quasicoating mineral grain forming "link – capping". Anorthic (lithomorphic) iron

(hydroxide nodule in brownish micromass. Open porphyric c/f related distribution pattern. Of the nodules in groundmass.

**Bt2 88-98cm PPL:** Strongly developed and weakly separated sub-angular blocky with vughy microstructure. Inter and intradvoids accommodating with hypocoating clay material. Enaulic-porphyric c/f related distribution pattern.

**Bt2 100-110cm PPL:** Strongly developed and separated sub-angular blocky with channel microstructure. Coalescent irregular dark-brown organic excrements on top and right slide forming an enuatic c/f related distribution pattern with quartz grain and complex packing voids. Quartz grains embedded in speckled brownish clay. Notice wedge-effect chitonic c/f related distribution pattern. Euhedral mineral grain at the left bottom slide. Hypo and quasicoating forming a "link – capping". Moderately impregnated orthic nodules.

**Bt2 100-110cm PPL:** Strongly developed moderately and separated sub-angular blocky with channel microstructure. Open porphyric c/f related distribution pattern. Compete dense infillings coating clay materials (crescent coating) moderately impregnated orthic nodule with dotted groundmass.

**C 120-130cm XPL:** Strongly developed and medium separated sub-angular blocky with dense infilling coating channel microstructure crystallitic b-fabric micromass orientation. Granostriated with interpedal plannes (bottom). Anhedral crystal mineral grain with interference blue color (bottom). Strongly impregnated groundmass iron hydroxides nodules with black dotted groundmass. Chitonic c/f related distribution pattern.

**C 120-130cm XPL:** Strongly developed and separated sub-angular blocky microstructure. Euhedral crystal mineral grain in a blue interference color. Chitonic c/f related distribution pattern.

**PROFILE NO: GNT03**

**AB 11-21cm XPL:** Strongly developed and highly separated crumb microstructure with compound packing voids. Monic c/f related distribution crystallitic b-fabric orientation. Orthic typic muoxides nodules. Complete dense infillings coating clay.

**AB 11-21cm PPL:** Strongly developed, but weakly separated vughy microstructure porphyric c/f related distribution.

**AB 21-31cm PPL:** chitonic c/f related distribution, free grain coating clay, quartz grains with simple packing voids, angular blocky microstructure.

**AB 21-21cm XPL:** Highly separated developed sub angular blocky microstructure. Chitonic c/f related distribution. Free grains coatings clay. Quartz grains, interpedal accommodating pedality. Simple packing voids. Striated with grano-porostriated b-fabric. Orthic typic nodules.

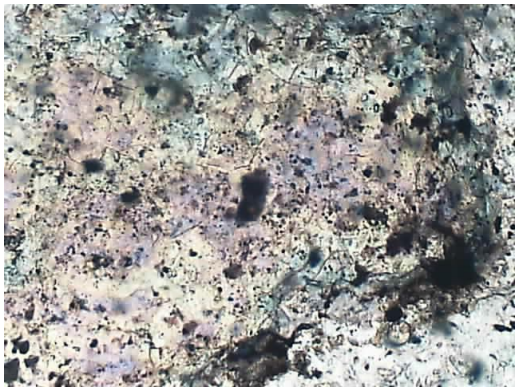
**Bt1 38-48cm PPL:** Moderately developed sub angular blocky microstructure and vughy microstructure. Porphyric c/f related distribution pattern, free grain of coatings clay.

**Bt1 48-58cm XPL:** Vughy microstructure with some channel crescent coating clay. Striated with grano-porostriated b-fabric orientation. Euhedral crystal evidence of cleavage extinction. Orthic typic nodules.

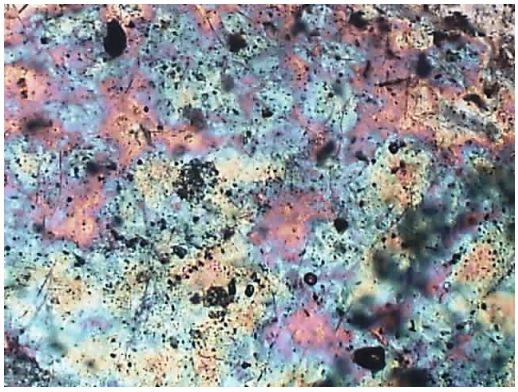
**Bt1 48-58cm PPL:** Moderately developed channel microstructure with open porphyric c/f related distribution. Complete dense infillings coating in banded orientation. Strongly impregnated orthic typic nodules.

**GNT 03**

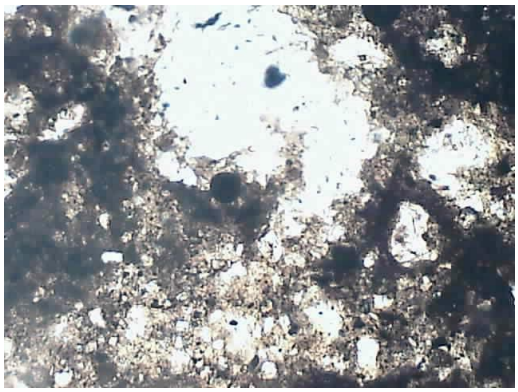
B 11-21 cm XPL



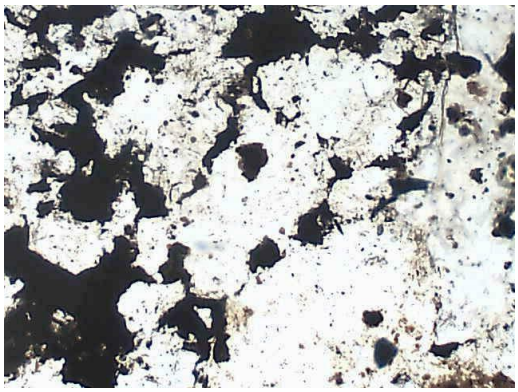
B 11-21 cm XPL



B 11-21 cm PPL

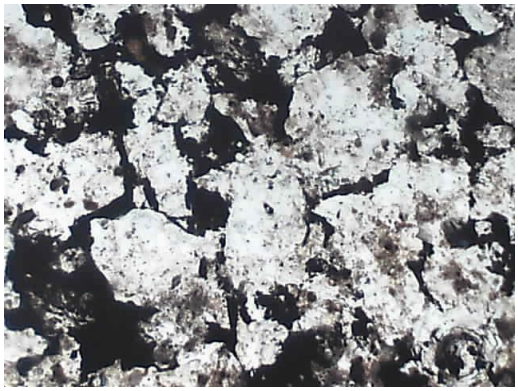


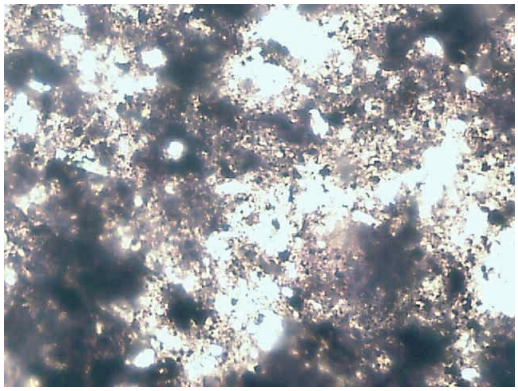
B 21-31 cm PPL



B 21-31 cm XPL

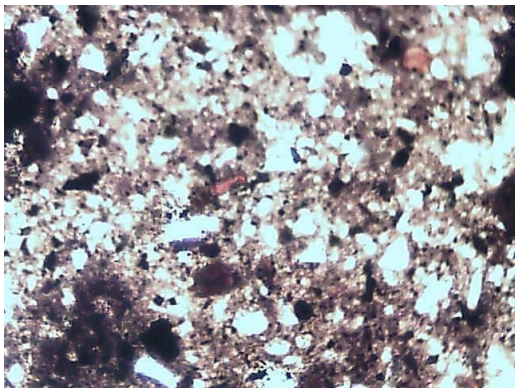
Bt2 38-48 cm XPL

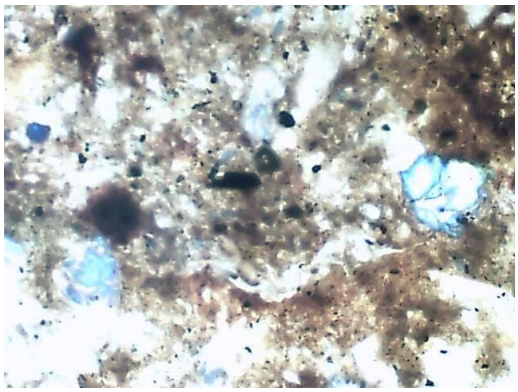




Bt2 38-48 cm PPL

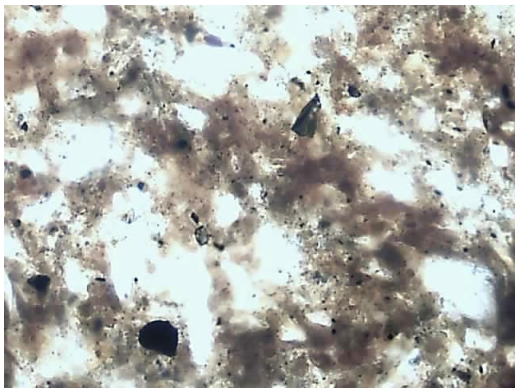
Bt2 48-58 cm XPL



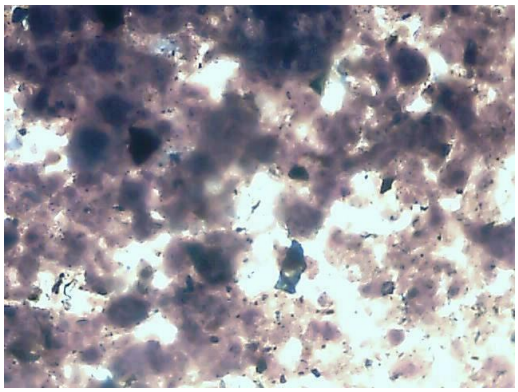


Thin-sections from the depth of 11-58cm in profile GNT03

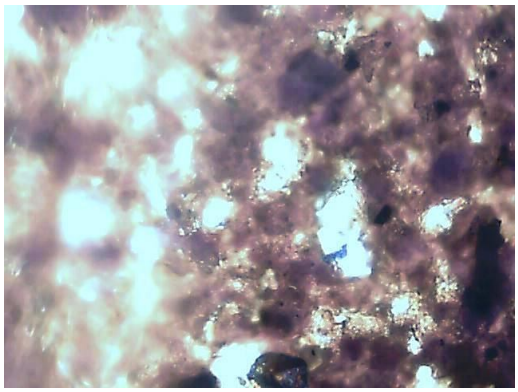
Bt2 48-58 cm PPL



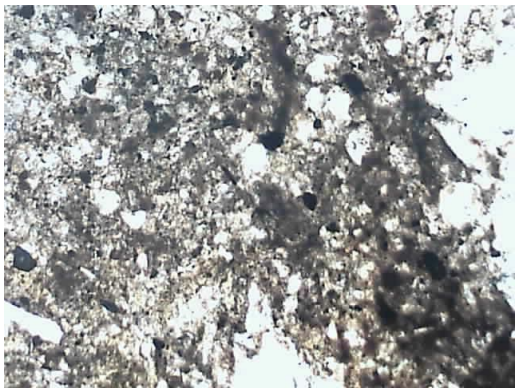
Bt3 66-76 cm XPL



Bt3 66-76 cm PPL

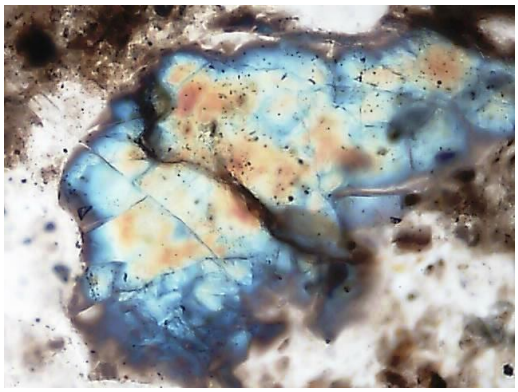


Bt3 76-86 cm PPL

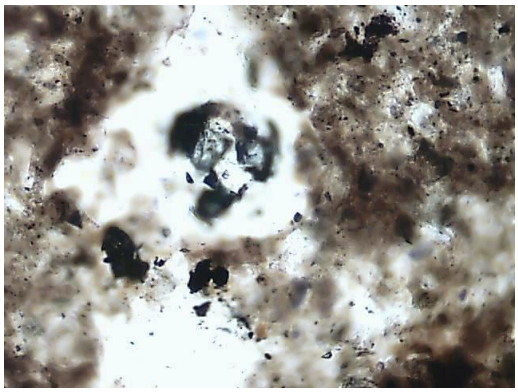


Bt 86-96 cm XPL

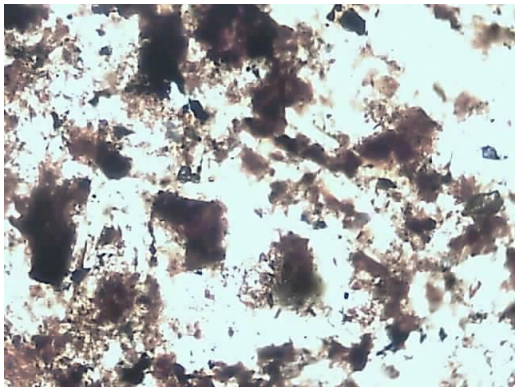
Bt 86-96 cm PPL

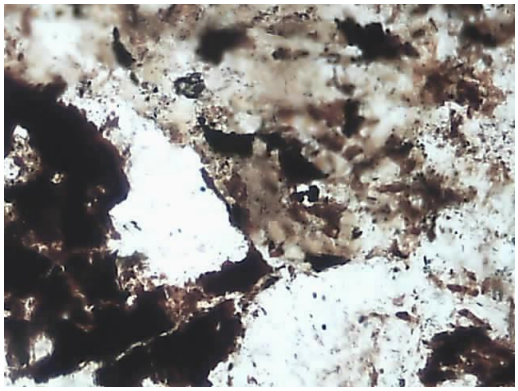


Bt2 101-111 cm PPL



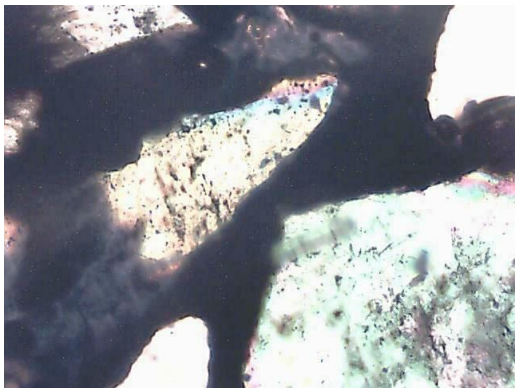
Bt 101-111 cm XPL





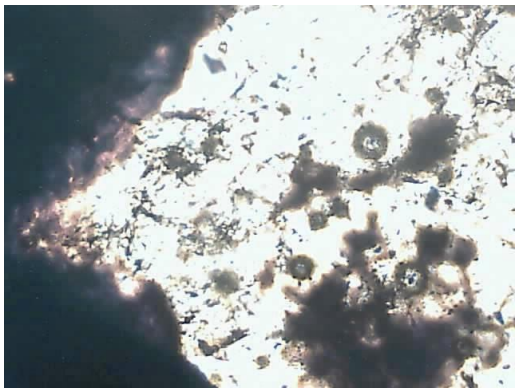
Thin-sections from the depth of 48-111cm in profile GNT03

Bt2 111-121 cm XPL

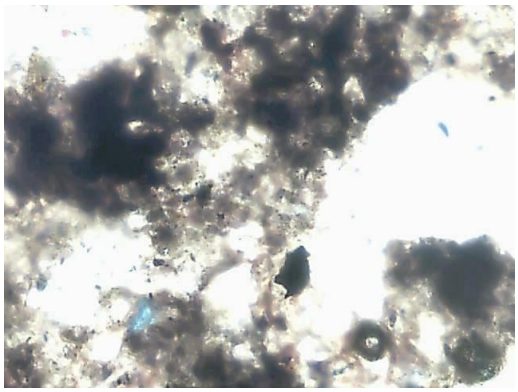


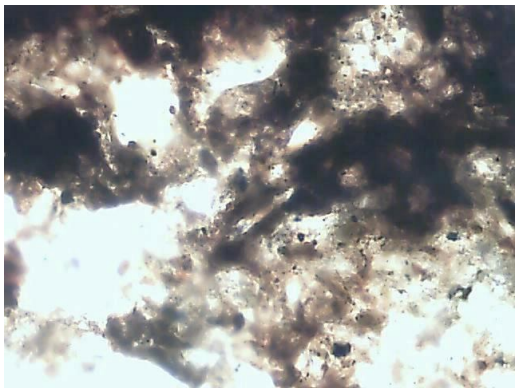
Bt2 121-131 cm XPL

Bt 111-121 cm PPL

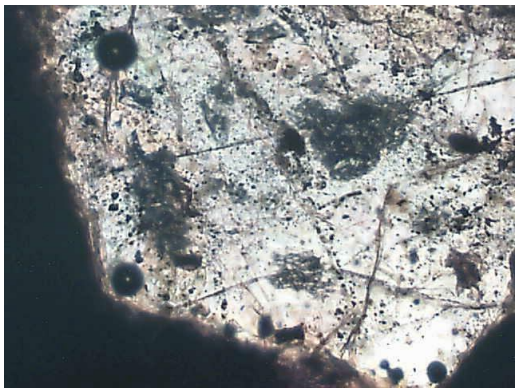


Bt 12-131 cm PPL





Bt2 131-141 cm XPL



Thin-sections from the depth of 111-141cm in profile GNT03

**Bt2 66-76cm XPL:** Moderately separated channel microstructure, open porphyric c/f related distribution. Complete dense infillings coatings. Grano-porostriated b-fabric groundmass orientation. Moderate impregnated orthic typic nodules.

**Bt2 66-76cm PPL:** Moderately separated channel microstructure with open porphyric c/f related distribution. Complete dense infillings coatings (micros pan). Moderate impregnated orthic typic nodules.

**Bt3 101–111cm PPL:** Moderately separated angular, blocky and channel microstructure with open porphyric c/f related distribution. Moderate impregnated orthic typic nodules. Complete dense infillings coating clay.

**Bt3 101-111cm XPL:** Moderately developed channel microstructure with open enualic c/f related distribution. Accommodating plans with intrapedal voids. Hypo-quasicoating (crescent coatings). Strongly impregnated orthic typic nodules.

**Bt3 111-121cm XPL:** Undifferentiated b-fabric microsmass orientation with central crescent coating clay. Weakly impregnated orthic typic nodules.

**Bt3 111-121cm PPL:** Weakly separated angular blocky grains.

**Bt3 121-131cm XPL:** Moderately separated channel microstructure with open porphyric c/f related distribution. Grano-porostriated b-fabric orientation. Subhedral crystal grain. Hypo-quasicoating (link capping) or crescent coatings.

**Bt3 121-131cm PPL:** Moderately separated channel microstructure with open porphyric c/f related distribution. Hypo-quasicoatings infillings (crescent coatings).

**PROFILE NO: GNT04**

**Bt1 11-21cm PPL:** Moderately developed, but weakly separated crumb microstructure with compound packing voids and channels microstructure are also evident monic c/f related distribution. Grano-porostriated b-fabric orientations. Completely dense infillings of coating clays. Euhedral orthic typic nodules.

**Bt1 11-21cm XPL:** Weakly developed and separated crumb microstructure on top and bottom of the slide with simple packing voids. Euhedral crystal mineral grains (centre). Undifferentiated b-fabric orientation. Complete dense free grain clay coatings. Monic c/f related distribution pattern.

**Bt1 21-31cm PPL:** Lenticular platy microstructure at right-side slide. Empty channel with loose porostriated b-fabric orientations. Monic c/f related distribution pattern. Typic orthic/anorthic nodules.

**Bt1 21-31cm XPL:** Typic orthic and separated sub angular blocky microstructure. Intra and transpedal connecting plannes. Gefuric c/f related distribution pattern. Granostriated (top centre) b-fabric orientations. Black, strongly impregnated anorthic nodule (centre) and geodic nodules (bottom).

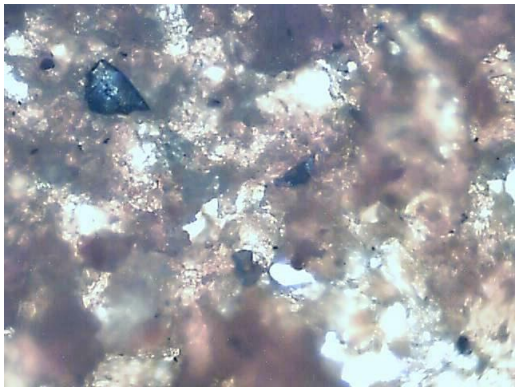
**Bt1 31-41cm XPL:** Finer monic c/f related distribution. Loose continuous infilling clay in the channel. Weakly developed and separated sub angular blocky microstructure (dusty). Typic and geodic nodules.

**Bt2 48-58cm XPL:** Moderately developed and separated vughy microstructure with some crescent coating clay channels. Grano-porostriated b-fabric orientation. Typic orthic nodules.

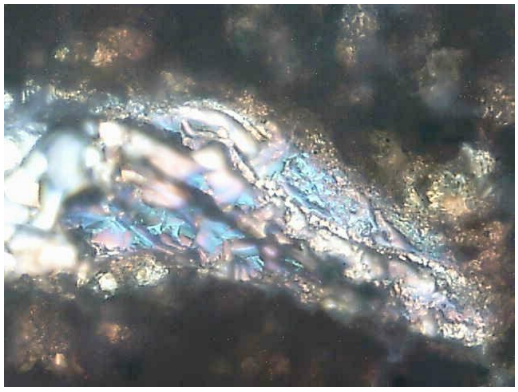
**Bt2 48-58cm PPL:** Vughy microstructure with porostriated b-fabric orientations. Porphyric c/f related distribution pattern. Geodic nodules. Accommodating planning in groundmass.

**GNT 04**

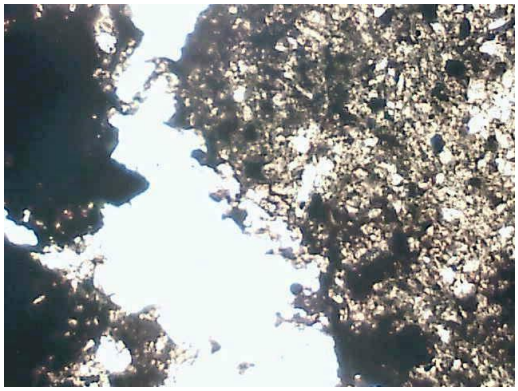
Bt1 11-21 cm PPL



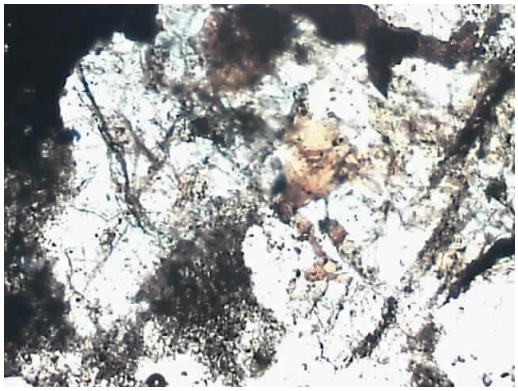
Bt1 11-21 cm XPL



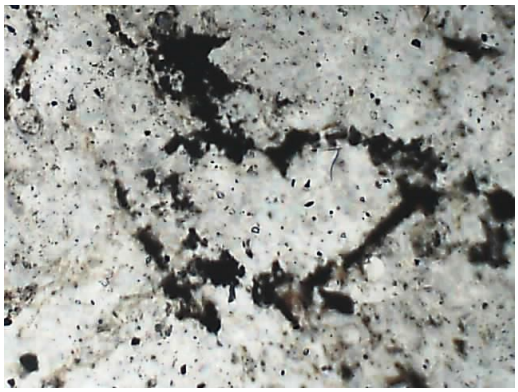
Bt1 21-31 cm PPL



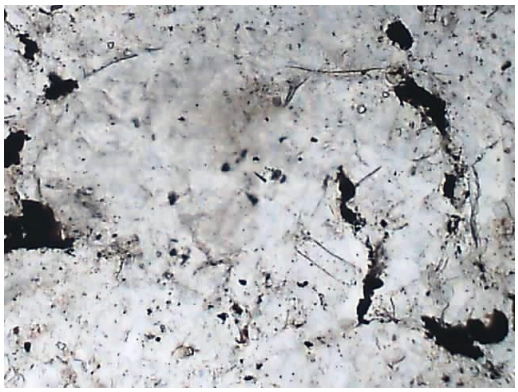
Bt1 21-31 cm XPL



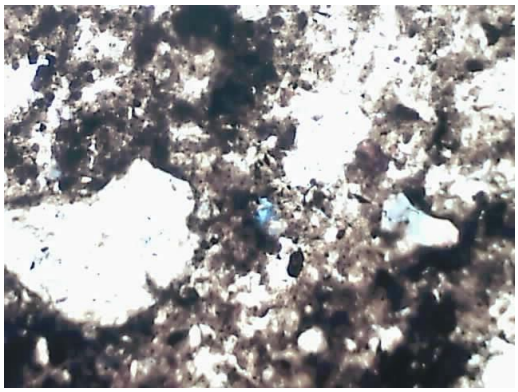
Bt1 31-41 cm PPL



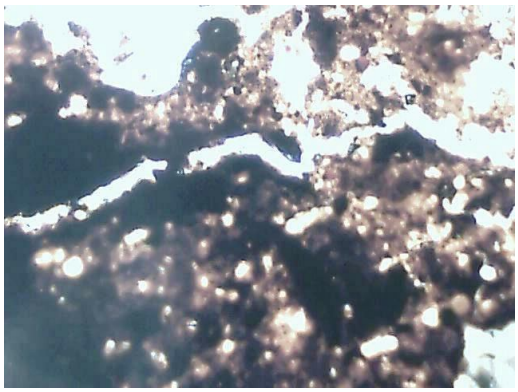
Bt1 31-41 cm PPL



B 48-58 cm XPL

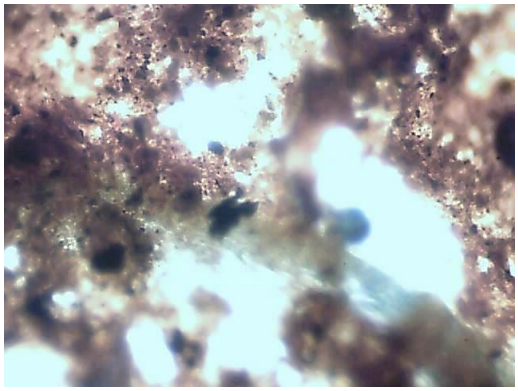


B 48-58 cm PPL

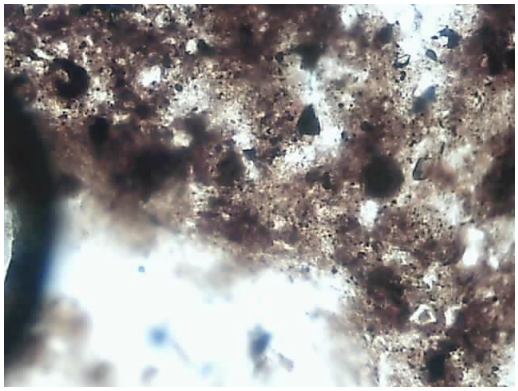


Thin-sections from the depth of 11-58cm in profile GNT04

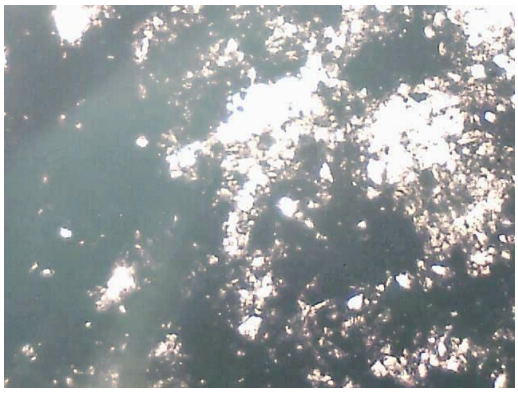
B 58-68 cm PPL



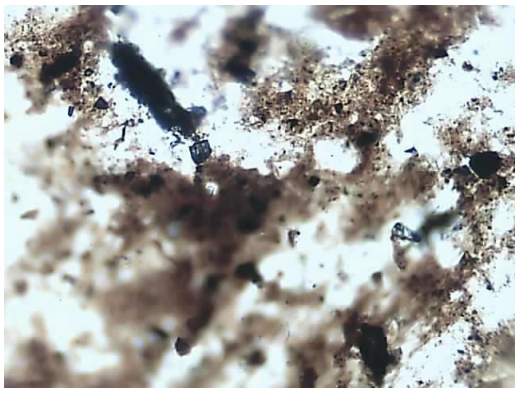
B 58-68 cm XPL



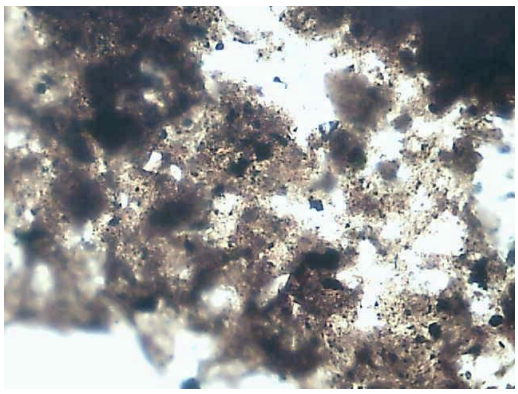
B 68-78 cm PPL



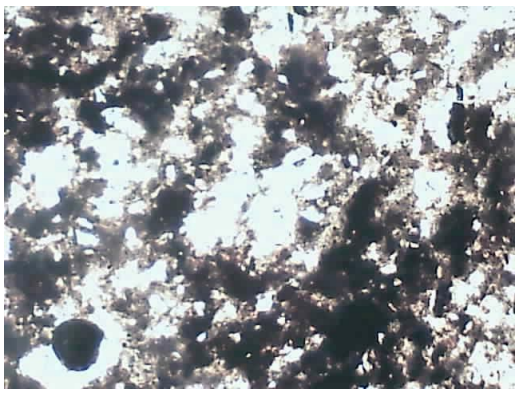
B 78-88 cm PPL



B 78-88 cm XPL

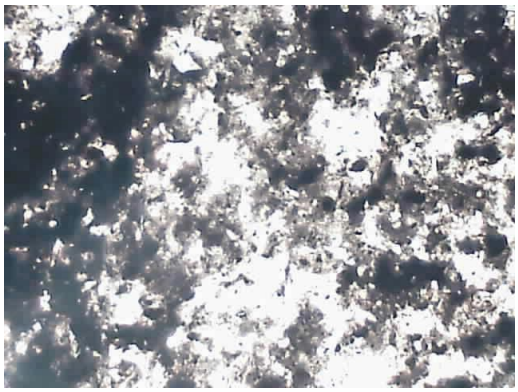
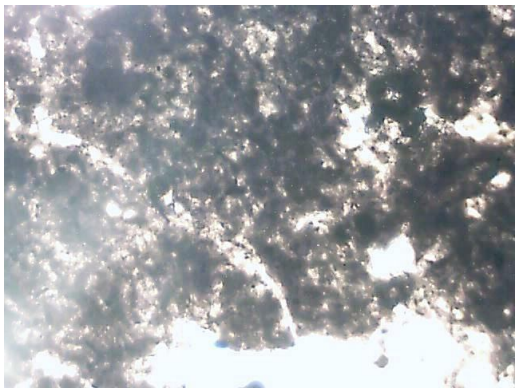


B 88-98 cm PPL



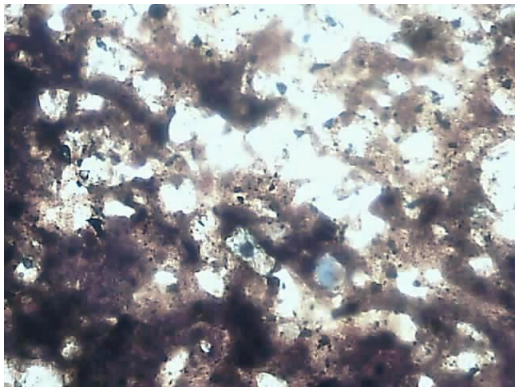
B 88-98 cm XPL

B 98-108 cm PPL

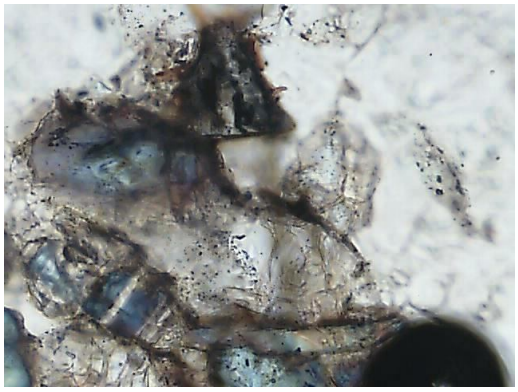



Thin-sections from the depth of 58-108cm in profile

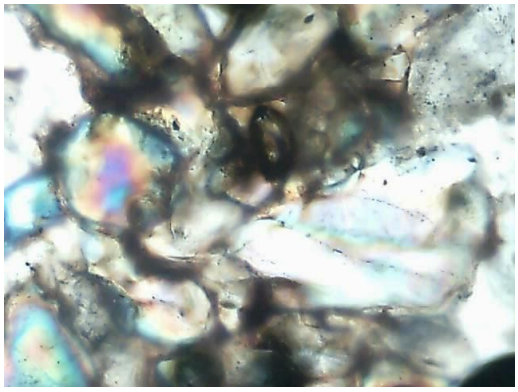
B 120-130 cm XPL



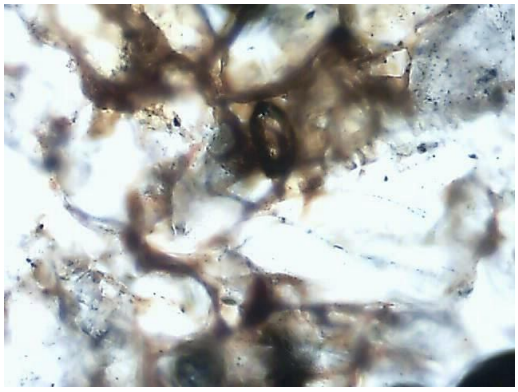
B 130-140 cm XPL



B 130-140 cm XPL



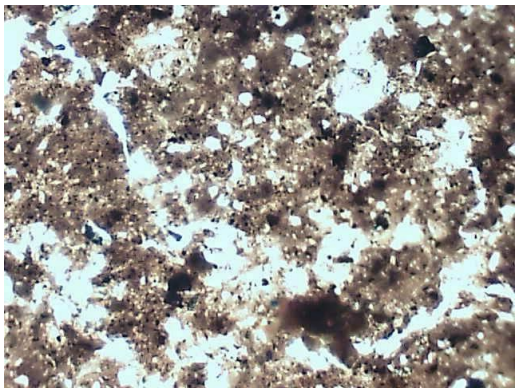
BC 140-150 cm PPL

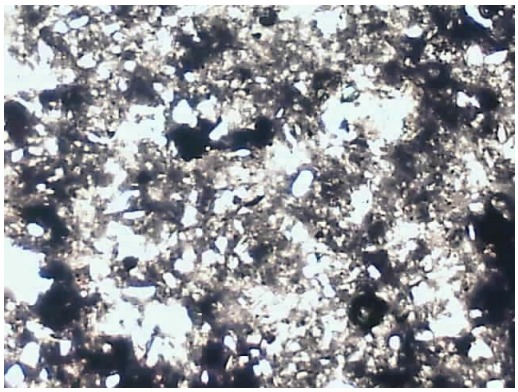


BC 140-150 cm PPL

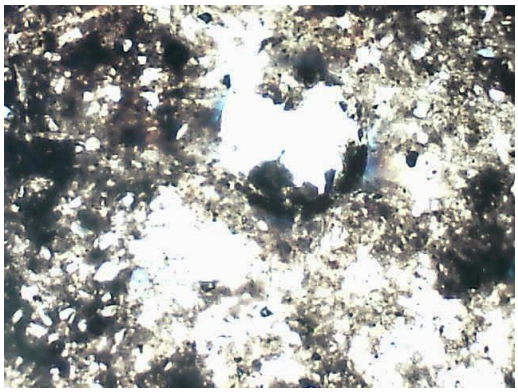


BC 150-160 cm PPL





BC 150-160 cm XPL



Thin-sections from the depth of 120-160cm in profile GNT04

**Bt2 58-68cm PPL:** Moderately developed with weakly separated channel microstructure. Finer monic c/f related distribution pattern. Completely dense infillings coating clay. Typic nodules.

**Bt2 58-68cm XPL:** Porphyric c/f related distribution pattern. Grano-porostriated b-fabric orientations. Loose continuous infillings clay in the channels. Typic orthic nodules.

**Bt2 68-78cm PPL:** Weakly developed angular blocky microstructure.

## APPENDIX D: CLAY MINERALOGY

Table 12: Profile distribution of the mineral contents (basaltic parent material)

| | Basaltic parent material | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | CHAHA BST01 Ap 0-35 cm | | | | TA-HOSS BST04 Ap 0-15 cm | | | |
| | Angle | d Å | $I/I_1$ | | | Angle | d Å | $I/I_1$ | |
| Mg-sat | 4.435 | 19.96 | 100 | Mica-vermiculite | Mg-sat | 6.02 | 14.72 | 6 | Vermiculite |
| | 26.84 | 3.33 | 8 | Quartz | | 11.25 | 7.07 | 100 | Kaolinite |
| | 38.11 | 2.37 | 28 | | | 12.97 | 6.84 | 40 | |
| Glyl | 7.51 | 11.79 | 100 | Hydroxy-interlayered vermiculite | | 21.74 | 4.01 | 66 | Mn(IV)oxides |
| Heated | 6.03 | 14.68 | 86 | Hydroxyaluminium interlayered vermiculite | | 25.11 | 3.55 | 51 | Birnessite |
| | 15.195 | 5.84 | 100 | Mixed layer(maghemite) | | 27.48 | 3.25 | 51 | Potassium feldspar |
| | Bw2 60-88 cm | | | | | 39.09 | 2.31 | 61 | Kaolinite |
| Mg-sat | 12.945 | 6.85 | 65 | Kaolinite | Glyl | 13.9 | 6.38 | 100 | Lepidocrocite |
| | 20.66 | 4.31 | 100 | Kaolinite | Heated | 8.60 | 10.31 | 12 | Vermiculite |
| | 21.475 | 4.14 | 47 | Geothite | | 20.96 | 4.25 | 100 | Hydro-mica montimor |
| | 26.515 | 3.37 | 40 | | | Bw1 15-110 cm | | | |
| | 38.36 | 2.35 | 26 | Vermiculite goethite | Mg-sat | 3.32 | 26.66 | 100 | Sillica |
| Glyl | 12.71 | 6.98 | 100 | Kaolinite | | 4.23 | 20.92 | 11 | |
| Heated | 15.43 | 5.75 | 100 | Maghenite | | 5.33 | 16.61 | 9 | |
| | 18.955 | 4.69 | 80 | | | 9.62 | 9.21 | 54 | Vermiculite |
| | Bt1 88-130 cm | | | | | 12.71 | 6.98 | 80 | Kaolinite |
| Mg-sat | 3.675 | 24.08 | 34 | Mica-vermiculite | | 21.06 | 4.23 | 41 | Quartz |
| | 7.29 | 12.15 | 100 | Sepiolite | | 25.84 | 3.45 | 25 | |
| | 13.15 | 6.74 | 100 | Kaolinite | | 35.52 | 2.53 | 14 | Hematite |
| | 20.925 | 4.25 | 25 | Quartz | Glyl | 6.84 | 12.94 | 10 | Smectite |
| | 26.41 | 3.38 | 16 | | | 9.03 | 9.82 | 9 | Smectite |
| | 37.58 | 2.39 | 27 | Gibbsite | | 12.78 | 6.94 | 100 | Kaolinite |
| Glyl | 4.51 | 19.63 | 9 | | Heated | 3.17 | 27.92 | 42 | Microcline(silica) |
| | 7.33 | 12.08 | 100 | Sepiolite | | 4.31 | 20.54 | 44 | |
| Heated | 3.35 | 26.42 | 59 | Microcline silica | | 13.04 | 6.51 | 100 | Plagioclase feldspars |
| | 15.29 | 5.80 | 100 | Maghemite | | Bw2 110-156 cm | | | |
| | Bt2 130-170 cm | | | | Mg-sat | 3.4 | 26.03 | 30 | Sillica |
| Mg-sat | 3.515 | 25.18 | 9 | | | 4.75 | 18.63 | 100 | Smectite (saponite) |
| | 12.6 | 7.04 | 100 | Kaolinite | | 12.73 | 6.97 | 23 | Iron microcline |
| | 13.325 | 6.66 | 80 | Plagioclase feldspars | | 25.29 | 3.53 | 33 | Kaolinite |
| | 25.5 | 3.50 | 96 | Chlorite | | 37.60 | 2.40 | 52 | |
| Glyl | 3.25 | 27.23 | 55 | Microcline | Glyl | 12.99 | 6.82 | 100 | Lepidocrocite kaol |
| | 4.45 | 19.89 | 8 | Hydromica-vermiculit | Heated | 4.84 | 19.31 | 100 | Saponite |
| | 7.08 | 12.52 | 100 | Hydromica | | 9.95 | 8.91 | 8 | Hematite |
| | 12.86 | 6.90 | 55 | Kaolinite | | 14.10 | 6.29 | 42 | Plagioclase(lepidocrocite) |
| Heated | 3.3 | 26.82 | 54 | Sillica | | 19.54 | 4.55 | 72 | Illite |
| | 23.695 | 3.76 | 100 | Maghenite | | BC 156-190 cm | | | |
| | | | | | Mg-sat | 4.45 | 19.91 | 49 | |
| | | | | | | 13.56 | 6.54 | 37 | Iron microcline |
| | | | | | | 14.75 | 6.02 | 72 | |
| | | | | | | 17.62 | 5.04 | 100 | Mackinwate ($Fe^3S_8$) |
| | | | | | | 18.81 | 4.73 | 46 | Lithiophorite-layered Mn |
| | | | | | | 20.91 | 4.26 | 86 | Quartz(hydro-mica monti |
| | | | | | | 25.37 | 3.52 | 24 | Nontronite |
| | | | | | Glyl | 3.57 | 24.83 | 25 | Hydrobiotite |
| | | | | | | 12.63 | 7.02 | 100 | Kaolinite |
| | | | | | Heated | 8.62 | 11.04 | 100 | Mica-vermiculite |

Table 13: Profile distribution of the mineral contents (Granitic parent material)

| | Granite parent material | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | GNT01 Ap 0-25 cm | | | | | GNT04 Ap 0-11 cm | | | |
| | Angle | d Å | I/I¹ | | | Angle | d Å | I/I¹ | Mineral Interpretations |
| | 12.925 | 6.86 | 32 | | | 5.05 | 17.53 | 17 | Smectite |
| | 21.03 | 4.23 | 15 | Quartz | | 6.86 | 12.91 | 100 | Mica-HIV minerals |
| | 25.56 | 3.49 | 27 | | | 13.21 | 6.71 | 33 | |
| | 27.11 | 3.29 | 100 | Quartz | | 16.62 | 5.34 | 31 | Hemaite |
| | 28.925 | 3.09 | 59 | Jarosite | | 17.46 | 5.09 | 10 | Maghemite |
| MgGlyl | 3.315 | 26.69 | 0 | Sillica | | 21.3 | 4.18 | 11 | Geothite |
| | 11.475 | 7.72 | 96 | Kaolinite | | 25.76 | 3.46 | 36 | |
| | 12.95 | 6.84 | 100 | Lepidocrocite | | 32.49 | 2.76 | 18 | Geothite+hematite |
| Heated | 9.285 | 9.54 | 13 | Vermiculite | Glyl | 3.3 | 26.82 | 41 | Sillica |
| | 12.555 | 7.06 | 100 | Chamosite(ironic)/Birnessite | | 5.41 | 16.36 | 100 | Smectite(montmorllinite |
| | 21.47 | 4.15 | 20 | Geothite | | 12.68 | 7.00 | 78 | Kaolinite |
| | AB 25-60 cm | | | | Heated | 8.32 | 10.64 | 100 | Vermiculite/mica |
| | 3.393 | 26.07 | 5 | Sillica | | Bt1 11-38 cm | | | |
| | 5.84 | 15.16 | 2 | Montimorllinite | | 4.62 | 19.18 | 74 | Smectite |
| | 12.995 | 6.82 | 23 | | | 13.4 | 6.62 | 61 | Plagioclase(oligoclase) |
| | 17.16 | 5.18 | 9 | Mica | | 21.79 | 4.09 | 16 | |
| | 21.695 | 4.10 | 37 | Iron microcline-low form | | 25.71 | 3.47 | 88 | Kaolinite |
| | 24.29 | 3.67 | 19 | Hematite | | 27.53 | 3.25 | 46 | Microcline(iron) |
| | 25.73 | 3.47 | 32 | Plagioclase(oligoclase) | | 37.62 | 2.39 | 100 | Halloysite |
| | 27.385 | 3.26 | 100 | Microcline($KAlSi_3O_8$) | Glyl | 12.69 | 7.00 | 100 | Kaolinite |
| | 38.325 | 2.35 | 10 | Anatase | Heated | 8.28 | 10.70 | 36 | Al-interlayered vermiculite |
| | 38.79 | 2.33 | 20 | Kaolinite | | 21.43 | 4.15 | 100 | Geothite |
| Glyl | 4.23 | 20.92 | 22 | | | Bt2 66-101 cm | | | |
| | 6.765 | 13.09 | 23 | Trace 2:1 phyllosilicate | Mg sat | 6.73 | 13.16 | 7 | Trace 2:1 phyllosilicate |
| | 12.74 | 6.96 | 100 | Kaolinite | | 7.38 | 12.00 | 15 | Smectite |
| Heated | 7.435 | 11.91 | 5 | | | 12.91 | 6.87 | 5 | |
| | 18.755 | 4.74 | 31 | Lithiophorite (Mn-rich) | | 21.90 | 4.07 | 5 | |
| | 21.295 | 4.18 | 100 | Geothite | | 27.49 | 3.25 | 11 | |
| | Bw1 60-100 cm | | | | | 37.53 | 2.40 | 100 | Chlorite |
| | 7.805 | 11.35 | 20 | Mica-vermiculite | Glyl | 13.02 | 6.81 | 100 | Lepidocrocite |
| | 14.095 | 6.29 | 5 | Trace lepidocrocite | Heated | 3.66 | 24.18 | 43 | Mixed layer smectite-mica |
| | 15.135 | 5.86 | 10 | Maghemite | | 9.40 | 9.43 | 100 | Lithiophorite (vermiculite) |
| | 19.065 | 4.66 | 7 | | | 20.41 | 4.36 | 62 | Kaolinite/Gibbsite |
| | 19.35 | 4.59 | 13 | | | 21.47 | 4.19 | 85 | Geothite |
| | 26.13 | 3.42 | 24 | | | BC 120-165 cm | | | |
| | 27.78 | 3.22 | 14 | | Mg sat | 4.81 | 18.42 | 1 | Trace smectite |
| | 38.15 | 2.36 | 100 | Halloysite($-H_2O$) | | 12.91 | 6.87 | 100 | Lepidocrocite |
| Glyl | 4.185 | 21.15 | 28 | | | 21.86 | 4.07 | 13 | |
| | 9.31 | 9.52 | 68 | Vermiculite | | 25.44 | 3.51 | 91 | Kaolinite(chlorite Fe-rich) |
| | 9.56 | 9.27 | 18 | | | 27.33 | 3.27 | 57 | Microcline |
| | 12.98 | 6.83 | 100 | Lepidocrocite | Glyl | 4.42 | 20.02 | 100 | Interstratification of mica-vermiculite |
| Heated | 4.25 | 20.83 | 51 | | Heated | 7.73 | 11.46 | 100 | “ |
| | 11.015 | 8.05 | 100 | Mica-Plagioclase | | 12.84 | 6.91 | 17 | Kaolinite |
| | Bw2 100-140 cm | | | | | | | | |
| | 4.43 | 19.98 | 3 | Kaolinite | | | | | |
| | 12.975 | 6.83 | 72 | Lepidocrocite | | | | | |
| | 1.045 | 5.53 | 8 | Maghenite | | | | | |
| | 21.865 | 4.07 | 26 | Labradiorite | | | | | |
| | 26.025 | 3.43 | 36 | | | | | | |
| | 27.83 | 3.21 | 100 | Rutile | | | | | |
| Glyl | 12.785 | 6.94 | 100 | Kaolinite | | | | | |
| Heated | 5.37 | 16.48 | 100 | Smectite(montomorllinite) | | | | | |
| | 7.685 | 11.52 | 9 | | | | | | |
| | 12.775 | 6.94 | 12 | Kaolinite | | | | | |
| | 21.2 | 4.19 | 23 | Geothite | | | | | |
| | 22.83 | 3.90 | 37 | Tridymite (Quartz) | | | | | |

XII.