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GENESIS AND CLASSIFICATION OF THREE FOREST
SOILS IN CENTRAL TAIWAN

by

Hen Biau King

A thesis submitted to
the Faculty of Graduated Studies and Research
in partial fulfillment of
the requirements for the degree of
Doctor of philosophy

Department of Earth Sciences
Carleton University
Ottawa, Ontario
June 1990

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The undersigned hereby recommend to
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GENESIS AND CLASSIFICATION OF THREE FOREST
SOILS IN CENTRAL TAIWAN

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for the degree of Doctor of Philosophy in
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ABSTRACT

This investigation represents the first detailed study of the genesis and classification of forest soil pedons in the mountains of Central Taiwan. Three pedons, developed from the most common bedrock materials (Tertiary shales, siltstones and sandstones) have been studied. These pedons developed under a subtropical climatic regime and warm-temperate montane rain forest vegetation at about 700 m a.s.l.

Pedon 1, a "Typic Dystrochrept, fine, vermiculitic, thermic", developed on fine siltstones on 2% slopes. Melanization and loosening have occurred, and braunification has produced a cambic Bw horizon.

Pedon 2, a "Typic Dystrochrept, fine, illitic, thermic", developed on shales on >60% slopes. Melanization, loosening and braunification (to produce a cambic Bw horizon) have occurred. Iron concretions, of pedogenic origin, are found in this soil and indicate that translocation and transformation processes involving iron oxides are active. These concretions, singly and in clusters (up to 40 cm across), distribute between 30 and 100 cm depth, have round to subangular polygonal structure and contain a grey matrix surrounded by two iron-rich layers. The inner dark reddish-brown layer is composed of 62% Fe_2O_3 (about equally hematite and goethite). It contains higher concentrations of Fe, Mn

and Ca than the soil matrix. The outer reddish-yellow layer is composed of 15% Fe_2O_3 , (92% is goethite). Only Fe and Zn contents are consistently greater in this layer than in the soil matrix. Ferrans (up to 600 μm thick), which may or may not be coated with ferri-argillans, are found in the planar voids of iron concretion clusters. These features indicate that translocation of iron and clay are active processes. A "life-cycle" for the iron concretions, which may explain their formation and destruction (based on the balance of erosion, Fe mobilization and reprecipitation at the site), is proposed. The name "shell concretions" is proposed for those structures, which are unlike any concretions previously described from soils.

Pedon 3, a "Typic Hapludult, fine-loamy, siliceous, thermic", developed on sandstones on >60% slopes. Melanization, loosening and lessivage (to produce an argillic Bt horizon) have occurred.

This investigation reveals the dominant soil forming factors and pedogenic processes of forest soils in the studied area and also demonstrates the utility of Soil Taxonomy for application to classifying forest soils in the mountains of central Taiwan.

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Partial and total hydrolysis are considered responsible for converting aluminosilicates (eg. K-feldspar) to phyllosilicate clay and oxide minerals (Hsu, 1977; Pedro, 1982).

The following reaction exemplifies partial hydrolysis:

Under moderate drainage conditions, the slow leaching allows gradual elevation of the silica concentration in reaction sites until the solubility product of kaolinite is attained. Under poor drainage conditions, sufficient Si, Al and bases may be retained to enable a 2:1 clay, of the smectite type, to form (Pedro, 1982).

Total hydrolysis may directly convert weatherable minerals to gibbsite if the required environmental conditions are met. Good drainage, high precipitation and warm temperature conditions, common in most Ultisols, enhance silica solubility. Under these conditions, where there is a very intense leaching environment, Hsu (1977) found that gibbsite forms as an early product of weathering of basic or intermediate rocks. The reaction is represented by:

Total and partial hydrolysis are, thus, synonyms of complete and incomplete desilication, respectively. In both desilications, the final products are controlled primarily by leaching, or by the concentration of silica remaining in

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CHAPTER 1 INTRODUCTION

The island of Taiwan consists of a western lowland area, which is intensively used for agricultural production, and central and eastern mountainous regions, which are largely forested. Taiwan's soils have developed in a warm, humid climate, which has supported vigorous forest growth.

The lowland soils, which developed under forest, have been modified by agricultural activities (in particular, by rice production rotated with vegetables). Most of the soil mapping and classification efforts, to date, have been confined to these lowland areas. The first systematic soil survey was conducted by the Taiwan Agricultural Research Institute (TARI) between 1948 and 1952. The survey results were published at a scale of 1:100,000 and were restricted to agricultural areas (Leung and Chen, 1957). The lowland agricultural area was again surveyed by TARI between 1974 and 1979. The survey results were published at a scale of 1:25,000 (Chen, 1982). In both surveys, the system of soil classification used was based on the Thorp and Smith (1949) revisions of the 1938 United States Department of Agriculture (USDA) soil classification system (Baldwin et al., 1938). The lowland soils were classified predominantly as zonal soils with some, intrazonal and azonal soils. A total of 15 Great Groups were identified (Table 1.1). According to the Soil Taxonomy system currently used by the USDA (Soil

Table 1.1 Soil classification of Taiwan*

Order	Great Group	
Zonal soils	Podzolic soils	Podzolic soils Brown podzolic soils Gray-brown podzolic soils Red-yellow podzolic soils
	Latosol soils	Reddish-brown latosol soils Yellow-brown latosol soils
Intrazonal soils	Calcimorphic soils	Brown forest soils Rendzina soils
	Halomorphic soils	Meadow soils Saline soils
	Hydromorphic soils	Planosol-like soils
Azonal soils	Alluvial soils Lithosols Regosols	
	Undetermined	
		Volcanic ash soils

* Leung, K.W. and Chen, T.T. 1957. Soils of Taiwan. J. Agri. Asso. China, New Series 20:1-26.

Survey Staff, 1975) the soils are predominantly in the Ultisol order, with there being some Inceptisols and Alfisols (Chang, 1988).

Very little investigation of the soils developed on the forest-covered, rapidly-uplifting, steeply-sloping and erosive mountainous areas of Taiwan has occurred. The rock materials of the mountains consist mainly of Late Paleozoic to Mesozoic metamorphosed limestones in the east, indurated Tertiary sediments (shales and sandstones) in the western regions of the central range and Miocene sediments in the western coastal foothills of the island (Figure 1.1; Ho, 1986). These materials have been uplifted, and continue to be uplifted by crustal movement (Biq, 1971). The soils of the mountainous regions are identified, on the 1:50,000,000 Soil Map of the World (USDA-SCS, 1972), as Hapludults, with Dystrochrepts on the western lowland slopes, and as Udic great groups of Alfisols, Entisols, Ultisols and Inceptisols in the mountain areas.

No truly detailed survey of the mountain region soils has been conducted and no studies of their genesis have occurred. The Taiwan Mountain Agricultural Resources Bureau (TMARB) investigated the sloping lands below 1000 m elevation, and published a map at 1:250,000 scale. The soils were classified, according to the Thorp and Smith (1949) revisions of the USDA system as zonal, intrazonal and azonal soils, belonging to six suborders: Red loam, Yellow-red

- I. Penghu islands (Pleistocene basalt).
- II. Coastal plain and western foothills province (Miocene clastic sediments).
- III. Central range province:
 - IIIa. Western subprovince (Tertiary, indurated sediments).
 - IIIb. Eastern subprovince (pre-Tertiary metamorphic complex).
- IV. Eastern valley (suture).
- V. Eastern coastal range province (Neogene rocks of volcanic derivatives, clastic sediments and chaotic deposits).

Figure 1.1 Geological map of Taiwan (Ho, 1986).

loam, Yellow Earth, Colluvial soils, Lithosols and Alluvial soils (TMARB, 1984).

The published work on the classification of soils of Taiwan (Leung and Chen, 1957; Chen, 1982; TMARB, 1984) has been based on the zonality concept and the impact of the soil forming factors on soil development. Final classification is based on the presumed genesis of the soils, rather than on specific measureable soil properties. The weaknesses of soil classification systems based on presumed genesis has been discussed by Buol et al. (1980) and FitzPatrick (1983) and will be further discussed in Chapter 2. Among the weaknesses, are the usefulness of the resulting maps for the purpose of making land management decisions. The Soil Taxonomy System (USDA-SCS, 1975) currently used in the United States, attempts to overcome these limitations by basing the classification of soils on well-defined, measureable soil properties. This approach has been well-received and the Soil Taxonomy system is increasingly being used by other countries. In Taiwan, this approach has recently been applied to the examination of the impacts of agricultural activities on the diagnostic properties of the rice-growing soils of the lowland regions (Food and Fertilizer Technical Centre, 1988). This thesis represents the first systematic attempt to apply the Soil Taxonomy system to the forest soils of Taiwan.

No forested soils of the mountains of Taiwan have been

studied in detail. Past studies have looked only at the general characteristics and horizonation in the soil and have involved few measurements of soil properties. The information is inadequate for definitive classification according to the Soil Taxonomy system and for gaining an understanding of the genesis of the soils. The current research program was formulated to allow a detailed study and accurate classification of selected pedons which have developed under mixed forests on the Tertiary sedimentary rocks of the central mountains of Taiwan. The sites were selected to allow soils developed on shales and sandstones to be investigated and for a comparison of the effect of topographic position to be made for the fine-grained parent rock material.

The thesis is structured to present in order: discussion of modern concepts of soil genesis and classification, with particular emphasis on the formation and classification of Ultisols and Inceptisols (the two orders found at the sites investigated); description of the locations investigated and the sampling and analytical procedures used; presentation of the results of analyses for each pedon, along with an interpretation of its genesis and classification; discussion of the micromorphology of the soil; and results and interpretation of investigations of the characteristics and origin of prominent iron concretions which are present in one of the soils developed from Tertiary shale.

CHAPTER 2 SOIL GENESIS AND CLASSIFICATION

2.1 Concepts of soil genesis

The theory of soil formation has evolved progressively as knowledge of soils has grown. The theories of soil genesis current in the mid-nineteenth century centered on rock disintegration accompanied by addition of some decayed organic matter (Fallou, 1862; Merril, 1906). In the late nineteenth century, the basis of current concepts of soil genesis was formulated by a group of soil scientists in Russia, led by V.V. Dokuchaev (1846-1903). Elements of it were concurrently and independently articulated in the United States, by E.W. Hilgard (1833-1906). In both cases, their studies stressed that factors in addition to rock weathering are also responsible for the development of horizonation. The Russian scientists, Glinka (1927) and Neutrujev (1927) for example, emphasized climate and vegetation as soil forming factors, while Hilgard (1892) noted the interactions of parent materials and climate on the forms and distribution of vegetation. Both groups recognized the regional significance of climate and vegetation as agencies of change. Jenny (1941) expounded on parent material, climate, topography, organisms and time as factors that affect formation of soil. He regarded these five factors as independent variables (an argument that is not convincingly true, except for time) and illustrated how soil

profile development is a product of these five factors.

Modern concepts of soil genesis are modifications of these earlier ones. According to the modern concept, soils are natural bodies formed on the land surface, occupying space and having unique morphology (Simonson, 1957). Simonson (1957) viewed soil formation as two overlapping steps, namely, accumulation of parent materials and differentiation of horizons in the profile.

Parent materials are usually accumulated through the weathering of rocks in place or through the transport and deposition of weathered rock materials (Simonson, 1978). Accumulated organic residues, from which organic soils are derived, are also considered as a kind of parent material. Weathering of rock is a twofold process: it is both disintegration (mechanical weathering), and decomposition (chemical weathering). These operate together, and help and reinforce each other's influence (Press and Siever, 1982). The in place weathering of rocks prepares raw parent material in which soil development may be initiated or, alternatively, various agents may transport the weathered rock debris, or material which has undergone some soil formation, and deposit it at a new location. Transported materials, such as glacial tills and alluvial deposits, are considered as new parent materials in which horizon differentiation, and hence soil development, may commence.

2.2 Processes of horizon differentiation

Simonson (1959) considered that four major processes lead to soil horizonation: additions, losses, translocations and transformations (Figure 2.1).

Additions refer to various substances that soils gain from outside the soil system. These include dissolved salts from precipitation, silicates in airborne dust and organic matter from plant materials, all of which are commonly added to the soil surface. In the case of organic matter, the rate of addition to a soil profile may exceed the rate of breakdown (loss) for varying time periods, which results in a net gain in organic content. This organic matter accumulation through time tends to produce an organic-rich surface horizon. The specific soil forming factors at the site will have an effect on the rate and nature of organic accumulation.

Losses refer to substances leaving the soil system through various processes, especially by leaching and erosion. Leaching is more pronounced in regions where precipitation exceeds evapotranspiration and results in percolation. This process commonly results in removal of soluble bases from the surface zone and the formation of an acid surface soil.

Translocations are accomplished by mobilization of substances in one zone within the soil system, followed by subsequent deposition in another. Translocation can be by upward, downward or lateral movement. The translocation of

Figure 2.1 Schematic representation of the solum of a soil pedon as an open system (reproduced from Buol et al., 1980).

Table 2.1 Processes that lead to soil horizonation (from Buol et al., 1980).

Process	Brief Definition
<u>Additions</u>	
1. Cumulization	Aeolian, hydrologic and man-made additions of mineral particles to the soil surface
2. Enrichment	General term for addition of material to a soil body
3. Littering	The accumulation of organic litter and associated humus, to a depth of less than 30 cm, on the mineral soil surface
4. Melanization	The darkening of light-colored mineral, initially unconsolidated, materials by admixture of organic matter (also involves translocation)
<u>Losses</u>	
5. Erosion, surficial	Removal of material from the surficial layer of a soil
6. Leaching (depletion)	General term for washing out or eluviating soluble materials from the solum
<u>Translocations</u>	
7. Alkalization (solonization)	The accumulation of sodium ions on the exchange sites in a soil
8. Calcification	Processes including accumulation of calcium carbonate in Cca and possibly other horizons of a soil

Table 2.1 Processes that lead to soil horizonation (from
Buol et al., 1980).

Process	Brief Definition
9. Dealkalization (solodization)	The leaching of sodium ions and salts from natric horizons
10. Decalcification	Reactions that remove calcium carbonate from one or more soil horizons
11. Desalinization	The removal of soluble salts from salic soil horizons
12. Desilication	The chemical migration of silica out of the soil solum and thus the concentration of sesquioxides in the solum, with or without formation of ironstone and concretions (also involves transformation)
13. Eluviation	Movement of material out of a portion of a soil profile, as in an albic horizon
14. Illuviation	Movement of material into a portion of a soil profile, as in an argillic or spodic horizon
15. Lessivage	The mechanical migration of small mineral particles from the A to the B horizons of a soil, producing relative enrichment in clay in B horizons (argillic horizons)
16. Leucinization	The paling of soil horizons by disappearance of dark organic materials, either through transformation to light-colored ones or through removal from the horizons
17. Pedoturbation	Biological, physical (freeze-thaw and wet-dry cycles) churning and cycling of soil materials, thereby homogenizing the solum in varying degrees

Table 2.1 Processes that lead to soil horizonation (from Buol et al., 1980).

Process	Brief Definition
18. Podzolization	The chemical migration of aluminum and iron and/or organic matter, resulting in the concentration of silica (i.e. silication) in the layer eluviated (also involves transformation)
19. Salinization	The accumulation of soluble salts to produce salic horizons
<u>Transformations</u>	
20. Braunification (Rubification, Ferrugination)	Release of iron from primary minerals and the dispersion of particles of iron oxide in increasing amounts; their progressive oxidation or hydration giving the soil mass brownish, reddish-brown, and red colors, respectively (also involves translocation)
21. Decomposition	The breakdown of mineral and organic materials
22. Gleization	The reduction of iron under anaerobic "waterlogged" soil conditions, with the production of bluish to greenish-gray matrix colors, with or without yellowish brown, brown, and black mottles, and ferric and manganiferous concretions
23. Hardening	Decrease in volume of voids by collapse and compaction and by filling of some voids with fine earth, carbonates, silica and other materials
24. Humification	The transformation of raw organic material into humus

Table 2.1 Processes that lead to soil horizonation (from Buol et al., 1980).

Process	Brief Definition
25. Loosening	Increase in volume of voids by activity of plants, animals, and humans and by freeze-thaw or other physical processes and by removal of material by leaching
26. Mineralization	The release of oxide solids through decomposition of organic matter
27. Paludization	Processes regarded by some workers as geogenic rather than pedogenic, including the accumulation of deep (>30 cm) deposits of organic matter, as in mucks and peats (Histosols)
28. Ripening	Chemical, biological, and physical changes in organic soil after air penetrates previously waterlogged material
29. Synthesis	The formation of new particles of mineral and organic species

1978). The differentiation of horizons in a soil profile is the product of the combination of subprocesses operating in the soil system over time.

Soil may also be viewed in the context of energy transfers in and through an open system (Buol et al., 1980). The system has a budget of input and output. According to this approach, all pedogenic processes may operate in a soil system with different intensities. The basic processes operating are the same, but their relative importance with different combinations of soil forming factors is not. The balance over time among the many processes in soil formation determines the soil profile produced (Simonson, 1978).

Soil horizon nomenclature uses the letters, O, A, E, B, C and R to designate master horizons of a soil profile. Appropriate prefixes and suffixes are sometimes used to indicate specific characteristics as subdivisions of a master horizon. For example, a Bt horizon designation, identifies a master B horizon with more translocated silicate clay than the assumed parent material and/or the overlying horizon. A brief description of the soil horizon nomenclature, currently used in Soil Taxonomy (Soil Survey Staff, 1987) is presented in Table 2.2.

2.3 Systems of soil classification

The early classification of soils was carried out almost exclusively by geologists and was largely based on geological

Table 2.2 Soil Horizon Nomenclature (Soil Survey Staff, 1987).

Master horizons and layers

- O horizons or layers:** Layers dominated by organic material, except limnic layers that are organic. Some are saturated with water for long periods or were once saturated but are now artificially drained; others have never been saturated.
- A horizons:** Mineral horizons that formed at the surface or below an O horizon and
 (1) are characterized by an accumulation of humified organic matter intimately mixed with the mineral fraction and not dominated by properties characteristic of E or B horizons (defined below) or (2) have properties resulting from cultivation, pasturing, or similar kinds of disturbance.
- E horizons:** Mineral horizons in which the main feature is loss of silicate clay, iron, aluminum, or some combination of these, leaving a concentration of sand and silt particles of quartz or other resistant minerals.
- B horizons:** Horizons that formed below an A, E, or O horizon and are dominated by obliteration of all or much of the original rock structure and by
 (1) illuvial concentration of silicate clay, iron, aluminum, humus, carbonates, gypsum, or silica, alone or in combination;
 (2) evidence of removal of carbonates;
 (3) residual concentration of sesquioxides;
 (4) coatings of sesquioxides that make the horizon conspicuously lower in value, higher in chroma, or redder in hue than overlying and underlying horizons without apparent illuviation of iron;
 (5) alteration that forms silicate clay or liberates oxides or both and that forms granular, blocky, or prismatic structure if volume changes accompany changes in moisture content; or
 (6) any combination of these.
- C horizons or layers:** Horizons or layers, excluding hard bedrock, that are little affected by pedogenic processes and lack properties of O, A, E, or B horizons. Most are mineral layers, but limnic layers, whether organic or inorganic, are included. The

Table 2.2 (continued)

Master horizons and layers

material of C layers may be either like or unlike that from which the solum presumably formed. A C horizon may have been modified even if there is no evidence of pedogenesis.

- R Layers: Hard Bedrock.** Granite, basalt, quartzite, and indurated limestone or sandstone are examples of bedrock that are designated R. The bedrock of an R layer is sufficiently coherent, when moist, to make hand digging with a spade impractical, although it may be chipped or scraped with a spade. Some R layers can be ripped with heavy power equipment. The bedrock may contain cracks, but these are few enough and small enough that few roots can penetrate. The cracks may be coated or filled with clay or other material.

Some commonly used suffixes

- a highly decomposed organic material
- b buried genetic horizon
- c concretions or hard concretionary nodules
- d dense unconsolidated sediments or materials
- e organic material of intermediate decomposition
- f frozen soil
- g strong gleying
- h illuvial accumulation of organic matter
- i slightly decomposed organic material
- k accumulation of carbonates
- m cementation or induration
- n accumulation of sodium
- o residual accumulation of sesquioxides
- p plowing or other disturbance
- q accumulation of silica
- r weathered or soft bedrock
- s illuvial accumulation of sesquioxides and organic matter
- t accumulation of silicate clay
- v plinthite
- w development of color or structure
- x fragipan character
- y accumulation of gypsum
- z accumulation of salts more soluble than gypsum

origin and lithologic composition. For example, Fallou (1862), a German geologist, classified soils into two classes: residual soils and alluvial soils. The former class included limestone, feldspathic, clay and quartz-bearing soils and the latter class included gravel, marl, loam and moor soils. The criterion for differentiating soils was what is currently called parent materials. In his system of classification, soil properties themselves were not taken into consideration.

In Russia, Sibirtsev (1901) refined Dokuchaev's concept of soil zones. He recognized the association of similar soils with certain climatic, vegetational or ecological regimes, and he designated these soils as zonal soils. On the other hand, soils whose development was dominated by some local factors, such as drainage or parent material, were named intrazonal soils. The azonal soil did not have distinct characteristics related to soil forming factors, except sometimes with time.

In the United States, Marbut (1935), after becoming aware of the Russian work, (1935) increased the emphasis on the soil-forming factors of climate and vegetation and reduced the emphasis on geological nature and origin of soil materials. He classified soils into two broad classes: Pedocals which had calcium carbonate accumulation, and Pedalfers which had aluminum and iron accumulation. With this system, Marbut placed great emphasis on "normal soils" (or mature, freely-drained soils) and little account was

taken of organic, poorly-drained or immature soils. This system had limitations in that it could not accommodate soils which accumulated both iron and carbonate, or neither of these constituents. In spite of its weakness, as discussed recently by Buol et al. (1980) and FitzPatrick (1983), many recently published geological textbooks still use the Marbut system to introduce soil classification.

The first comprehensive system of soil classification was the work of Baldwin et al. (1938), who reintroduced the zonal system of Sibirtsev and deemphasized the Pedalfer-Pedocal concept. Although this system was revised and improved by Thorp and Smith (1949), it still possessed problems which limited its application, as pointed out by Buol et al. (1980) and FitzPatrick (1983). Problems included: essentially identical soils could be zonal in some areas and intrazonal in another; the system was genetically based, that is, the classification of a given soil was dependent on the supposed processes by which it had formed; and furthermore, the two highest categorical levels were based mainly on environmental factors, rather than intrinsic properties of soils. These problems led to the development of a new approach to soil classification in the United States.

In 1951, the development of a new comprehensive system of soil classification was initiated (Smith, 1968). After several approximations, Soil Taxonomy (Soil Survey Staff, 1975) was published. This new comprehensive system marked

the beginning of the modern era in soil classification in that a new approach was taken. Firstly, soils are differentiated according to properties that can be measured quantitatively and reproducibly. Genesis is not employed except as a guide to relevance and weighting of soil properties (Smith, 1968). Secondly, it is designed to accommodate changes when the need arises. Its flexibility allows expansion and revision to accommodate soils that are newly found. Thirdly, new taxa names that have precise definitions were created. It was believed that new names embodying the new concept and new definitions would avoid confusion with old names, some of which are used for quite different kinds of soils in different countries. For example, podzolic soils are defined differently in Japan (Matsui, 1981) and in Canada (Canada Soil Survey Committee, 1978). Finally, the system develops the concept of diagnostic horizons, which are used in defining most of the soil orders. A diagnostic horizon is defined as the combinations of specific soil characteristics that are indicative of certain classes of soils (Badayos, 1985). These diagnostic horizons are quantitatively defined and are used to differentiate between taxa, with the soils being classified according to their presence or absence.

Soil Taxonomy uses a multiple-category system which has six categories: order, suborder, great group, subgroup, family and series. There are 10 orders, 47 suborders, 241

great groups (John Witty, personal communication, March, 1988). The system is described in detail in Soil Taxonomy (Soil Survey Staff, 1975; 1990). Names of the eleven orders with their derivation and major characteristics are presented in Table 2.3.

Most of the soils of Taiwan have been classified as either Ultisols or Inceptisols. Ultisols dominate in the western lowlands of Taiwan, whereas Inceptisols dominate on the hillslopes and in mountainous regions (USDA-SCS, 1972). The genesis and properties of these two orders will be discussed further.

2.4 Genesis and properties of Ultisols

2.4.1 Definition and distribution of Ultisols

Ultisols are soils that have an argillic horizon (enriched with translocated clays) and low base saturation (less than 35%). The subsurface horizons are stained by accumulated sesquioxides and are commonly reddish to yellowish color (Soil Survey Staff, 1975). The Ultisols were classified as Red-yellow Podzolic or Red-brown Lateritic soils in the United States system of 1938 (Baldwin et al., 1938; Thorp and Smith, 1949).

The properties of the argillic horizon, which is used as a subsurface diagnostic horizon for Ultisols, and hence, must be present, have been summarized (Buol et al., 1980) as:

Table 2.3 Names of soil orders in Soil Taxonomy (Soil Survey Staff, 1990) with their derivation and major characteristics.

order	derivation	major characteristics
Alfisols	Nonsense symbol	Unleached forest soils; well-developed argillic or natric horizon with high base saturation.
Andisols	<i>Ando, dark colored</i>	volcanic soils.
Aridisols	<i>L. aridus, dry</i>	Dry soils, ochric epipedon.
Entisols	nonsense symbol	Recent soil with little profile development, ochric epipedon common.
Histosols	<i>Gr. Histos, tissue</i>	Peat or bog, organic soils.
Inceptisols	<i>L. inceptum, beginning</i>	Embryonic soils with cambic horizon.
Mollisols	<i>L. mollis, soft</i>	Dark soils of grassland, mollic epipedon, high base saturation.
Oxisols	<i>Fr. oxide, oxide</i>	highly weathered soils of tropics, oxic horizon.
Spodosols	<i>Gr. Spodos, wood ash</i>	Spodic horizon with Fe, Al and humus accumulation.
Ultisols	<i>L. ultimus, last</i>	similar to the Alfisols except with low base saturation, argillic horizon.
Vertisols	<i>L. verto, turn</i>	dark in color, high in swelling and shrinking clays, deep cracks when dry.

"In general, this is a B horizon that has at least 1.2 times as much clay as some horizon above, or 3% more clay content if the eluvial layer has <15% clay, or 8% more clay if eluvial layer has >40% clay. It is formed by illuviation of clay, and illuviation argillans are usually observable unless there is evidence of stress cutans. It should be 1/10 as thick as all overlying horizons or more than 15 cm, whichever is thinner."

Ultisols occur in the mid- to low-latitude humid climates, which have high precipitation relative to evaporation in one or more seasons (Soil Survey Staff, 1975). Most of the soils of south-eastern Asia (including Taiwan) and south-eastern North America are Ultisols. Ultisols are also prominent on the east and northeast coasts of Australia. Large areas occur in southern Brazil and Paraguay (Brady, 1984).

The Ultisol order is subdivided into five suborders: four depending on the profile wetness, Aquult, Udult, Ustult and Xerult; and one depending on organic matter content of the soil, Humult. Further subdivision into great groups is based on the presence of diagnostic horizons in addition to the argillic horizon or on soil characteristics (such as an abrupt textural change). For example, Udults are the more or less freely drained, humus-poor Ultisols with udic soil moisture regimes which have a moisture control section that is not dry in any part as much as 90 cumulative days in most years. Udults have an ochric (low in organic matter content hence light in color) epipedon and a thin or moderately thick argillic horizon.

Within the experimental forest, three pedons, representing soils of this area, were selected for study. Pedons 2 and 3 (Figure 3.1) were formed on Tertiary dark-colored shales and sandstones, respectively, and were under natural forest vegetation. Pedon 1, developed on light-colored Tertiary siltstones, is located on a 2% slope, near a ridge top, 1.5 km north-east of pedon 2 at an elevation of 700 m above sea level. The site had been clearcut in 1976 and is currently planted with oil tea (*Camilia olerfera*).

The profile descriptions of these pedons are presented in Chapter 4.

3.2 Sampling and sample storage

Samples for general analytical analysis, bulk density determination and micromorphological studies were collected from each pedon.

Composite samples of approximately 1 kg were collected, from each 10 cm depth increment of each pedon, for general physical and chemical analysis. The air-dry samples were crushed with a rubber-tipped pestal in a ceramic mortar and were sieved through a 2 mm screen. Samples of the <2 mm fraction were labelled and stored in polyethylene bags for analysis. All data are reported on the basis of <2 mm fraction, unless otherwise specified.

A few oriented clods, up to 30 cm across and containing iron concretions, were also collected from pedon 2. These

landscape positions that are moderately-stable well-drained sites. In association with Oxisols, they are typically found on younger or less stable landscape positions than are occupied by Oxisols (Lepsch and Buol, 1974). When in association with Alfisols, Ultisols occupy the more stable positions of the same age or are on the older surfaces (Daniels et al., 1978). In areas with coarse-textured parent materials, Spodosols may develop in low, poorly-drained positions with Ultisols on the better-drained sites (Daniels et al., 1975).

Time - The formation of a silicate B horizon that meets the argillic criteria is time-dependent because weathering, clay formation and translocation are relatively slow processes (Birkeland, 1984). The time involved in Ultisol development depends on climate, topography, parent material and vegetation, and their influence on initiation and rate of specific pedogenic processes (Miller, 1983). Daniels et al. (1971), in the study of the Coastal Plain surfaces in North Carolina, claimed that the intensity of Ultisol development may vary greatly with changes in climate and internal water table level over time. Ultisols of the upper- and middle-Coastal Plain of the southeastern United States are on landscapes that have been exposed for several million to 10 million years (Daniels et al., 1970). In a later study of the same area, Daniels et al. (1978) found Ultisols on parent materials of Pleistocene or older age, with the estimated time since subaerial exposure and the

commencement of weathering and pedogenesis ranging from 35,000 to approximately 5,000,000 years. The solum thickness and the proportion of soils with plinthite and gibbsite content increased progressively from the younger soils of 3 million years to the older of 6-10 million years. Buol et al. (1980) tabulated estimates of the rate of formation of some Ultisols, which suggest that they can develop rather quickly: Ultisols (Red-Yellow Podzolic soil) in Australia required about 29,000 years for the formation of the solum.

2.4.3 Some major properties of Ultisols

Most Ultisols are characterized by high acidity, low base status, low organic matter content, low CEC and low base saturation in the subsoil. Table 2.4, compiled from 11 Ultisols (covering all 5 suborders and 11 of the great groups) indicates the typical range of selected properties (Soil Survey Staff, 1975).

Organic carbon contents of the 11 Ultisols (Table 2.4) ranged from 2.2 to 6.7%, with an average 4.0% for the surface horizon. High organic matter content (about 6.7% organic carbon) in Ultisols is usually associated with the Humic taxa. The organic matter distribution of Ultisols is represented by a maximum accumulation in the surface horizon, with a sharp decrease in the B and C horizons. This distribution can be attributed to: the warm climates and

good soil drainage conditions which provide an environment suitable for high mineralization rate of added organic matter and the generally low populations of organisms that effectively mix the soils to any appreciable depth (Miller, 1983).

The color of the surface horizon of Ultisols varies from dark gray to dark reddish-brown. It ranges from gray on poorly-drained sites to yellowish and brownish hues on

Table 2.4 Some properties of 11 Ultisols (data were compiled from analytical data of 11 pedons in Soil Taxonomy (Soil Survey Staff, 1975)).

	A1		B2		C	
	range	mean	range	mean	range	mean
Org. C ¹ , %	2.2-6.7	4.0	0-2.0	0.4	0-0.5	0.2
pH ² : H ₂ O	4.0-6.0	5.4	3.8-5.4	4.8	3.9-5.3	4.8
KCl	3.4-5.3	4.6	3.1-5.0	4.2	3.2-4.4	4.0
CEC ³ : pH8.2	4.6-33.9	20.9	8.9-30.5	16.3	1.8-37.3	14.5
pH7.0	2.8-23.6	13.4	9.8-19.9	14.6	10.0-29.2	17.1
BS ⁴ , pH8.2, %	3-46	24	1-39	11	2-24	8
Clay, %	3.4-67.2	26.9	22.5-81.0	48.3	6.6-39.6	23.6

1. Organic carbon : Acid-dichromate digestion, FeSO₄ titration.

2. pH is measured in 1:1 H₂O and 1:1 1M KCl respectively.

3. Cation exchange capacity in cmol(+)/kg

at pH 8.2 : BaCl₂-TEA, pH 8.2

pH 7.0 : NH₄OAc buffered at pH 7.0

4. Percent base saturation= [Sum of bases]/CEC(pH 8.2) X 100

moderately and well-drained sites, respectively. In all cases, high surface organic matter accumulation tends to darken the A horizon. For the argillic B horizon, the color changes from yellowish to brownish and reddish hues, as drainage of the site gradually improves.

Ultisols are acid: both their pH values and percent base saturation decrease as depth increases (Table 2.4). The higher (but still low) pH and base saturation near the surface of Ultisols are the result of recycling of bases through native vegetation. The relatively low pH and base saturation are attributed to intensive leaching and the relatively low content of weatherable minerals in the soils. The argillic horizon of Ultisols is commonly reported to be deficient in exchangeable calcium (Soil Survey Staff, 1975). Where extremely low levels of bases are present, it may be partly due to the absence of weatherable minerals. The almost complete depletion of the exchangeable bases (exchangeable Ca and Na were undetectable and exchangeable Mg and K levels ranged from 0 to 0.2 cmol(+)/kg), found from the entire profile of one Typic Hapludult (pedon 118, Soil Survey Staff, 1975), suggests almost complete removal of weatherable minerals from this soil, the parent material of which was residuum from weathered mica schist that had quartz veins and a moderate mica content. In some cases, an increase in base saturation is found below the mid or lower sola. This is most often observed in areas where Ultisols

are associated with Alfisols or other soils with higher base status.

2.4.4 Pedogenesis of Ultisols

The Ultisols are soils of mid to low latitudes which have a horizon that contains an appreciable amount of translocated clay but few bases (Soil Survey Staff, 1975). The two dominant pedogenic processes involved are lessivage and leaching. Lessivage refers to the mechanical translocation of clay from the A to the B horizon of a soil to form the relatively clay-rich argillic horizon (Bt), which is a diagnostic horizon for Ultisols. Extensive leaching promotes the removal of bases from the soil profile to produce a solum with low base status.

Enrichment of clay in the B horizon of Ultisols may either be due to formation in situ or its translocation from the A horizon and deposition in the B horizon. In all cases it is necessary to determine that the change in clay content did not precede soil development in the form of a textural discontinuity in the parent material.

2.4.4.1 Formation of clays

The soil temperature regimes in Ultisols, which are warmer than 8°C (MAST) and accompanied by extensive leaching over a long period of time, result in an alteration of weatherable minerals into secondary clays and oxides.

Partial and total hydrolysis are considered responsible for converting aluminosilicates (eg. K-feldspar) to phyllosilicate clay and oxide minerals (Hsu, 1977; Pedro, 1982).

The following reaction exemplifies partial hydrolysis:

Under moderate drainage conditions, the slow leaching allows gradual elevation of the silica concentration in reaction sites until the solubility product of kaolinite is attained. Under poor drainage conditions, sufficient Si, Al and bases may be retained to enable a 2:1 clay, of the smectite type, to form (Pedro, 1982).

Total hydrolysis may directly convert weatherable minerals to gibbsite if the required environmental conditions are met. Good drainage, high precipitation and warm temperature conditions, common in most Ultisols, enhance silica solubility. Under these conditions, where there is a very intense leaching environment, Hsu (1977) found that gibbsite forms as an early product of weathering of basic or intermediate rocks. The reaction is represented by:

Total and partial hydrolysis are, thus, synonyms of complete and incomplete desilication, respectively. In both desilications, the final products are controlled primarily by leaching, or by the concentration of silica remaining in

solution. Other aluminosilicate primary minerals, such as biotite and muscovite, are also altered, through a vermiculite intermediate, to form kaolinite and/or gibbsite, under environmental conditions favorable to Ultisol formation (McCaleb, 1959; Tardy et al., 1973).

2.4.4.2 Translocation of clays

The mechanisms of translocation of phyllosilicates from an upper to a lower horizon are not well understood, but the translocation is generally considered to involve dispersion of the clay, movement in suspension by percolating water and finally deposition in areas where percolating water stops or where flocculating agents are encountered (Soil Survey Staff, 1975). These mechanisms of clay movement have been postulated, based on field observations and laboratory analysis.

In both field and thin-section studies, the presence of oriented clay coatings, lining ped surfaces or voids, generally is taken as evidence for clay particle translocation (Fedoroff and Eswaran, 1985). Detailed chemical analyses have revealed that these clay films have properties that more closely resemble the clays of the A horizon and than those of the B horizon (Buol and Hole, 1961). In thin section studies, Brewer (1976) described the micromorphological characteristics of clay coatings and stated that films of oriented clay, along voids and ped surfaces, have sharp

boundaries with the soil mass which probably result from translocation.

Depth distribution curves of clay content of many Ultisols show a clay-depleted A horizon overlying a clay-enriched B horizon (Figure 2.2). This clay distribution pattern is commonly taken as evidence of vertical clay translocation within a profile. In some studies, however, it has been suggested that the B horizon clay may not be derived entirely by illuvial processes, but that some clay may be formed in situ in the B horizon. Results of studies of a Paleudult on the North Carolina coastal plain (Cady and Daniels, 1968) revealed that (a) total clay ($< 2 \mu\text{m}$) showed a typical distribution pattern for Ultisols with the highest concentration in the B2 horizon, (b) kaolinite was found throughout the solum but the maximum concentration occurred in the C horizon where it was the predominant clay mineral in the clay fraction, and (c) the maximum gibbsite concentration was found in the lower B2 horizon. They concluded that the relatively high gibbsite and low kaolinite contents in the B2 horizon of the soils on that old surface suggested clay destruction to form gibbsite in the B2 and that other transformations to form kaolinite may be occurring in the C horizon. Due to the trace amount of gibbsite found in the C horizon of this Ultisol and many others, McCaleb (1959) and Bryant and Dixon (1963) suggested that resilication of gibbsite to kaolinite (or halloysite) may be occurring in

Figure 2.2 Vertical clay distribution patterns of four Ultisols [data taken from Soil Survey Staff (1975), numbers in parenthesis refer to pedon numbers].

* "Tropohumult" has been removed from the great groups of Udults and is replaced with Hapludult (Soil Survey Staff, 1987).

the C horizon.

2.4.4.3 Iron minerals

Many Ultisols were described as Red-Yellow podzolic soils in the 1949 USDA system (Soil Survey Staff, 1975). This is because eluviation and illuviation of sesquioxides, which is also referred to as podzolization, are important processes operating in Ultisols. As a result of oxide movement, a light-colored A2 may or may not meet albic requirement and red to yellowish B2 horizon are developed.

The common iron materials found in the B2 horizon of Ultisols are goethite and hematite, with some associated magnetite and ferrihydrite (amorphous hydrous iron oxide). All these iron minerals, except magnetite, have been identified as products of weathering (Schwertmann and Taylor, 1977; Bigham et al., 1978). Goethite is the dominant crystalline form in most well-drained Ultisols. Hematite ranks as the second most important iron mineral and has formed under a relatively higher temperature regime (Birkeland, 1984). Gamble and Daniels (1972) from studies of two Paleudults, concluded that little ferrihydrite accumulated in the B horizon.

The formation of secondary iron-bearing materials in the soil depends partly upon pH-Eh conditions as well as Fe concentration (Birkeland, 1984). Daniels et al. (1975) found that the free-iron content (dithionite-citrate-extractable

Fe) was higher in Paleudults than in associated Paleaquults. They attributed these differences to the different oxidation and reduction histories. Under reducing conditions, which are present in Aquults, and with some organic matter present, ferric iron may be reduced to ferrous iron, which is more soluble and may migrate to other sites before precipitation takes place.

The transformation of iron materials from goethite to hematite or vice versa is still open for further research. The following simplified possible pathways of iron oxide formation under aerobic pedogenic conditions have been proposed (Schwertmann, 1988). Figure 2.3 shows the processes of formation of hematite and goethite and the factors that influence them in the soil environments. Ferrihydrite ($\text{Fe}_5\text{HO}_8 \cdot 4\text{H}_2\text{O}$) appears to be a necessary precursor for hematite, but not for goethite. Hematite can convert to goethite, but only by dissolution and reprecipitation. A change to cool-moist climatic conditions could initiate such a conversion (Birkeland, 1984).

Daniels et al. (1975) studied free iron sources in an Aquult-Udult sequence from North Carolina. They concluded that very little iron has been lost from soils that had deep water tables during most of their formation. The major changes that have taken place are translocation within the solum. Recently, Farmer et al. (1980) found that, in some Spodosols, some of the amorphous Al-silicates convert to

Figure 2.3 Hematite and goethite: schematic representation of their competitive processes of formation and factors influencing them in soil environments. Small arrows indicate whether increasing or decreasing expression of the factor favors hematite formation, with the opposite effect for goethite. Higher soil temperature may not only induce dehydration of ferrihydrite and thereby reinforce hematite formation directly, but may also accelerate Fe release and organic matter decomposition and thereby favor hematite formation indirectly (from Schwertmann, 1988).

surfaces of mineral grains and on pore surfaces. A few mineral grains (mainly quartz) in the Bw1 (15-60 cm) and Bw2 (60-120 cm) horizons have very thin oriented clay coatings ($< 10 \mu\text{m}$) on their surfaces. More are present in the Bw2 than Bw1. The groundmass (s-matrix of Brewer) of the BC horizon (ca. 140 cm) shows a striated b-fabric. The surfaces of many mineral grains of the BC horizon are coated with oriented clay films, indicating illuviation or deposition of translocated clay, but it covers far less than the 1% of the cross section that is required for a Bt horizon (Appendix III). The clay content changes with depth and the presence of argillans give evidence of lessivage operating, although not very strongly, in this profile.

X-ray diffraction patterns for Mg-saturated and glycerol-solvated samples (Figure 4.6a-d) show very strong 1.4 nm peaks and very weak 1.0 nm peaks throughout the profile. No 1.77 nm peaks were found. The 1.4 nm peaks do not collapse to 1.0 nm upon K-treatment at room temperature although the intensities reduce slightly. Heating to 300°C causes partial collapse and to 700°C causes complete collapse to yield 1.0 nm peaks (Figure 4.6a-d). The response of the clay to these pretreatments indicates the loss of hydroxy- in erlayers during heat treatment and suggests that the major clay minerals are aluminum-interlayered vermiculites (Douglas, 1977). The absence of a 1.77 nm peak rules out the presence of montmorillonite, and the collapse

identify general physical and chemical properties that are representative of Inceptisols. Their only common feature is their immature state of development, which is characterized by the weakly-developed cambic B horizon.

2.5.2 Genesis of Inceptisols

Inceptisols are formed on practically all types of parent materials, but are most commonly in soils of more clayey nature. Lekwa and Whiteside (1986) studied coastal plain soils of southeastern Nigeria and found that an Inceptisol (Dystrochrept) was developed on loamy material and a Spodosol (Tropaquod) on sandy parent material. Both developed on poorly-drained sites associated with Ultisols on better-drained sites. Parent material differences (e.g. from acid vs. from calcareous rocks) explain some Inceptisol and Alfisol distribution patterns in parts of continental Europe (Dudal et al., 1966) and in the east, southeast and midland regions of England (Cruikshank, 1972).

Inceptisols are usually developed on recent geological materials under climatic conditions where precipitation exceeds evapotranspiration at some time of year. It should also be noted (Foss et al., 1983) that Inceptisols may occur on old geological formations where any or all of slow weathering processes (in areas of low precipitation and temperature), rapid rates of erosion, presence of parent materials resistant to weathering and high water tables

decrease the rate of horizon differentiation.

Most Inceptisols occur under forest vegetation (Foss et al., 1983), but of the 15 pedons listed in Soil Taxonomy (Soil Survey Staff, 1975), 13 pedons were under grass and shrub vegetation.

Buol et al. (1980) claimed that the relative intensity of the different soil weathering processes produces the many types of Inceptisols that are found in different regions. Foss et al. (1983) have evaluated the relative importance of four pedogenic processes (Figure 2.4) with respect to their role in the formation of the suborders within the Inceptisol order. The relative intensity is controlled by variation in soil environments, including differences in wetness, mineralogy and temperature regimes.

The Aquept suborder develops in depressions, flat plains, or flood plains where the water table is high or soils are saturated with water at some period of the year, unless artificially drained. Gleization, which produces bluish to greenish-grey matrix colours, predominates.

Translocation, and/or removal of carbonate is considered as an important process in the formation of the Ochrept and Tropept suborders. They also have the most pronounced cambic horizons. Transformation, in this case the hydrolysis of weatherable minerals leading to in situ clay and sesquioxide formation, is considered as the most important process in the development of a cambic horizon.

Figure 2.4 The relative intensity of soil-weathering processes of the major suborders of Inceptisols. The relative intensities (I), although highly variable even for suborders, reflect the overall values for the class (from Foss et al., 1983).

Pedogenic Process	Suborders				
	Aquepts I-->	Ochrepts I -->	Andepts I -->	Umbrepts I -->	Tropepts I -->
Accumulation of organic matter	==>	==>	====>	=====>	==>
Removal or re- distribution of carbonates	==>	====>	====>	====>	=====>
Hydrolysis of weatherable minerals resulting in formation of clay and sesquioxides	==>	====>	====>	====>	=====>
Oxidation- reduction reactions with fluctuating or high water table	=====>	=>	=>	=>	=>

These two suborders are differentiated according to their temperature regimes. Tropepts are the Inceptisols of isothermality regimes. They have a relatively higher intensity of leaching of carbonates and/or other cations than do the Ochrepts which have ochric epipedons and occur in mesic or warmer temperature regimes.

Umbrepts are Inceptisols with mainly umbric epipedons, surface horizons with high organic matter accumulation (melanization) and low base status (<50%). Melanization is, under humid conditions, probably the predominant pedogenic process in the formation of an umbric epipedon (Soil Survey Staff, 1975).

Inceptisols developed on volcanic ash, cinders, or other vitric pyroclastic materials are classified as Andepts. They have a low bulk density ($<0.85 \text{ Mg/m}^3$) of the fine-earth fraction in the epipedon and/or cambic horizon (Buol et al., 1980).

2.5.3 Summary of Inceptisol formation

Inceptisols are immature soils that are usually developed on younger geological materials or in areas where environmental conditions are unfavorable for soil development (Foss et al., 1983). Inceptisols usually have an ochric or umbric epipedon over a cambic horizon. Leaching has been considered an important soil forming process operating in Inceptisols (Buol et al., 1980) and results in

eluviated soils (Smith, 1965). Melanization, illuviation and translocation, hydrolysis, oxidation and reduction may all operate to develop Inceptisols, but their relative intensities and importance vary quite widely. Inceptisols are distributed widely over the world, under a wide range of environmental regimes and across a complete spectrum of parent materials (Buol et al., 1980).

CHAPTER 3 LOCATION AND ANALYTICAL PROCEDURES

3.1 Site selection and description

The research site (Figure 3.1) is located 4 km north of Sun Moon Lake in central Taiwan. It is within the experimental forest managed by the Lien-Hua-Chi Research Station of the Taiwan Forestry Research Institute.

The elevation of the research area ranges from 700 to 800 meters above sea level. The bedrock (Figure 3.1) consists of Tertiary sandstones to siltstones interbedded with shales (Chung and Tsai, 1975).

The climate of this region is warm and humid. The average annual precipitation is about 2100 mm, ranging from 1100 to 3400 mm, of which 80% occurs in the May to September wet season (Koh et al., 1978). The wet season is characterized by high intensity and short duration summer rainstorms, and includes a few torrential rainfalls associated with typhoons. Maximum daily rainfalls of 600 mm, with intensities over 100 mm per hour, have been recorded in this region (Koh et al., 1978). Figure 2 presents climatic data for the research area.

The area is covered by a warm-temperate montane rain forest consisting of evergreen mixed-hardwood forest with *Cryptocarya chinensis*, *Tucheria sinkoensis*, *Engelhardtia roxburghiana* and *Helicia formosana* as the dominant overstory tree species (Liu, 1972).

Figure 3.1 Map of Lien-Hua-Chi experimental watershed showing the location and bedrock geology of pedon 2 and pedon 3. Pedon 1 is shown on the smaller scale map of the left and is located about 1.5 km north east of pedon 2 at 700m above sea level.

Figure 3.2 Climatic data for the research area: monthly mean temperature (dots); monthly mean precipitation (solid line); and monthly mean evapotranspiration (dashed line) calculated by the Penman method (Hsia and Lin, 1981 and J.Y. Hsia, unpublished data).

Within the experimental forest, three pedons, representing soils of this area, were selected for study. Pedons 2 and 3 (Figure 3.1) were formed on Tertiary dark-colored shales and sandstones, respectively, and were under natural forest vegetation. Pedon 1, developed on light-colored Tertiary siltstones, is located on a 2% slope, near a ridge top, 1.5 km north-east of pedon 2 at an elevation of 700 m above sea level. The site had been clearcut in 1976 and is currently planted with oil tea (*Camilia olerfera*).

The profile descriptions of these pedons are presented in Chapter 4.

3.2 Sampling and sample storage

Samples for general analytical analysis, bulk density determination and micromorphological studies were collected from each pedon.

Composite samples of approximately 1 kg were collected, from each 10 cm depth increment of each pedon, for general physical and chemical analysis. The air-dry samples were crushed with a rubber-tipped pestal in a ceramic mortar and were sieved through a 2 mm screen. Samples of the <2 mm fraction were labelled and stored in polyethylene bags for analysis. All data are reported on the basis of <2 mm fraction, unless otherwise specified.

A few oriented clods, up to 30 cm across and containing iron concretions, were also collected from pedon 2. These

were wrapped tightly in polyethylene bags. They were stored in a refrigerator before making thin sections.

Samples for micromorphological studies were obtained using Kubiena boxes, following the procedures outlined by Sheldrick (1984). The Kubiena boxes (7.6 cm long by 6.5 cm wide and 5.0 cm high, with open top and bottom) were made from 20 gauge galvanized steel. In the field, the box was pushed carefully, with hand pressure and/or gently with a wooden hammer, into the smooth-faced pedon to minimize the damage from stress cracks. When the front side of the box was even with the soil face, the box (with the contained soil) was carefully cut from the pedon using a sharp knife, and the soil was trimmed even with the sides of the box. Both open sides were covered with plywood lids (8.5 X 7.0 X 0.5 cm). The orientation was marked on the box and it was wrapped tightly in a polyethylene bag to prevent moisture loss, and was labeled. It was then stored in a refrigerator until thin sections were prepared. Five to six samples were collected from each pedon.

For bulk density measurement, nine to ten duplicated samples were collected from each pedon using either the core sampler method or the excavation method (Blake and Hartge, 1986). The core sampler method was used for pedon 1, which contained practically no coarse fragments throughout the profile. The excavation method was used for the other two pedons.

3.3 General laboratory analysis

The general analytical techniques used in this study followed the procedures outlined by Sheldrick (1984) unless otherwise specified. All analytical results are presented in Appendix I.

3.3.1 Bulk density

Samples for bulk density measurement were dried at 105°C for 24 hours in a forced-air oven. They were then cooled in a desiccator to room temperature and weighed to the nearest decigram. All data were reported on the basis of oven-dry weight.

3.3.2 Particle size distribution

Composite samples of the fine-earth fraction were used for particle-size distribution. Approximately 20 grams was moistened with 100 ml distilled water and treated with 30% H₂O₂ to remove organic matter. Free sesquioxides were removed by the dithionite-citrate-bicarbonate method. Soluble salts were removed by repeated centrifugation and decantation procedures. Sands were dry fractionated using a series of sieves. The silt and clay were determined by pipette analysis (Sheldrick, 1984).

3.3.3 Organic carbon content

Twenty grams of the composite samples were ground to

<100 mesh. 250 mg of ground soil were used to analyze for C content using the LECO induction furnace carbon analyser.

The results of total C, in Appendix I, are the average of duplicate samples and are reported as organic carbon content.

3.3.4 Soil reaction

Three methods of measuring soil pH were used. They were 1:1 soil:water ratio, 1:2 soil:0.01M CaCl_2 ratio and 1:2 soil:1M KCl ratio. The pH was measured using a glass electrode and a model MV60 pH-meter, manufactured by Engineered Systems and Designs.

3.3.5 Exchange acidity

A 5.0g soil sample was extracted with 1M KCl. The filtrate was titrated with standard 0.1M NaOH using phenolphthalein solution as indicator (Hunter, 1980).

3.3.6 Exchangeable cations and base saturation

Two methods were used to determine the exchangeable cations in the soil samples. They were 1M NH_4OAc buffered at pH 7.0 and 2M NaCl solution. The extracts were analyzed, using an atomic absorption spectrophotometer, for K, Ca, Mg and Al content. Sodium was determined only in the NH_4OAc extract.

The cation exchange capacity of the soil samples was

estimated by the sum of exchangeable cations plus exchange acidity (Hunter, 1980). The percent base saturation was calculated from the exchangeable cation and cation exchange capacity results.

3.3.7 Extractable Fe, Al, Mn and Si

Two reagents were used to extract different fractions of Fe, Al, Mn and Si. These were dithionite-citrate and acid ammonium oxalate solutions.

For the dithionite-citrate-extractable Fe, Al, Mn and Si determination, a 0.500 g finely ground (< 35 mesh) soil sample was shaken with sodium citrate reagent and sodium dithionite overnight. The extract was collected by centrifuging the suspension. Concentrations of Fe, Mn and Si were determined by atomic absorption spectrophotometry using an air-acetylene flame and Al was determined using a nitrous oxide-acetylene flame.

For acid ammonium oxalate-extractable Fe, Al, Mn and Si analysis, a 0.250 g soil sample (< 35 mesh) was shaken with 15 ml of extracting solution in the dark for 4 hours. Concentrations of Fe, Mn, Al and Si were determined in the same manner as those for the dithionite-citrate method.

3.3.8 Loss on ignition

Samples were oven dried (105°C) overnight, weighed and placed in a muffle furnace. They were heated slowly in the

furnance to 850°C (temperature increased about 2°C/min.) and stayed at that temperature overnight. The weight loss upon furnace ignition was used to calculate percent loss on ignition.

3.3.9 Total elemental analysis by X-ray fluorescence method

A portion of the soil sample was powdered to < 200 mesh in a stainless steel Bleuler Rotary Mill. 1.300 g of this sample was mixed with $\text{Li}_2\text{B}_4\text{O}_7$, fused and poured to form a glass pellet. Each pellet was analyzed for its major (Si, Ti, Al, Fe, Mg, Ca, Na, K, Mn, P and S) and trace (Ba, Cr, Zr, Sr, Rb, Y, Nb, Zn, Ni and V) elements by the X-ray fluorescence (XRF) method on a semi-automated Philips PW 1410 spectrometer.

Data are reported as percent oxides for the major elements and $\mu\text{g/g}$ for the trace elements (Appendix I).

3.4 Mineralogical analysis

Mineralogical analysis involved identification of minerals using X-ray diffraction (XRD) and Mossbauer spectroscopy.

3.4.1 X-ray diffraction method

The soils were prepared for X-ray diffraction analysis by fractioning the soil into various size classes and preparing glass slides of each fraction.

Clay and silt fractions were separated by a sedimentation procedure. The processes of gravity sedimentation, clay removal, and resuspension were repeated until essentially all of the clay fraction ($< 2 \mu$) had been separated from the silt fraction. The fractionated clay in suspension was flocculated by adding slightly acidified 0.5M MgCl_2 . Chloride was removed from the flocculated clay by washing with distilled water, centrifuging and decanting repeatedly until saturated AgNO_3 solution indicated complete removal. The clay fraction was then freeze-dried and stored in plastic vials. The silt fraction was oven-dried at 65°C and stored in plastic vials.

Two subsamples of the clay fraction were prepared, one Mg-saturated and the other K-saturated. Saturation by Mg and K was achieved by treating a sample of the freeze-dried clay 3 times, including one overnight treatment, either with 0.5M MgCl_2 solution or 1M KCl solution. After each treatment, the suspension was centrifuged and the supernatant was discarded. Excess salts were removed by at least 3 washings with an ethanol-water mixture until no Cl^- was detected by saturated AgNO_3 . The clay paste from the centrifuge tubes was smeared on petrographic slides using a spatula to produce a uniform thin oriented layer (Theisen and Harward, 1962). The sample was then dried at room temperature. The K-saturated sample was ready for XRD analysis at this point. The air-dried Mg-saturated sample was exposed to ethylene glycol vapor at 60°C

for 1 hour to produce a glycolated sample.

X-ray diffraction analysis was conducted using a Phillips PW 1710 automated diffractometer with Cu-K alpha radiation and a Ni filter. The Mg-saturated sample was examined in the glycolated state. The K-saturated sample was examined after air-drying or after heating to 100°C, 300°C, 550°C and 700°C.

Silt, fine to very fine sand and medium to coarse sand fractions, selected from the A, B and C horizons of each pedon, were crushed separately in an agate mortar with ethanol to produce pastes. Saprolites from each pedon were also powdered and solvated with ethanol. Each paste was smeared on a glass slide, dried at room temperature and analyzed using XRD.

3.4.2 Mössbauer spectroscopy

Mössbauer spectroscopy was used to study the Fe chemistry of the iron concretions found in pedon 2. Iron concretions collected from pedon 2 were separated mechanically into three subsamples along visible boundaries based on their morphological features (i.e. color and hardness). Each subsample was pulverized using a stainless steel Bleuler Rotary Mill. They were analyzed for their relative Fe and Al contents by XRF and the speciation of iron-containing compounds was determined by Mössbauer spectroscopy. Mössbauer spectra were obtained at RT, 80K and 12-20K, using a closed-

cycle cryostat for cooling the absorber. Hematite was observed by a characteristic six-line magnetic spectrum at RT. Goethite was magnetically ordered at 80K and below. Spectra containing both hematite and goethite were analyzed by the quantitative field distribution method (Amarasiriwardena et al., 1986). All the iron speciation reported is based on low temperature Mössbauer spectra. The Mössbauer spectroscopy was conducted by Dr. L.H. Bowen, Department of Chemistry, North Carolina State University, Raleigh, Nc, USA.

3.5 Micromorphological analysis

Soil thin sections and polished thin sections were used to study soil micromorphological features. Soil thin sections were examined under a petrographic microscope and the chemical compositions of some features in the polished thin sections were further examined with an electron microprobe.

3.5.1 Soil thin sections and polished soil thin sections

The soil block contained in the Kubiena boxes and the iron-concretion clusters were impregnated slowly with plastic solution in a desiccator under vacuum at a pressure of, approximately 66 kPa. The plastic solution was a mixture of 2000 ml acetone, 2000 ml polyester resin, 1 ml catalyst and 0.2 ml accelerator. After impregnation the plastic was allowed to harden at room temperature for one month and the

samples were then cured for two days in an oven at 50°C.

The impregnated samples were cut vertically into slabs about 1 cm thick using a large diamond saw. If the samples were found not to be well impregnated, the slabs were coated again with plastic solution and dried in an oven at 50°C overnight. The slabs were cut into slices, approximately 3.5 x 2.5 x 1 cm. One side of each slice was ground successively on 70, 45, 30 and 15 μ m diamond laps to obtain a smooth, flat surface. This surface was coated with an epoxy mixture and covered by a petrographic glass slide. After the epoxy was cured completely, the 1 cm thick mounted slice was reduced to about 0.5 mm thick by removing excess soil using a small diamond saw. This surface of each slice was ground successively on 70, 45, 30 and 15 μ m laps until the slice was about 30 μ m thick. The thickness was checked by confirming that quartz grains showed white to gray color changes under a polarizing microscope.

The surface was coated with neutral Canada balsam and covered with a clean and moisture-free cover glass. All finished thin sections were labelled and their orientation was marked. The thin sections were described according to the terminology proposed by Bullock et al. (1985). The results of thin section studies are reported in Appendix II.

3.5.2 Electron microprobe analysis

The chemical compositions of microscopic regions on the

surfaces of polished thin sections were analyzed by energy dispersive spectrometry (EDS) with a Cambridge Instruments Microscan 5 electron microprobe equipped with an Ortec Si X-ray detector. Analyzing conditions were 15 kv accelerating potential and specimen current of 10 nanoamperes measured on a pure iron standard. The electron beams were rastered over an area of up to 150 x 150 um, the area chosen depending on the purposes of the analysis.

The analyses were performed along linear traverses, which extended from the interior core to the outer layer, on polished thin sections of one discrete ovoid concretion and on several concretions from a large cluster. Similar analyses were performed on selected features on the surfaces of polished thin sections of some soil blocks collected at various depths.

Samples and standards were coated with a conductive carbon film of 20 um thickness. Spectra of samples and standards of known composition were collected and the peak values for each element were recorded. The concentration of an element on a rastered area of the sample was calculated using the formula: $C_u = P_u/P_s \times C_s$. Where C_u and C_s are the concentrations and P_u and P_s are net peak values for the element in the unknown (sample) and the standard, respectively. The reported concentrations can only be regarded as semiquantitative, due to the higher clay content, higher porosity and rougher surfaces on the sample than on the

standard (Sawhney, 1986). No matrix corrections were applied to the data.

CHAPTER 4 SOIL DEVELOPMENT AND CLASSIFICATION

4.1 Introduction

The genesis and classification of three pedons will be studied. This study involved field description of each pedon, followed by detailed laboratory examination.

The interpretation will proceed by testing the uniformity of the soil material throughout the entire profile for each pedon, followed by attempts to establish the initial state of the soil material in each horizon. As far as possible, the changes in soil properties during the course of development are evaluated quantitatively, based on the net gain or loss of certain soil constituents relative to less-weatherable reference material. From these changes, the pedogenic processes operating in the soil can be inferred. The possible predominant pedogenic processes, such as addition of organic matter, translocation of clay, transformation of sesquioxides and development of other pedofeatures will be discussed.

Each pedon is classified according to its measureable properties using the U.S. System of Soil Taxonomy (Soil Survey Staff, 1975).

4.2 Pedon 1: on stable landscape, from Tertiary fine siltstones

4.2.1 Pedon description

Classification: Typic Dystrochrept, fine, vermiculitic, thermic

Location: Lien-Hua-Chi, Nan-tou, Taiwan, Rep. of China

Physiographic position: near a ridge top, site has approximately 2% slope

Parent material: Tertiary light colored fine siltstones

Vegetation: originally warm-temperate montane rain forest. This was cut in 1976, and the site is now occupied by an oil tea (*Camelia olerifera*) plantation.

Horizon	Depth, cm	Description
A	0-15	Light yellowish brown (10YR 6/4, m) clay loam; weak to moderate fine granular and subangular blocky; friable (moist); very sticky and plastic (wet); abundant fine to coarse free growing roots; clear, smooth boundary.
Bw1	15-60	Brownish yellow (10YR 6/8, m) clay loam; moderate fine subangular blocky; firm (moist); very sticky and very plastic (wet); plentiful very fine to medium free growing roots; gradual smooth boundary.
Bw2	60-120	Brownish yellow (10YR 6/8, m) clay loam; moderate fine subangular blocky; firm (moist), very sticky and very plastic (wet); very few fine free growing roots; clear smooth boundary.
BC	120-180	Reddish yellow (7.5YR 6/8, m) clay loam; moderate fine subangular blocky; firm (moist), very sticky and very plastic (wet); very few fine free growing roots; gradual smooth boundary.
2C	180-210	Yellowish red (5YR 5/8, m) sandy clay loam with many medium yellow

(10YR 7/8, m) spots of weathered coarse shale fragments; strong fine subangular blocky; firm (moist); very sticky and very plastic (wet); clear smooth boundary.

R 210+

A lithological discontinuity of saprolitic sandstone was encountered.

4.2.2 Soil development

4.2.2.1 Test of the uniformity of soil material

The test of uniformity of parent material can be done in the field and checked with laboratory analysis. Barshad (1964) suggested several criteria for establishing uniformity of parent material. These criteria include total mineralogical analysis, particle-size distribution of resistant minerals of the nonclay fraction, ratio of two resistant minerals in a specific nonclay fraction, particle-size distribution in a specific fraction based on nonclay fraction, clay distribution with depth and the change in chemical composition of the nonclay fraction. The criteria used to test the uniformity of this pedon are the depth distribution of zirconium in the 0.25-0.05 mm sand fraction (Figure 4.1a) and potassium in the 0.25-0.05 mm sand fraction (Figure 4.1b).

During the examination of the soil profile in the field, an obvious lithological discontinuity of saprolitic sandstone was encountered at 210 cm. This lithological discontinuity was clearly evident in the depth distribution curves of Zr

Figure 4.1 Pedon 1: the depth distribution of (a) Zr and (b) K in the 0.25-0.05 mm sand fraction. The dashed line indicates assumed original index mineral trend.

and K in the 0.25-0.05 mm sand fraction (Figure 4.1a,b). Zirconium concentration (Figure 4.1a) varied very little with depth until reaching the sandstone contact, at which depth it suddenly decreased. The depth distribution of K (Figure 4.1b) showed no observable variations from the surface down to 170 cm, and then increased sharply.

These two criteria confirm the parent material in which pedon 1 has developed was relatively uniform to approximately 210 cm depth, where a discontinuity from siltstone to sandstone-derived material occurred. The higher concentration of K at 190 cm (Figure 4.1b) compared to that above suggests the existence of a zone of mixing (2C) during the process of geological deposition. Since the depth to the discontinuity is between 180 and 210 cm, it is assumed that materials below the discontinuity had very little influence on the pedogenesis of pedon 1.

4.2.2.2 Quantitative evaluation

In order to evaluate the changes of a soil during the course of its formation, it is usually necessary to establish the initial state of the soil material. With the initial state established, the changes in soil properties of each horizon (or layer) can be readily evaluated quantitatively.

The materials of lower BC horizon (140-180 cm) were selected as representative of the initial state of the soil material of this pedon. This selection was based on the

following assumptions.

1. Uniformity test. The soil materials have been interpreted as fairly uniform from the surface layer down to at least 180 cm depth (Figure 4.1a,b). Once the soil parent materials have been established as having been uniform and from one material, the least-weathered material in the profile, in this case the lower BC and upper C horizons is assumed to best represent the original state of the parent material.

2. Bulk density trend. The depth distribution of bulk density of this profile (Figure 4.2) reveals that below 100 cm depth, it increases slowly and constantly to 180 cm depth and above 80 cm it decreases sharply and consistently towards the surface. An assumed original bulk density trend of the soil material is then shown in Figure 4.2. This was determined by assuming the bulk density at depths below 160 cm changed insignificantly during the soil formation period, and that this bulk density represents the original bulk density of the soil material from which pedon 1 is derived.

Barshad (1964) stated that the bulk density of the fine-earth fraction should be used for calculation. Pedon 1 contained very few coarse fragments throughout the entire profile, and hence the bulk density as determined using the core sampler method can be treated as the bulk density of the fine earth.

3. Index minerals. The Zr has been selected as the

Figure 4.2 Pedon 1: the depth distribution of bulk density. The dashed line shows the assumed original bulk density trend.

index element which is used to calculate gains and losses, or changes of certain properties, that may occur during soil formation. Its selection is based on the fact that the concentration of this element remains practically unchanged throughout the entire pedon (Figure 4.1a).

Among many methods available for quantitative evaluation of change, the method proposed by Marshall (1941) is based on the quantitative determination of an index mineral that is resistant to weathering and is relatively immobile. This mineral must be contained in the nonclay fraction of the soil. Zirconium concentration in the fine plus very fine sand fraction, as determined with XRF in this study, is therefore taken as the index mineral for quantitative evaluation of change. The average concentration of Zr in the lower BC and upper C horizons, the assumed initial soil materials, is used for the calculations.

The procedures that are used to calculate the changes in soil weight, volume and clay content and weight changes of the mobile components of pedon 1 are illustrated in Appendix II and the results of the calculations are reported in Table II.1 of Appendix II.

4.2.2.3 Changes caused by soil development

1. Changes in horizon weights and volumes. Results of the quantitative evaluation of soil development showed that change of soil weight of each horizon is insignificant

Figure 4.3 Pedon 1: percent changes of (a) soil volume and (b) soil weight relative to that originally present.

(Figure 4.3b). There is, however, a quite substantial gain of soil volume in the A (0-20 cm) horizon and a relatively smaller but consistent gain in the Bw1 horizon (20-60 cm). The Bw2 (60-120 cm) and the BC (120-180 cm) horizons showed very little change in volume (Figure 4.3a). These volume increases in the solum are manifested in the depth- distribution of bulk density (Figure 4.2). Since there is little change in weight for each horizon, the decrease in bulk density towards the soil surface would then represent the effect of loosening by various factors during pedogenesis. The small volume increases between 120 and 180 cm (Figure 4.2) are interpreted as being caused by physical processes only and the large volume increases in the upper part of the solum are probably caused by biological factors in addition to physical processes.

The physical processes which may have slight effect on parent material loosening include rooting activity by plants, soil temperature variations, soil creep, unloading of topsoil materials (resulting from erosion) or even including earthquake activity. Other changes occurring during soil development, in terms of organic matter, clay and sesquioxides could have major effects on volume.

2. Gain of organic matter. The action of biological factors is quite evident in this pedon. The depth distribution of organic carbon (Figure 4.4) indicates that organic carbon is concentrated in the surface layer and decreases

Figure 4.4 Pedon 1: the depth distribution of organic carbon content.

rapidly with depth. The high concentration in the surface layer is typical of soils formed under forests where plant residue, dominantly leaves and twigs, falls to the surface and is subsequently mixed into the soil. The accumulation of organic matter in the soil is balanced by biocycling. Small but detectable amounts of organic carbon in the layers below the A horizon are believed to be derived partly from decayed roots and partly from organic matter translocated by animals or in suspension.

Organic components in the surface layer have been readily identified in the thin sections (Appendix III) as dark brown to black, partially-decomposed and fragmented plant tissues, mainly cell walls of roots of varying size (3-10 μm). The well-decomposed amorphous fine fraction of organic origin is well mixed into the soil matrix. In thin sections, of both the surface soil and the subsoils, it appears as isotropic brownish masses.

3. Clay movement. The depth distribution curve of the clay fraction (Figure 4.5a) shows a very slight but consistent increase of clay content with increasing depth. The quantitative evaluation data (Figure 4.5b) show that clay contents have not changed appreciably during pedogenesis, although a small decrease in clay in top 50 cm have been noted.

Thin sections from the A horizon (Appendix III) indicate very few oriented clay films (argillans) on the

Figure 4.5 Pedon 1: (a) the depth distribution of clay fraction, and (b) the percent change of clay relative to that originally present.

surfaces of mineral grains and on pore surfaces. A few mineral grains (mainly quartz) in the Bw1 (15-60 cm) and Bw2 (60-120 cm) horizons have very thin oriented clay coatings (< 10 μm) on their surfaces. More are present in the Bw2 than Bw1. The groundmass (s-matrix of Brewer) of the BC horizon (ca. 140 cm) shows a striated b-fabric. The surfaces of many mineral grains of the BC horizon are coated with oriented clay films, indicating illuviation or deposition of translocated clay, but it covers far less than the 1% of the cross section that is required for a Bt horizon (Appendix III). The clay content changes with depth and the presence of argillans give evidence of lessivage operating, although not very strongly, in this profile.

X-ray diffraction patterns for Mg-saturated and glycerol-solvated samples (Figure 4.6a-d) show very strong 1.4 nm peaks and very weak 1.0 nm peaks throughout the profile. No 1.77 nm peaks were found. The 1.4 nm peaks do not collapse to 1.0 nm upon K-treatment at room temperature although the intensities reduce slightly. Heating to 300°C causes partial collapse and to 700°C causes complete collapse to yield 1.0 nm peaks (Figure 4.6a-d). The response of the clay to these pretreatments indicates the loss of hydroxy-in erlayers during heat treatment and suggests that the major clay minerals are aluminum-interlayered vermiculites (Douglas, 1977). The absence of a 1.77 nm peak rules out the presence of montmorillonite, and the collapse

Figure 4.6 Pedon 1: X-ray diffraction patterns of the clay fraction from (a) A (10-20 cm), (b) Bw1 (40-50 cm), (c) Bw2 (90-100 cm) and (d) BC (130-140 cm) horizons (units in nm).

of the 1.4 nm peak to 1.0 nm peak rules out the presence of chlorite.

The X-ray diffraction patterns of the clay samples from the entire profile are practically identical (Figure 4.6a-d). This similarity indicates that very little transformation of clay has occurred during profile development.

4. Transformation of sesquioxides. The depth distribution curve of dithionite-citrate-extractable Fe (Fe-dc) shows a maximum concentration in the Bw2 (60-110 cm) horizon; and a minimum concentration in the lower A (10-20 cm) horizon (Figure 4.7a). The amount of oxalate-extractable Fe (Fe-o) is greatest (0.8%) near the surface, decreases gradually to 0.3 % at 50 cm and remains fairly constant for the rest of the solum. The total Fe content, as determined with XRF, changes very little with depth, although there is slight depletion in the surface horizon and slight accumulation in the B horizon relative to the C horizon (Figure 4.7a).

The Fe-dc procedure extracts microcrystalline hematite and goethite, plus amorphous inorganic Fe-oxides and organic-complexed Fe. The Fe-o procedure extracts amorphous inorganic Fe-oxides and organic-complexed Fe. The difference in the quantity of iron extracted by these two reagents is taken as the amount of microcrystalline hematite and goethite present in the soil (McKeague et al. 1971). The difference between total iron and that extracted by Fe-dc is

Figure 4.7 Pedon 1: the depth distribution of (a) total Fe, dithionite-citrate-extractable Fe (Fe-dc) and oxalate-extractable Fe (Fe-o) and (b) the percent change of dithionite-citrate-extractable Fe relative to that of originally present.

attributed to the Fe contained within the silicate minerals.

Figure 4.7a reveals that the microcrystalline Fe oxides are the major forms of iron in this pedon. Amorphous inorganic Fe and organic-complexed Fe constitutes only a small fraction of the total Fe content and is concentrated near the soil surface. The results of quantitative evaluation of changes of Fe-dc during pedon formation (Figure 4.7b) reveal that the top 40 cm loses some Fe-dc and the underlying Bw horizon gains some Fe-dc, relative to that originally present in the parent material. In absolute amount, as calculated from the quantitative evaluation method, the top 40 cm of soil material loses about 137 mg/cm^2 and the underlying 80 cm thick Bw horizon gains about 537 mg/cm^2 of Fe-dc relative to that originally present (Table II.1 of Appendix II). This implies that only about one quarter of the pedogenic Fe-dc in the Bw horizon has been translocated from the overlying surface soil and the rest, three-quarters, of the Fe-dc has formed in situ by transformation processes. These observations, together with the small amount of total Fe depleted from top 40 cm and the small increase between 40 and 120 cm relative to BC (120-180 cm) horizon, suggest that transformation of Fe exceeded translocation of Fe in this pedon.

The Bw horizons, with dithionite-citrate-extractable-iron accumulation, have a brownish yellow (10YR 6/8) colour. The brownish-yellow colored materials in the thin sections

examined under the petrographic microscope are optically amorphous and isotropic and are presumably iron oxides (Appendix III).

4.2.2.4 Soil genesis

The studied pedon has undergone relatively little pedogenic change, as judged from the very small changes of Zr, clay and total Fe content relative to the initial state, and it lacks advanced minerals in silicate clay such as kaolinite group minerals. Buol et al. (1980) suggested that all pedogenic processes may operate in the soil system to some extent but with different relative intensities. In this pedon, melanization (addition of organic matter) and loosening (increase in soil volume) would rank as the two relatively-active pedogenic processes. Braunification (transformation of iron-containing materials) is also an important process. Podzolization (translocation of organic matter and amorphous Fe and Al compounds) and lessivage (clay movement) are considered as minor pedogenic processes operating in the studied pedon.

Based on the evidence obtained, the following scenario of formation of pedon 1 soil is postulated.

Pedon 1 is originally derived from physically-disintegrated siltstone materials that contained about 35% clay, were low in bases and had a bulk density of about 1.4 Mg/m^3 . During the early stage of weathering, physical breakdown

predominated and there would have been little soil horizon differentiation, other than an accumulation of organic matter. At this stage the pedon would have an A-C horizon sequence.

As development continued, organic matter gradually became incorporated to greater depth in the soil system, through the processes of translocation and bioturbation. During this period, the bulk density of the soil materials gradually decreased, commencing from the surface and working downward. Chemical changes also occurred, in response to the warm soil temperature regime and sufficient soil moisture supply: oxidation, reduction and hydrolysis of Fe-containing minerals took place. This weathering of Fe-containing materials has produced the various forms of iron-oxide that were extracted by the d: hionite-citrate solution. As precipitation far exceeds evapotranspiration in this site, some of the Fe-ox in the surface layer may be reduced to the more-soluble ferrous state during times of saturation and translocated downward to the underlying subsoils. The oxides produced in situ by these weathering reactions and moved by translocation, have stained the soil materials, to yield reddish to brownish-yellow color, which is the major identifying characteristic of the cambic (Bw) horizon.

Lessivage, the downward movement of clay particles, is considered to be active in this soil system, but is respon-

sible for only a small amount of clay movement in the solum. The content of illuviated clay in the B horizon does not meet the requirements of an argillic horizon. This conclusion is supported by the mechanical analysis, the quantitative evaluation and the thin section studies.

This combination of soil development by transformation and translocation of Fe has produced an A-Bw-2C horizon sequence.

4.2.3 Soil classification

In Soil Taxonomy (Soil Survey Staff, 1975), soils are classified according to properties that can be precisely defined and quantitatively measured. Hence, the morphological, physical, mineralogical and chemical properties of the soil are used along with its temperature and moisture regimes to classify pedon 1. The only diagnostic horizons in Pedon 1 are an ochric epipedon and cambic horizons [Bw1 (15-60 cm) and Bw2 (60-120 cm)]. It must thus be classified as an Inceptisol at the order level.

The Inceptisol order is divided into six suborders, with wetness, mineralogy, organic matter content and temperature regime being the applied criteria. In this case of a well-drained subtropical soil, the differentiation is based on the organic matter content of the A horizon. The A or surface horizon at this site is thin (0-15 cm) and is light yellowish brown (10YR 6/4) in color and meets the criteria

of an ochric epipedon. This soil is, therefore, classified as an Ochrept at the suborder level.

The great groups of Ochrepts are differentiated on the basis of soil temperature regime and moisture regime, on the presence of a fragipan or duripan, or on the base saturation status. The studied pedon has neither a fragipan nor a duripan. It has a udic moisture regime (i.e. in most years the soil is not dry in any part for as long as 90 consecutive days). The mean annual temperature of 22°C classifies the soil temperature regime as thermic (Soil Survey Staff, 1975). These moisture and temperature regimes are not among those which are identified as bases for differentiation at the great group level. Designation is thus determined from the base saturation status of the soil. Ochrepts of humid and perhumid regions in mid-latitudes with less than 60% base saturation (NH_4OAc) in the subsoil horizons, as this pedon has, are classified as **Dystrochrepts** at the great group level.

This Dystrochrept (a) does not have a layer (>18 cm thick) in the upper 75 cm that has texture coarser than loamy fine sand, (b) does not have mottles, (c) has a content of organic carbon that decreases regularly with depth (Figure 4.5), (d) does not have a lithic contact within 50 cm of the soil surface, and (e) does not have an argillic horizon in any part of the pedon. It is therefore a **Typic Dystrochrept** at the subgroup level.

2

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

of an ochric epipedon. This soil is, therefore, classified as an Ochrept at the suborder level.

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This Dystrochrept (a) does not have a layer (>18 cm thick) in the upper 75 cm that has texture coarser than loamy fine sand, (b) does not have mottles, (c) has a content of organic carbon that decreases regularly with depth (Figure 4.5), (d) does not have a lithic contact within 50 cm of the soil surface, and (e) does not have an argillic horizon in any part of the pedon. It is therefore a **Typic Dystrochrept** at the subgroup level.

The fine earth of pedon 1 contains over 35% clay by weight, and rock fragments are <35% by volume. It is in the "Fine" particle-size class (Soil Survey Staff, 1975).

Vermiculite is the predominant clay mineral and the temperature regime is thermic. At the family level, pedon 1 is classified as a "Typic Dystrochrept, fine, vermiculitic, thermic."

4.2.4 Summary

Pedon 1, located on gently sloping terrain near a ridge top in central Taiwan, is derived from Tertiary siltstones. There was a lithological discontinuity at approximately 180 cm depth and a lithic contact to sandstone was encountered below the C horizon at 210 cm depth.

The soil is relatively immature. Only small changes in soil weight, clay content and clay mineralogy have occurred during the course of soil development. The relatively active pedogenic processes operating in the soil system are melanization (addition of organic matter) and loosening (increase in soil volume) with some indications of braunification (in situ iron transformation). Two other weakly-acting pedogenic processes are podzolization (translocation of organic matter and amorphous Fe and Al compounds) and lessivage (translocation of clay).

The genesis processes operating in this pedon have produced an ochric epipedon and a cambic horizon. This soil

is classified as a "Typic Dystrochrept, fine, vermiculitic, thermic" with an A-Bw1-Bw2-BC-2C horizon sequence.

4.3 Pedon 2: on steeply sloping terrain from Tertiary shales

4.3.1 Pedon description

Classification : Typic Dystrochrept, fine, illitic, thermic
Location : Lien-Hua-Chi experimental watershed No. 3, Nan-Tou, Taiwan

Physiographic position : on 60% slope, facing east

Parent material : Tertiary shales

Drainage class : moderately well drained

Vegetation : mixed evergreen hardwoods

Horizon	Depth, cm	Description
A11	0-10	Yellowish brown (10YR 5/6, m) silty clay; moderate fine subangular blocky; friable (moist); sticky and plastic (wet); abundant fine to coarse free growing roots; clear smooth boundary.
A12	10-30	Yellowish brown (10YR 5/6, m) silty clay; moderate fine subangular blocky; friable (moist); slightly sticky and slightly plastic (wet); plentiful fine to coarse (ca. 4 mm in diameter) free growing roots; gradual smooth boundary.
Bw	30-60	Yellowish brown (10YR 5/8, m) silty clay with fine to medium few distinct reddish yellow (7.5YR 6/6, m) and brown (7.5YR 5/2, m) mottles; friable (moist), sticky and plastic (wet); few fine free growing roots; hard concretions (up to 40 cm across) distributed discontinuously; gradual, smooth boundary.
BC	60-100	Reddish yellow (10YR 6/6, m) shaly silty clay loam; moderate fine subangular blocky; friable (moist); sticky and plastic (moist); hard

		concretions (up to 25 cm across) distributed discontinuously; clear wavy boundary.
C	100-150	Light yellowish brown (10YR 6/4, m) shaly silty clay loam; moderate fine subangular blocky; friable (moist), sticky and plastic (wet); few fine free growing-roots; clear smooth boundary.
2C	150-210	Yellowish brown (10YR 5/6, m) shaly to flaggy clay loam with fine to medium common faint (10YR 3/6, m) to distinct (7.5YR 5/8, m) mottles; firm (moist), sticky and plastic (wet); moderate medium subangular blocky to massive; roots absent.

4.3.2 Soil development

4.3.2.1 Test of the uniformity of soil material

The criteria used to test the uniformity of pedon 2 are identical to those for pedon 1. They are depth distribution curves of Zr in the 0.25-0.05 mm sand fraction (Figure 4.8a) and of K in the 0.25-0.05 mm sand fraction (Figure 4.8b).

Zr concentration only varied a small amount from the surface to a depth of 110 cm, increased gradually to 150 cm depth and decreased slightly thereafter (Figure 4.8a). This is interpreted to indicate the presence of a lithological discontinuity at 110-130 cm depth below the surface. The pattern of K distribution is quite similar to the Zr distribution, except for a slight peak in K concentration at 50 cm depth. The K distribution supports the interpretation

Figure 4.8 Pedon 2: the depth distribution of (a) Zr and (b) K in the 0.25-0.05 mm sand fraction.

of a possible change of parent material at approximately at 110-130 cm depth. The local peak in K concentration at 50 cm depth mirrors a small change in Zr. Neither have obvious explanations, but the returning of K and Zr concentrations below 60 cm to what they were at 30 cm suggests these materials are similar, even if there is a small aberration between them. The weak peaks at 50 cm may be interpreted as a thin layer that is different, with what is above and below it being similar. Both the Zr and K profiles suggest that the solum of pedon 2 has not been developed in a uniform parent material. This change in lithology complicates quantitative evaluation of the changes that have been taken place during the course of soil development.

The presence of iron concretions and their fragments in the solum provides further complications for quantitative evaluation. The size (up to 30 cm across) and distribution of the concretionary bodies in the soil pedon made it impossible to collect representative samples for bulk density determination. Because reliable determinations of bulk density are required for quantitative evaluation of changes, the calculations could not be performed for pedon 2.

4.3.2.2 Soil genesis

When examining the pedon 2 soil profile in the field, some features were particularly obvious. These included: the relatively uniform yellowish-brown color of the soil matrix throughout the entire pedon; prominent hard iron concretion clusters, particularly between 30 and 110 cm depth; and shaly fragments below 100 cm depth.

The description, properties and genesis of the iron concretions will be treated in detail in Chapter 5. Other pedofeatures related to soil development will be discussed here.

1. Accumulation of organic matter (melanization). The depth distribution of organic carbon (Figure 4.9c) illustrates that the organic material concentrates in the surface and decreases rapidly with depth. This distribution is supported by field observation of plant root distribution in the profile (refer to 4.3.1 Pedon description) and thin sections studies (Appendix III). There were abundant and plentiful fine to coarse living plant roots in the A11 and A12 horizons, respectively. In the underlying Bw horizon, only few fine roots were found and roots were virtually absent below the Bw horizon at 60 cm depth.

Cross and longitudinal sections of living roots are easily identified in thin section studies and other organic residues, at various stages of decomposition are readily observed as dark brown (PPL) isotropic masses in the matrix

Figure 4.9 Pedon 2: the depth distribution of (a) soil reaction, (b) base saturation and contents of (c) organic carbon and (d) clay.

of the surface soil horizon. Dark brown coalesced dense isotropic materials (probably animal droppings) were also evident in these thin sections.

The high concentration of organic matter in the surface horizon and the abrupt decrease in organic matter content with depth may be partly explained by some physical properties of the soil. Tensiometer readings of the site indicate that the subsoil (60-120 cm) is nearly saturated with water during the wet season (from late April to September). The water content of the subsoil is routinely above the field capacity and the matric potential rarely exceeds -800 mb even during the dry season (from October to the following early April) (F.W. Horng, unpublished data). The alternation of wet and dry seasons affects the aeration conditions of the soil, and consequently the growth and die back of the fine roots in the alternately unsaturated and saturated zones. Other physical factors, such as the high bulk density of the subsoils may impede root penetration to some extent.

2. Transformation and translocation of soil materials.

Clay The depth distribution of clay (Figure 4.9d) shows a decrease with depth and provides no evidence of secondary clay enrichment in the solum. It is believed that the wide variations in clay content among layers reflect the nature of the sedimentary parent materials. Variable quantities of iron concretion fragments in each layer may

affect clay content determinations. The iron concretion fragments in the sample are very difficult to separate into primary particles, even with application of both chemical (dithionite-bicarbonate) and physical (ultrasonic vibration dispersion) treatments. Consequently, the clay particles that are cemented in iron concretion fragments may be counted in other larger particle size classes.

Although the depth distribution curve does not provide evidence of clay movement in the solum, the thin section studies reveal that some clay particles have been translocated and deposited in void spaces within the iron concretion clusters (Chapter 5). This movement of clay, however, could be quite local.

The mineralogy of the clay fraction is essentially uniform throughout the entire pedon. The X-ray diffraction patterns are characterized by two intense peaks at 1.0 and 0.33 nm, weaker peaks at 0.50 and 0.20 nm and a very weak peak at 0.25 nm (Figure 4.10a-d). The slightly broadened peak at 1.0 nm for the Mg-saturated glycol-solvated specimen at 25°C is reduced to a narrow and sharp peak upon heat treatment, indicating that hydromuscovite is present. The hydromuscovite is believed to derive from the parent material since it was also detected in silt, fine sand and medium to coarse sand fractions. Several very soft green-colored, medium sand-sized single grains were hand-picked and analyzed by EDXRA. Results, presented in Table 4.1,

Figure 4.10 Pedon 2: X-ray diffraction patterns of the clay fraction with various treatments from (a) A (10-20 cm), (b) Bw1 (40-50 cm), (c) Bw2 (90-100 cm) and (d) BC (130-140 cm) horizons (units in nm).

Table 4.1 EDXRA result showing some sand-sized single grains are hydromucovite minerals in pedon 2. Results of other two analyses from reported literature (Deer et al., 1972; Weave and pollard, 1973) are also included for comparisons.

oxide weight, %		structural formular**			
Pedon 2*	Weave and Pollard, 1973	Deer et al. 1972	Pedon 2	Weave and Pollard, 1973	Deer et al. 1972
SiO ₂	54.38±0.50	46.54	Si	3.57	3.00
TiO ₂	0.07±0.02	0.17	Al	0.43	1.00
Al ₂ O ₃	26.98±0.93	36.37	Al ³⁺	1.61	1.77
Fe ₂ O ₃	-	0.72	Fe ²⁺	0.08	0.04
FeO	4.33±0.18	0.36	Fe ²⁺	0.11	0.02
MgO	3.07±0.05	0.50	Mg	0.20	0.05
CaO	0.23±0.05	0.22	Ca	0.07	0.01
Na ₂ O	0.28±0.10	0.46	Na	0.03	0.06
K ₂ O	7.17±0.13	8.06	K	0.58	0.67

* averages and standard deviations of 6 determinations of 3 single grains.

** structural formular is calculated based on O₁₀(OH)₂.

show that the 1.0 nm mineral of the studied soil samples was very similar to the hydromuscovite reported by Weaver and Pollard (1973) but contained lower Al_2O_3 , and higher SiO_2 , FeO and MgO than the hydromuscovite (Table 4.1) reported by Deer et al. (1972). The hydromuscovite in this soil has more isomorphic substitution of Al by Fe and Mg ions and less substitution of Si by Al than that reported by Deer et al. (1972).

It is concluded, from the uniformity of the clay mineralogy within this soil profile, that the quantity of pedogenic aluminosilicate clay minerals in this soil is below the detection limit. It is of interest to note quartz was detected in the silt and coarser fractions but not in the clay fraction.

Sesquioxides The depth distribution patterns of total iron and dithionite-citrate- and oxalate-extractable sesquioxides are shown in Figure 4.11. These determinations were made on the fine-earth fraction of soil samples. These fractions excluded iron concretions but did include varying amounts of concretion fragments which were less than 2 mm in size. Most of the Fe in these concretion fragments is not extractable by dithionite-citrate.

The quantities of amorphous inorganic and organic-complexed Fe, extracted by oxalate, are low (0.5% at surface horizon) and decrease gradually (to 0.1% at 180 cm) with depth. This distribution suggests some weathering of iron-

Figure 4.11 Pedon 2: the depth distribution of total, dithionite-citrate- and oxalate-extractable Fe. The shaded areas indicate the difference in amount of Fe that was extracted by dithionite-citrate and oxalate solutions.

bearing minerals throughout the zone where oxalate-extractable iron is above 0.1%.

The total Fe contents are relatively low (ca. 3%) in the A horizon (0-30 cm), increase rapidly (to about 4.5%) in Bw (30-60 cm) and BC (60-100 cm) horizons, and then decrease gradually (to about 3.3%) at 150 cm depth. The low total Fe content in the A horizon and its increase in the Bw and BC horizons suggest Fe mobilization in the A horizon and its downward movement and accumulation in the Bw and BC horizons.

It is, however, interesting to note that, although the Bw and BC horizons contain nearly equal amounts of total Fe, the Bw horizon contains significantly more non-extractable and less microcrystalline Fe-oxides than the BC horizon (Figure 4.11a). These differences in distribution of microcrystalline Fe-oxides can be explained by the formation and decomposition of the iron concretions in this soil. The detailed genesis and life cycle of the iron concretions will be presented in the Chapter 5, but a brief discussion on horizon differentiation and their role in it is given here.

The different quantities of microcrystalline Fe-oxides and non-extractable Fe in the fine-earth fraction of the Bw and BC horizons may be related to the quantity and solubility of iron concretion fragments in the respective horizons.

Firstly, the quantity factor: investigation of thin

sections shows that the Bw and the BC horizons contain about 15 and 5% iron concretion fragments, respectively, in the size range that is easily visible to the naked eye. The percentages of less than 2 mm-sized fragments in each horizon are believed comparable to the easily visible ones. These fragments contain 19.3% Fe compared to only 3% Fe in the adjacent soil matrix (Table 5.2c). This implies that the higher the percentages of iron concretion fragments in the soil matrix the higher the Fe content.

Secondly, the solubility factor: the proportion of the Fe present that can be extracted by a solution is dependent upon the methods of extraction employed. The solubility of Fe-oxides, especially the aged fractions (Lindsay, 1979), is low. The insoluble amounts, not removed by the single extraction of the samples, are grouped into the nonextractable fraction. This also implies that the higher the percentages of iron concretion fragments in the sample (in this case, in the Bw horizon) the greater the amount of nonextractable Fe that sample has.

Furthermore, the Fe released from iron concretions and their fragments in the Bw horizon (30-60 cm) upon weathering may be either reoxidized and precipitated in situ, contributing to the cambic horizon formation or, more likely moved downward and precipitated in the underlying BC horizon. The Fe "freshly" translocated from the Bw and precipitated in the BC horizon would be expected to be more readily

extractable than that of the still existing Fe concretion fragments in the Bw horizon. Thus, the downward translocated Fe may explain the higher amounts of dithionite-citrate-extractable Fe in the BC than in the overlying Bw horizon.

Other interesting features to note are the equal amounts of microcrystalline Fe and the different amounts of non-extractable Fe in the A and Bw horizons. These suggests that non-extractable Fe is being lost from the A horizon and taken to the BC horizon. This seems strange since the non-extractable Fe should be the least mobile form. It could be that the microcrystalline iron is being mobilized from A and the non-extractable iron is gradually becoming more easily extracted from the A, so some of both the "microcrystalline" and the "non-extractable" are being translocated to the BC. The non-extractable fraction in the Bw may not yet be being as much mobilized.

In summary, horizon differentiation in pedon 2 has resulted predominantly from melanization (formation of A11 and A12 horizons) and braunification (formation of a cambic horizon) and, to a less extent, translocation of Fe (from A to Bw and to BC horizons). The only evidence of clay movement is some clay skins in the voids within iron concretions clusters.

4.3.3 Soil classification

Pedon 2 is a mineral soil that does not have any diagnostic subsurface horizons other than a cambic horizon, between 30 and 60 cm. It is, therefore, an Inceptisol at the order level according to the criteria of Soil Taxonomy (Soil Survey Staff, 1987).

The surface horizon or epipedon is a well-drained mineral horizon developed under forest cover and a thermic temperature regime. It qualifies as an ochric epipedon and the pedon is accordingly classified as an Ochrept at the suborder level.

The Ochrepts can be differentiated on the basis of soil moisture and temperature regimes, the presence of a fragipan or duripan, or base saturation status. Pedon 2, as with Pedon 1, is differentiated on the basis that its base saturation (neutral NH_4OAc method) is <60%. At great group and subgroup level, Pedon 2 classified as a Typic Dystrochrept.

The fine earth fraction of the pedon 2 contains over 35% clay by weight, and the coarse fragments are less than 35% by volume. It is in the "Fine" particle-size class (Soil Survey Staff, 1975). It developed under a thermic soil temperature regime and has hydromuscovite as the predominant mineral in the clay fraction. At the family level, pedon 2 is classified as a "Typic Dystrochrept, fine, illitic, thermic".

4.3.4 Summary

Pedon 2 is derived from Tertiary shale, on a steep terrain subject to rapid surface erosion. The soil profile is relatively young and characterized by a weak cambic B horizon.

There is an indication of lithological discontinuity or transition at 110 cm depth. The mineralogy of the clay fraction and micromorphological features, however, reveal that the soil materials above and below 110 cm depth must have originated from similar sources.

The predominant pedogenic processes are accumulation of organic matter in the surface, transformation of Fe-containing compounds to form a weak cambic horizon, and redistribution and local concentration of Fe to produce iron concretions. The iron concretions are thought to be pedogenic in origin and will be discussed in greater detail in the next chapter.

Pedon 2 is classified as a "Typic Dystrochrept, fine, illitic, thermic" with an A-Bw-BC-2C horizon sequence.

4.4 Pedon 3: on steeply sloping terrain from Tertiary sandstone

4.4.1 Pedon description

Classification : Typic Hapludult, fine-loamy, siliceous, thermic

Location : Lien-Hua-Chi experimental watershed No. 3, Nan Tou, Taiwan

Physiographic position : on 69% slope facing south

Parent material : Tertiary sandstone

Drainage class : well-drained

vegetation : mixed evergreen hardwoods

Horizon	Depth, cm	Description
A1	0-10	Yellowish brown (10YR 5/4, m) sandy loam; moderate fine granular to subangular blocky; friable (moist), sticky and plastic (wet); abundant fine to coarse free growing roots; clear smooth boundary.
E1	10-25	Yellowish brown (10YR 5/8, m) sandy loam; weak, fine subangular blocky; friable (moist), sticky and plastic (wet); abundant fine to medium free growing roots; gradual smooth boundary.
E2	25-40	Brownish yellow (10YR 6/8, m) sandy loam; weak subangular blocky; friable (moist), very sticky and very plastic (wet); plentiful, fine to medium free growing roots; gradual smooth boundary.
E/B	40-60	Brownish yellow (10YR 6/8, m) gravelly sandy loam; weak subangular blocky; friable (moist), sticky and plastic (wet); plentiful fine to coarse free growing roots; clear smooth boundary.
2Bt	60-90	Strong brown (7.5YR 5/8, m) subrounded gravelly to cobbly sandy loam; weak subangular blocky; firm (moist), sticky and very plastic (wet); few fine to medium distorted roots; gradual smooth boundary.
3BC	90-120	Strong brown (7.5YR 5/8, m) subangular gravelly to cobbly sandy loam with distinct few fine yellow (10YR 7/6, m) mottles; massive; firm (moist), sticky and plastic (wet); clear smooth boundary.
3C1	120-160	Reddish yellow (7.5YR 6/6, m) subrounded gravelly to cobbly sandy loam; firm (moist), slightly sticky

		and slightly plastic (wet); roots absent; diffuse smooth boundary.
3C2	160 +	Brownish yellow (7.5YR 6/8, m) cobbly sandy loam; very firm (moist); sticky and plastic (wet); massive.

4.4.2 Soil development

4.4.2.1 Test of the uniformity of soil material

The criteria used to test the uniformity of pedon 3 soil material are the depth distribution curves of Zr and K in the 0.25-0.05 mm sand fraction (Figure 4.12a,b)

The Zr concentration with depth (Figure 4.12a) shows a small variation in the top 60 cm, decreases rapidly between 60 and 100 cm and remains relatively unchanged below 100 cm depth. The obvious changes at 60 and 100 cm depth are taken as possible lithological discontinuities.

The K concentrations change very little in the top 60 cm, maximize between 60 and 100 cm depth and drop, to the same level as those of the top 60 cm, at 100 cm depth, and remain relatively unchanged thereafter (Figure 4.12b). This depth distribution supports the Zr results and together they indicate the existence of two lithological discontinuities, one at 60 cm depth and the other at 100 cm depth, and hence of three different parent materials.

The bulk densities of fine earth between 60 and 100 cm depth (Figure 4.13) are lower than above and below this zone. The bulk density distribution curve adds further

Figure 4.12 Pedon 3: the depth distribution of (a) Zr and (b) K in the 0.25-0.05 mm sand fraction.

Figure 4.13 Pedon 3: the depth distribution of total and fine earth bulk densities.

evidence of possible lithological discontinuities, at 60 and 100 cm depth in pedon 3. The presence of these lithological discontinuities eliminates the possibility of undertaking a quantitative evaluation of the changes that have been taken place during soil formation, because it is not possible to establish the initial state of the top two deposits of soil materials, which have undergone relatively intensive weathering. The genesis of pedon 3 will be discussed according to its physical, chemical, biological, mineralogical and morphological properties.

4.4.2.2 Soil genesis

Pedon 3 has lithological discontinuities at approximately 60 and 100 cm depth from soil surface. The materials, starting from the surface down, are designated as material I (0-60 cm), material II (60-100 cm) and material III (100-180 cm) for the convenience of discussion.

1. Accumulation of organic matter (Melanization). The content of organic carbon is 1.5% in the surface (0-10 cm) horizon, decreases rapidly to about 0.5% at 30 cm depth and is approximately constant at 0.3-0.2% for the rest of the profile (Figure 4.14c). The apparent reasons are similar to those for the pedon 1 soil which has been discussed in the section 4.2.2.3. High rates of accumulation and decomposition of forest litterfall are usually characteristic of subtropical forests (Bazilevich and Rodin, 1966). The

accumulation on the surface, relatively rapid decomposition and slow biological mixing probably are responsible for maintaining high organic matter contents only in the surface horizon (0-20 cm). Horng et al. (1986) estimated the biomass accumulation of the studied site and reported that the forest floors accumulated about 7 tons/ha/yr of organic matter. This accumulation is close to the average for forest floor in tropical forests (Cole and Johnson, 1978).

In the thin section studies (Appendix III) organic matter was readily observed as conspicuous plant residues of living or partially-decomposed roots in the A (0-20 cm) horizon and as isotropic dark brown masses in the matrix of the surface and subsoil horizons.

2. Bulk density changes. The depth distribution of bulk density, with and without included coarse fragments (>2mm particles), are shown in Figure 4.13. The bulk densities with coarse fragments included are referred to as total bulk densities and those excluding coarse fragments are referred to as fine-earth bulk densities. The differences in these bulk densities reflect the contents of coarse fragments in the sample.

The depth distribution curves of total and fine-earth bulk densities in material III (100-180 cm depth) increase linearly with depth and are essentially parallel to each other. This indicates that the amount of coarse fragments does not vary significantly between 100 and 180 cm depth.

It is also interesting to note that between 100 and 140 cm, the depth distribution curves of clay content (Figure 4.14) and dithionite-citrate-extractable Fe content (Figure 4.15) are similar to those of total and fine-earth bulk densities distributions. This could suggest that material III has rather uniform composition and weathering of the whole material has proceeded in a similar manner. The distributions of mobile components, clay and Fe, provide evidence that no movement and accumulation have occurred in material III. Loosening or physical weathering of saprolitic materials, may be the only pedogenic process operating to a significant extent in soil material III.

The total bulk density of material II (60-100 cm depth) remains essentially constant with depth, but the fine bulk density increases towards the surface (Figure 4.13). This implies that the quantities of coarse fragments decrease and the fine-earth materials increase towards the soil surface. The lower total bulk density implies that the weathering of soil material II has been more intensive than for the underlying material III, and the increasing of fine-earth towards the surface may imply more intense weathering in its upper parts. The 60-100 cm depth zone also corresponds with the maximum clay content (Figure 4.14d), and maximum total Fe and dithionite-citrate-extractable Fe contents (Figure 4.15a) in the pedon. The greater clay content in this depth range (Figure 4.14d) undoubtedly explains part of the

Figure 4.14 Pedon 3: the depth distribution of (a) soil reaction, (b) base saturation, (c) organic carbon and (d) total clay content.

Figure 4.15 Pedon 3: the depth distribution of total Fe, dithionite-citrate- and oxalate-extractable Fe and Al from soil samples of fine earth fraction.

increase in fine-earth bulk density. The clay content profile supports the downward movement of clay by lessivage. This is further supported by thin section investigations (discussed later).

The top 30 cm of surficial soil material I (0-60 cm) has no coarse fragments and hence the magnitudes of the total and fine-earth bulk densities (Figure 4.13) are identical. The absence of coarse fragments indicates that intensive weathering has occurred. Between 30 and 60 cm depth the total bulk density continues to increase with depth, with coarse fragments being present but the fine-earth bulk density remains essentially constant.

3. Clay movement (lessivage). The depth distribution of clay indicates that the clay contents are low (ca. 15%) in the surface, increase approximately linearly with depth, to a maximum (ca. 24%) at 70 cm depth and decrease thereafter until approximately 120 cm depth (Figure 4.14d). Although there were lithological discontinuities at 60 and 100 cm, the smooth total clay content curve (Figure 4.14d) suggested the increased clay between 40-180 cm was mostly likely translocated (lessivage) from the A and E to the Bt horizon.

The occurrence of lessivage is also supported by thin section studies (Appendix III). Clay films (>1% of the area and <50 μm thick) were not observed in thin sections until 35 cm depth. The quantities and the thickness of clay films

increased with depth. Clay films occupied about 5% of the cross-sectional area and were up to 250 μm thick in the thin section from 55 cm depth. The most abundant and the thickest clay films (argillans) were recorded in the samples collected about 70 cm depth, in the Bt horizon.

The maximum accumulations of clay content occur between the 70-80 cm depth (Figure 4.14d). The location for maximum clay deposition may be explained by the mechanisms of water movement, distribution and depletion within the soil profile. During wet seasons, some clay may become suspended in the soil solution and is carried down with the percolating water. The clay will be removed from suspension either when it is filtered out in a zone of low hydraulic conductivity or when the water slows or ceases its downward movement. In pedon 3, the higher bulk density (Figure 4.13), firmer consistence, massive structure, and presence of mottles (section 4.4.1) below 90 cm, is suggestive of lower hydraulic conductivity and slower water movement than in the soil above. Suspended clay should be precipitated somewhat above this level and hence the maximum accumulation between 70 and 80 cm depth.

The X-ray diffraction analysis (Figure 4.16) shows that hydromica is the main clay mineral for all layers of the soil and that kaolinite and smectite were not detectable in the clay fraction. This leads to the conclusions that these three lithological different materials originated from

Figure 4.16 Pedon 3: X-ray diffraction patterns of the clay fraction with various treatments from (a) A (0-10 cm), (b) 2Bt (70-80 cm), (c) 3C1 (130-140 cm) and 3C2 (160-180 cm) horizons (units in nm).

similar mineralogical sources but with different modes of deposition and that transformations of clay have not occurred at detectable level.

4. Translocation of sesquioxides (eluviation and illuviation). The depth distribution curves of total, dithionite-citrate- and oxalate-extractable sesquioxides in pedon 3 are shown in Figure 4.15. Total and dithionite-citrate-extractable Fe are depleted in the A and E horizons (0-60 cm) and have accumulated in the underlying Bt horizon (60-90 cm). This distribution pattern strongly suggests downward movement of Fe occurring in this soil. The Fe redistribution in the pedon 3 is not reflected by the dithionite-citrate-extractable Al (Figure 4.15b). The report of Miller (1983) that Fe may be translocated as independent finely-divided Fe-oxides in nearly all Ultisols developed in siliceous parent materials, and that this process may be one of the major factors in the genesis of A and E horizons low in Fe content, may explain the Fe distribution in this pedon. The relatively-higher total Al content between 60 and 100 cm depth (Figure 4.15b), which corresponds with the Bt horizon, is interpreted to result from the illuviated clay content (Figure 4.14d).

In summary, factors influencing the formation of pedon 3 are the humid and warm subtropical climate, vigorous growth of evergreen mixed-hardwood forest and the presence of two lithological discontinuities in siliceous sandy

parent materials. The pedogenic processes operating on pedon 3 are melanization, lessivage and translocation (eluviation and illuviation) of iron oxides, which have led to an A-E-2Bt-3C horizon sequence.

4.4.3 Soil classification

Pedon 3 is a mineral soil that has a thermic temperature regime and has an argillic horizon but not a fragipan. It has base saturation (by sum of cations) less than 35% at all depths (Figure 4.13b). It, therefore, meets the requirements of an Ultisol at the order level (Soil Survey Staff, 1987).

The Ultisol order is subdivided into five suborders, using criteria of profile wetness and organic matter content (Buol et al., 1980). Pedon 3 has a udic soil moisture regime (Figure 3.2) with fully drained characteristics. It is then classified as a Udult at the suborder level (Soil Survey Staff, 1987).

The Udult suborder is subdivided into 7 great groups, according to the presence of diagnostic subsurface horizons, their properties and clay activity. This Udult has neither plinthite nor fragipan. It does not have the sharp change in clay content required for a kandic horizon nor does it meet the color requirements of the Rhodudults. This Udult classifies as a Hapludult at the great group level (Soil Survey Staff, 1987).

This Hapludult has an argillic horizon 30 cm thick,

a solum more than 50 cm thick and texture finer than loamy fine sand in the argillic horizon. It does not form cracks and has a continuous argillic horizon throughout the pedon, not interrupted by ledges of bedrock. It is, therefore, classified as a Typic Hapludult at the subgroup level.

The texture of the fine earth is sandy loam and the amount of clay is <35%. The pedon contains 15% or more, by weight, of particles that are coarser than fine sand and is in the "fine loamy" particle-size class. Pedon 3 developed from sandstones and is "siliceous" in nature and under a "thermic" soil temperature regime.

Pedon 3 classifies as a "Typic Hapludult, fine-loamy, siliceous, thermic".

4.4.4 Summary

Pedon 3 is derived from Tertiary sandstones on a steep terrain under a mixed hardwoods about 120 m north of pedon 2.

The soil has two major lithological discontinuities at 60 and 100 cm below the soil surface. The soil materials are thought to have originated from similar mineralogical sources. Major pedogenic processes that have operated in the soil are melanization, lessivage and translocation of Fe-oxides. These processes have led to the formation of an ochric epipedon and an argillic B horizon. Pedon 3 is formed under similar soil climate to that of shale-derived pedon 2 but has developed on a siliceous sandstone. It classifies

as a "Typic Halpudult fine-loamy, siliceous, thermic" (Soil Survey Staff, 1987).

CHAPTER 5 IRON CONCRETIONS

5.1 Introduction

Concretions are defined as "hardened local concentrations of certain chemical compounds that form indurated grains or nodules of various sizes, shapes and colors" (Soil Survey Staff, 1951). The concretions which are investigated in this study, consist of a soft, uncemented core which is surrounded by layers indurated by iron compounds. They are most commonly cemented together in clusters, but individual concretions are found also.

Hardened local concentrations of iron compounds are relatively common in soils. In ortstein or podzolic B horizons (spodic horizon), iron accumulation is characteristic and may have a cementing function, although Wang et al. (1978) concluded that Al-organic matter complexes appear to be the dominant cementing material in ortstein soils of the Maritime Provinces of Canada. Placic horizons are also cemented by iron compounds (Soil Survey Staff, 1975; Canada Soil Survey Committee, 1978; De Coninck and McKeague, 1985). An extensive iron-rich material in soils is plinthite which is characterized as being "an iron-rich, humus-poor mixture of clay with quartz and other diluents. It commonly occurs as dark red mottles, which usually are in platy, polygonal or reticulate patterns" (Soil Survey Staff, 1975). Plinthite will irreversibly harden, when exposed to repeated

wetting and drying, through the formation of a rigid network of hematite and goethite crystals that cement the material together (Birkeland, 1984).

The concretions found in the Typic Dystrochrept (Pedon 2) and studied in this investigation bear no similarity to ortsteins or placic horizons and are also dissimilar to the normal descriptions of plinthite or ironstone. They are unlike iron-rich concretions from North Carolina, U.S.A., or from Brasilia, Brazil and are morphologically different from several examples of plinthite seen in Ultisols in the U.S. southeast (J.K. Torrance, personal communication, 1986). No references to similar concretions have been found in the soil science literature. An attempt has been made to examine the macromorphology, micromorphology, chemistry and mineralogy of these concretions and to develop a hypothesis as to their genesis and "life-cycle".

5.2 Results and discussion

5.2.1 Macromorphology

The concretions defined in the U.S.D.A. Soil Survey Manual (Soil Survey Staff, 1951) include all units, embedded in the soil materials, recognizable from adjacent material by a difference in concentration in one or more components. "Concretion" as defined by Brewer (1964) is restricted to those structures with a concentric fabric about a center, which may be a point, a line or a plane.

The iron concretions in Pedon 2, developed in Tertiary shale, are distributed discontinuously, either singly or in clusters, between approximately 30 and 110 cm depth. The most intact and strongly developed concretions occur between approximately 50 and 70 cm depth. Some discrete concretionary bodies are present (the largest observed being about 4 cm across), but most commonly they occur as clusters of concretions, solidly joined together, up to 30 cm across.

Cross-sections of concretion clusters (Figure 5.1) reveal that various-sized individual concretions form a polygonal network structure. While the concretions are rigidly held together at several locations, they have well-defined boundaries and, over most of their surface, are separated from neighbouring concretions by voids.

An individual concretion in a cluster of concretions has a crust or shell and is subround to subangular blocky in shape. The well-developed crusts are dark reddish brown (5YR 2.5/2) to dark brown (7.5YR 3/2) in color, indurated to a hardness of 4 to 5 on Mohs' scale and may be up to 3 mm thick. The shell envelopes a soft (hardness <2) gray (10YR 6/1) matrix which is, in most cases, slightly and unevenly stained with various hues typical of low concentrations of iron oxides. This soft grayish core is morphologically similar to the sapolite (shale parent material) at 150 to 300 cm depth. The narrow spaces (usually < 1 mm wide)

Figure 5.1 Sectional view of a concretion cluster showing polygonal network structure, gray soft core rimmed by dark hard crust. The units of each individual cluster are separated by voids over most of their surface.

between the hard shells of neighbouring concretions in the clusters are, in some cases, infilled with yellowish to reddish materials rich in iron oxides.

A discrete ovoid concretion (5 cm long and 3 cm diameter, slightly flattened on one side) was collected for detailed investigation. This concretion is macromorphologically similar, except somewhat different in shape, to the individual units in the clusters. In cross-section (Figure 5.2), this concretion is revealed to consist of three essentially concentric zones: a gray (N 5) fine-textured core, that is very soft (about 1 Mohs); a dark reddish-brown (7.5YR 3/3) inner layer, about 3 mm thick and very hard, which is the equivalent of the well-developed crust of individual concretions in clusters; and a reddish-yellow (7.5YR 6/6) outer layer, which graded gradually into the surrounding soil matrix and appears similar to the yellowish and reddish material which filled some of the spaces between the concretions in clusters.

The concretions studied, whether as discrete bodies or as clusters are macromorphologically different from concretions reported in the literature (Winters, 1938; Brewer, 1964; Gallaher et al., 1973; Ojanuga and Lee, 1973; Childs, 1975; Schwertmann and Fanning, 1976; Childs and Leslie, 1977; Sidhu et al., 1977; Arshad and St. Arnaud, 1980; Amouric et al., 1986).

Most of the reported concretions were found in the soil

Figure 5.2 Sectional view of a portion of a discrete ovoid concretion showing distinct concentric structure with a gray soft interior surrounded by iron-rich inner and outer layers.

profiles as individual units and the boundaries between the concentric layers or zones in the concretions were not as abrupt as those found in this study. Gallaher et al. (1973) found some concretions that had a strong brown (7.5YR 5/6) surface coating about 1 mm thick, encasing a very dark gray (7.5YR 3/0) core about 6 mm across. But those concretions were soft, with a hardness of <2 on Mohs' scale. They were also much smaller in size (ca. 6-8 mm across) than the individual concretions in pedon 2.

Very few studies have described concretions that are solidly joined together to form large clusters. Amouric et al. (1986) investigated some concretion clusters in Western Senegal. Their largest individual concretions, which were about 4 mm across, consisted of hematite-rich purple-red cores rimmed by goethite-rich crusts which were cemented tightly by materials similar to the core. The clusters of concretions averaged about 1-2 cm. Individual concretions, iron-rich throughout, from the southwestern upland of Nigeria were up to 30 mm across but did not form cemented clusters (Ojanuga and Lee, 1973).

Since these concretions are unlike any previously described in soils, King et al. (1990) have proposed that they be called "shell concretions".

5.2.2 Changes in concretion morphology with depth

Thin sections from oriented soil blocks and from sapro-

lite were examined to investigate the nature of the concretions at different depths. It is probably easiest to discuss the morphological changes by starting with the saprolite. At 300 cm depth, the saprolite appears essentially uniform (Figure 5.3a). Where some fractures are present, there are only minor indications of localized concentration of iron oxide minerals. Saprolite at 150 cm had a greater degree of fracturing and evidence of localized concentration of iron oxides (Figure 5.3b). Rather than forming a coating on the outer surface of the shale fragments, the iron has impregnated the void space in the outer 0.2 to 0.3 mm of the fragments (Figure 5.3c). These ferruginous zones, are essentially isotropic and have sharp inner and outer boundaries. The interiors of the shale fragments appear to be slightly grayer than the saprolite at 300 cm, possibly reflecting some iron depletion. In some cases the voids between shale fragments are partially filled with reddish-yellow oriented cutanic materials (Figure 5.3d,e). Where present, this is clearly an accumulation of material onto the surface of the saprolite fragments.

In many cases the saprolite fragments are joined together, by continuity of the ferruginous zones from one subangular unit to another. Where these links are sufficiently abundant, the bonds are able to survive subsequent weathering. Concretions linked in this manner become concretion clusters during subsequent stages of soil genesis.

- Figure 5.3 Thin sections of
- (a) a saprolite at 300 cm depth which lacks evidence of iron concentration along fractures;
 - (b), (c) saprolite at 150 cm depth which has open fractures and iron oxide impregnation of the outer portion of the rock fragments. The iron oxide coatings (Fe) on the surface of voids join together to form a reticular (or polygonal) structure. The interiors (labelled as Co) of the shale fragments appear to be grayer than the saprolite at 300 cm, reflecting some iron depletion.
 - (d) laminated cutanic fillings (labelled as "Cu") in fractures, 150 cm depth. There also appears to be detachment of crusts in the thin section.
 - (e) laminated cutanic fillings (labelled as "Cu") and dislodged fragments from the iron oxide-impregnated zone, 60-90 cm depth, and
 - (f), (g) and (h) scattered ferruginous fragments in the soil matrix from 50, 25, and 5 cm depth, respectively.

Thin sections of soil blocks from 50 cm to the surface (Figure 5.3f-h) reveal an abundance of small ferruginous fragments of iron concretions in the soil matrix, with a tendency to decreasing size as the surface is approached. In the immediate surface zone, only ferruginous fragments are observed and indeed no concretions or concretion clusters are found on the surface.

5.2.3 Micromorphology

Thin sections of saprolites, several concretions in clusters, a discrete concretion and fragmented of concretions will be described using the methods and the terminology of Bullock et al. (1985), unless otherwise indicated. The saprolites were selected from 300 and 150 cm depths. A discrete concretion and a concretion cluster were obtained from 20 cm and between 50-70 cm depths, respectively. Soil blocks containing concretion fragments were collected from 100, 50, 25 and 5 cm depths. The descriptions of the thin sections will proceed from the saprolite upward. The crust (or shells) and the encased cores of concretions are described separately. Pedogenic features associated with planar voids between individual concretions in the cluster are examined. All the descriptions, including color, are based on thin sections examined under a petrographic microscope (Leitz, Laborlux 11 POL, German).

5.2.3.1 The saprolite (300 cm depth, Figure 5.3a)

The fabric units comprising the saprolite (e.g. sand grains, silt and clay particles) are referred to as basic inorganic components of the saprolite (Bullock et al. 1985). The components smaller than 10 μm across are referred to as the fine materials and those larger than about 10 μm across are referred to as the coarse materials.

Coarse materials: All the minerals, quartz being the dominant mineral, present are moderately sorted as to size and randomly distributed in space. This fraction comprises about 20% of total thin section area. The grain size ranges from 10-60 μm , with most being approximately 30 μm . The shape varies greatly, with most being subangular. A few micaceous mineral grains, < 1% of the total coarse fraction and about 120 μm long by 10 μm wide, lie roughly parallel to the fractures of the saprolite. Trace amounts of subrounded zircon, about 20 μm across, are present.

Some amorphous isotropic dark brown (plane polarized light) materials, either linear lenticular (up to 300 μm long by 20 μm wide and tapering at both ends) or circular (up to about 20 μm across), are randomly present. The lenticular features are oriented in similar directions. These materials occupies <1% of the cross-sectional area.

Fine materials: The fine materials are inorganic. They are brown under transmitted plane light and yellow under polarizers. The clay-size microcontrasted materials show an

irregular pattern of interwoven fine streaks, which successively extinguish when the microscope stage is rotated. The presence of these streaks probably indicates clay minerals stained by iron oxides or hydroxides.

Voids: (a) Planar voids or fractures, in the saprolite, comprise < 1% of the total thin section area. They average about 30 μm wide, and have linear and parallel distribution pattern. (b) The surfaces of the voids are irregular but highly accommodated to each other and have no coatings.

5.2.3.2 Concretions

5.2.3.2.1 The cores of the concretion (Figure 5.1; 5.2; 5.3b,c; 5.6b)

Coarse materials The mineralogy (i.e. quartz, mica and zircon) and the size, sorting, shape and frequency (as expressed on total thin section area) of the mineral grains in the cores of concretions (Figure 5.1; 5.2; 5.3b,c; 5.6b) are similar to those of saprolite (Figure 5.3a). The most striking difference between the core and the saprolite is that the amorphous dark-brown isotropic materials are greatly reduced in size, frequency and colour intensity in the core.

Fine materials The fine materials of the core are grayish in color whereas those of the saprolite were brown. This change in colour suggests that a redistribution of iron oxides has occurred during concretion genesis and that iron

oxides have been depleted in the cores.

5.2.3.2.2 The crusts of the concretions.

The hard crusts (Figure 5.1, 5.2, 5.3b-e and 5.4 b-f) were formed through impregnation of the groundmass immediately adjacent to the surfaces of fractures in the saprolite by some isotropic brownish (ferruginous) materials. These crusts are composed of up to 62% Fe_2O_3 (Table 5.1). This type of impregnation is termed hypocoating by Bullock et al. (1985). The evidence for impregnation is that the coarse fraction of the crust has the same mineral grains (mainly quartz) with the same distribution pattern as the interior cores (Figure 5.2).

The ferruginous hypo-coatings vary in thickness and degree of impregnation. At 150 cm depth in the upper most part of the saprolite (Figure 5.3b,c), this type of coatings is usually thin (<0.25 mm) but in well-formed concretions, some were 2 mm thick (Figure 5.2). The boundaries between the impregnated surface zone and the interior core are smooth and clear.

The degree of impregnation varies widely, from strongly impregnated near the surface of the fracture to weakly impregnated at the boundary with the interior matrix. The surface zone impregnation, in many locations, is so intense that it appears to have completely occupied the void spaces. This has resulted in subsequently deposited iron materials

Figure 5.4 Sectional views of:

- (a) a void between two adjacent concretions in a cluster. Note two coatings (i.e. ag: argillans, fe: ferran) subsequently coated on the surface of the crusts (ct: crusts).
 - (b) partially fragmented crusts of a concretion, with infilling of argillans (ag), in the voids between adjacent crusts (ct) of concretions.
 - (c) densely coated fan-like ferrans (fe) in voids between concretions.
 - (d) disintegrating fan-like ferrans (fe) and argillans (ag).
 - (e) cracked ferrans (fe) showing polygonal pattern
 - (f) some angular cracked ferrans dislodged from main body of ferrans showing different degrees of decomposition.
- All samples were taken from about 60 cm depth.

(as in Figure 5.4c-e and 5.6b at point 5, arrows) being juxtaposed on the hypo-coatings and forming ferruginous accumulations, comprising up to 73% Fe_2O_3 (the b-5 of Table 5.2), called ferrans.

The crust of a discrete ovoid concretion (Figure 5.2) consisted of two layers, the inner layer was strongly impregnated by dark red (5YR) ferruginous materials and the outer layer was weakly impregnated with light yellowish-brown (7.5YR) materials and was more porous. The boundary between the outer layer and the surrounding soil matrix is smooth and diffuse. The distribution of coarse materials ($>10\text{ }\mu\text{m}$) is micromorphologically identical in the inner and the outer layers.

At some locations within the concretion clusters, impregnated crusts are found to break up into smaller pieces commencing from the outmost edge and gradually proceeding inwards (Figure 5.3e; 5.4c,d). In some cases, the entire strip of dense impregnated crust has been peeled off and separated from the interior groundmass (Figure 5.3d,e).

5.2.3.3. The concretion fragments in soil blocks

Many small iron-rich particles, varying in size and shape, are scattered throughout the solum of Pedon 2, with a tendency of decreasing size and amount as the soil surface is approached (Figure 5.3f-h). Micromorphologically, these particles appear to be internally similar to the crusts of

the well-formed concretions. Even those that are quite small ($< 5\mu\text{m}$) have clear to sharp boundaries.

5.2.3.4 The ferrans and argillans

There are two types of cutanic materials, ferrans and argillans, sometimes overlaid on one another, which occupy what were originally void spaces between individual concretions. Both coatings have sharp extinction bands under crossed polarized light (XPL), indicating lamination characteristics (Figure 5.3d,e; 5.4a-f).

Ferrans The translucent amber coatings (under plane polarized light) which are juxtaposed on the crusts of concretions are nearly pure iron-oxides (from 73 to 91% Fe_2O_3 , as determined by the electron microprobe, Table 5.2b and d) and qualify as ferrans (Bullock et al., 1985) or as sesquans (Brewer, 1964). The ferrans range from about $40\mu\text{m}$ thick, in the saprolite at 150 cm depth, to $>0.6\text{mm}$ thick in well-formed concretion clusters at 60-70 cm depth (Figure 5.4c,e). Some large fan-shaped ferrans, which have laminations and have also developed columnar "microjoints" structures (Figure 5.4c as indicated with an arrow), are present in some large planar voids (up to 1.5 mm wide). These ferrans, in some locations, change their color from the original translucent amber to opaque yellowish (plane polarized light) with developing vughs within them (Figure 5.4d as indicated with an arrow). These vughs have developed

along the microjoints structures in the ferrans suggesting gradual disintegration. The vughs, up to 20 μ m wide, are arranged in a linear distribution pattern perpendicular to the laminations of the ferrans. In nearby, but narrower voids, some ferrans remained translucent amber in color, but their internal structure indicates the development of close-spaced (approximately 20 μ m), angular polygonal cracking patterns (as shown in the middle portion of Figure 5.4e). The "microjoints" (or cracked units) are similar in size, about 20 μ m along each side. Those near the outer edge have changed to pale orange color (plane polarized light) or have even transformed to amorphous materials and become dislodged from the main body of the cracked ferrans (as shown in the middle portion of Figure 5.4f). The formation of cracking patterns and subsequent dislodgement of the units developed is probably the result of shrinkage within the ferran, caused by dehydration. Other changes may be a consequence of reduction of Fe to the ferrous form, which has a higher solubility.

Argillans The second type of cutanic material is juxtaposed on the hypo-coatings of ferruginous materials (Figure 5.3d,e and 5.4a,b) or on ferrans (Figure 5.4d and 5.6b). Under plane polarized light these cutans range from light yellow to yellowish-brown, while under crossed polarizers, they are greyish-white to light yellow and show extinction bands. They are comprised of uniform clay,

without apparent inclusion of large particles. Judging from their morphology, texture, structure and chemistry (refer to section 5.2.4 and Table 5.2d) they qualify as argillans (Brewer, 1964). Those stained with iron oxides are termed ferri-argillans (Brewer, 1964). The thickness of the ferri-argillans varies widely, from $< 10\mu\text{m}$ to $200\mu\text{m}$ thick (Figure 5.4d, for example, shows approximately $600\mu\text{m}$ thick ferrans and approximately $200\mu\text{m}$ thick argillans). In some locations, the argillans occupy over 80% of the total planar voids. The presence of argillans, on ferrans and isolated crust fragments in planar voids, indicates that they are formed after the accumulation of ferrans or production of crust fragments. The occurrence of ferrans and argillans, within iron concretion clusters and in some portions of the saprolite, provide evidence that translocations of iron and clay particles are currently occurring. The translocation of iron during pedogenesis is believed to be important in the formation of the iron concretions.

5.2.4 Chemistry

The bulk chemical composition, as determined by XRF, of the three zones of the ovoid concretion (Figure 5.2), the soil matrix (60-80 cm depth) and the underlying saprolite (at 150 cm depth) are presented in Table 5.1. The saprolite and the soil matrix are similar in composition, the main difference being slightly less Si and more Fe in the soil

Table 5.1 Chemical composition (by weight) of a concretion, the soil matrix and saprolite as determined by X-ray fluorescence (data normalized to 100%).

Oxides	Concretion (Figure 5.2)			Soil Matrix	Saprolite
	Outer Layer	Inner Layer	Interior Core	60-80 cm	150 cm
Na ₂ O,%	0	0	0.06	0.38	0.12
K ₂ O,%	2.50	1.32	3.19	3.94	4.66
CaO,%	0.05	0.16	0.06	0.03	0.02
MgO,%	0.71	0.85	0.92	0.70	0.74
TiO ₂ ,%	0.64	0.37	0.72	0.75	0.85
MnO,%	0.03	0.11	0.02	0.01	0
Al ₂ O ₃	14.8	8.21	14.68	19.46	20.08
SiO ₂ ,%	66.63	27.02	77.14	68.33	71.29
Fe ₂ O ₃ ,%	14.67	61.96	3.18	6.38	2.25
Ba, ppm	323	551	220	447	449
Cr, ppm	74	228	37	62	101
Zr, ppm	224	335	172	259	227
Sr, ppm	52	148	45	59	70
Rb, ppm	155	42	82	222	250
Y, ppm	34	95	22	34	39
Zn, ppm	179	281	11	70	17

matrix (which does contain some <2 mm concretion fragments). The interior core is enriched in Si and slightly depleted in Fe and most of the trace elements analyzed when compared to the soil matrix. The hard inner layer of the concretion is greatly enriched in Fe, Mn and Zn, and somewhat enriched in Ca, Ba, Cr, Zr, Sr and Y relative to both the saprolite and the soil matrix. It has much reduced proportions of Si, Al, K, and Rb and somewhat less Ti. The outer layer is somewhat enriched in Fe and Zn and depleted in Al and most other elements. It has also worthy of note that the trace elements were commonly depleted in the interior core and enriched in the hard inner layer. It would appear that a redistribution of chemicals has occurred during formation of the concretions. This has been a common observation in studies of concretions (Drosdoff and Nikiforoff, 1940; Childs, 1975; Rusanova et al., 1975; Schwertmann and Fanning, 1976; Childs and Leslie, 1977; Sidhu et al., 1977). In common with all other iron concretions studied, these exhibit higher concentrations of Fe and Mn and lower concentrations of Si than the surrounding soil materials. The patterns with other elements have not been consistent in studies of iron concretions.

A more localized study of the major element distribution in the same ovoid concretion was conducted using EDXRA to analyze along four linear traverses which extended from the outer layer to the interior core (Figure 5.5). The changes

Figure 5.5 Changes of major element concentration along linear traverses from the outer layer to the interior core of an iron concretion (the photo of the concretion is shown in Figure 5.2). Each point represents the average of 3-5 determinations by EDXRA.

in concentration occur rather abruptly at the boundaries between zones, with Fe, Mn, Ca, and Ti enriched and Si, Al and possibly K depleted in the inner layer, relative to the core. The outer layer has generally greater Fe, and less Si, Mg and K than the core. With the exception of Ti, the relative abundance patterns by XRF and EDXRA results are consistent for the core and inner layer and outer layer. The reasons for disagreement with Ti are not obvious but may reflect local variability which would show up in the EDXRA analysis with its focus on very small areas. When the weight percent of oxides determined by EDXRA is summed, 52% of the outer layer, 101% of the inner layer and 62% of the core are accounted for. The presence of void space, organic matter and hydrated minerals, not detectable by the EDXRA method (Bisdons et al., 1976), reasonably accounts for the differences. The great differences in chemical composition along the traverses also clearly indicate a redistribution of certain elements during concretion formation.

The same EDXRA technique was also applied on polished thin-sections of fragmented concretions from various soil depths. The Figure 5.6 indicates the locations where the electron microprobe analyses were conducted. The results (Table 5.2) indicate that the hard crust of well-formed concretions had 36.0% Fe_2O_3 while those of fragments ranged from 27.5 to 11.7%. The lower Fe_2O_3 content in the well-formed concretion from the than in the discrete ovoid

Table 5.2 Chemical composition of 3 concretion fragments (Figure 5.6a-c) and a portion of well-formed concretion (Figure 5.6d) as determined by EDXRA.

Location*	Fe ₂ O ₃ %	MnO %	TiO ₂ %	SiO ₂ %	Al ₂ O ₃ %
<u>a: Concretion fragment at 5 cm depth</u>					
1. Soil matrix	4.1	3.1	1.2	39.2	20.8
2. Crust	22.4	1.0	1.3	36.6	16.3
3. Crust	15.8	1.0	1.2	38.7	18.4
4. Soil matrix	4.4	0.7	1.1	42.6	19.2
<u>b: Concretion fragment at 25 cm depth</u>					
1. Soil matrix	8.9	0.9	1.1	48.5	25.4
2. Crust	13.3	1.0	1.9	41.5	23.5
3. Core	2.8	0.8	1.5	59.6	24.4
4. Crust	11.7	1.0	2.2	42.6	24.4
5. Ferran	72.9	1.3	1.3	4.8	7.2
6. Soil matrix	5.8	0.8	3.1	47.3	19.5
<u>c: Concretion fragment at 50 cm depth</u>					
1. Soil matrix	3.5	0.5	1.1	57.2	20.2
2. Core	3.6	0.8	1.5	83.5	9.2
3. Crust	27.5	1.0	1.2	41.8	14.4
4. Soil matrix	4.0	0.7	1.3	44.8	22.2
<u>d: Well-formed concretion at 60 cm</u>					
1. Ferran	90.9	0	0.5	1.8	0
2. Argillan	1.9	0	0	25.7	18.3
3. Crust	36.0	0	0.2	57.0	1.8

* The number assigned for each location in the tested concretion fragment is the same as shown in Figure 5.6.

Figure 5.6 Traverse lines across fragmented concretions sampled at (a) 5, (b) 25 and (c) 50 cm depths and (d) a void between a well-formed concretions sampled at 60 cm. Squares indicated locations where the EDXRA analyses were conducted. The chemistry is listed in Table 5.2. (A: argillan; Co: core; Ct: crust; F: ferran, and Sm: soil matrix).

concretion (illustrated as in Figure 5.3) probably indicates variations in the degree of impregnation, as well as redistribution of chemicals, during the genesis of the concretions.

The ferrans of the well-formed concretion and the concretion fragment consist of 91 and 73% Fe_2O_3 , or 98 and 83% of total (Fe, Si, Al, Mn and Ti) oxides combined, respectively. The lower iron contents of ferrans on fragmented concretions can be attributed to loss by weathering. Void spaces and hydrated materials, that were not detectable by EDXRA, may account for part of these differences.

The fine yellowish materials (Figure 5.6d) infilling voids between crusts were Si- and Al-rich materials (96% of total oxides weight, Table 5.2d) and showed clear extinction (XPL) bands. This is consistent with them being argillans formed by clay translocation and deposition. The yellowish color is believed due to the presence of small amounts of iron oxides. These ferri-argillans are most often found occupying planar voids in concretion clusters (Figure 5.3e, for example) and are also present in some voids in the saprolite (Figure 5.3d).

5.2.5 Mineralogy

The x-ray diffraction patterns for the two layers and the core of the discrete ovoid concretion and the surrounding soil matrix are presented in Figure 5.7. The slightly

Figure 5.7 X-ray diffraction patterns of three concentric zones of an iron concretion (as shown in Figure 5.2) and the surrounding soil matrix. (G, goethite; H, hematite).

asymmetric 1.0 nm peak, with a shoulder on the low angle side, which is reduced by heating, indicates the presence of interstratified hydromica-vermiculite. This interstratified clay is much less important in the inner layer compared to other locations, as is quartz (0.426 nm). Goethite (0.418 and 0.270 nm peaks) reflects very strongly in the inner layer, strongly in the outer layer, is undetectable in the interior core and may be present in the soil matrix. Hematite (0.368 and 0.252 nm peaks) is only detected in the inner layer of the crust of the concretion.

A more definitive speciation of the iron can be accomplished by Mossbauer spectroscopy. Figure 5.8 presents the Mossbauer spectra at 80°K for the outer layer, the inner layer and the interior core of the ovoid concretion. These spectra are fitted with two sextets and two distributions of hyperfine fields. The iron speciation for these samples, calculated from the Mossbauer spectra, is presented in Table 5.3. Speciation of iron compounds for the surrounding soil matrix and saprolite at 150 and 300 cm depths are also presented. The Mossbauer results are entirely consistent with those of XRD. In the outer layer 92% of the Fe is present as goethite with the rest being present as ferric- and ferrous-containing silicate minerals. The inner layer has almost all its iron present as oxides with roughly equal amounts of hematite and goethite. The small amount of iron oxides present in the interior core (undetectable by XRD)

Figure 5.8 Mössbauer spectra of (a) goethite-rich outer layer, (b) hematite- and goethite-rich inner layer and (c) hematite- and goethite-depleted interior core of a concretion (as shown in Figure 5.2), fitted with two sextets and two distributions of hyperfine fields at 80°K.

Table 5.3 Total Fe_2O_3 content by XRF and speciation of iron compound by Mossbauer spectroscopy. Saprolite samples were run at room temperature, all others at 80°K .

	Fe_2O_3	hematite	goethite	ferric	ferrous
	%	% of total			
Concretion					
Outer layer	14.67	0	92	4	4
Inner layer	61.96	47	50	2	1
Interior core	3.18	29	19	28	23
Soil matrix	6.38	0	79	12	9
Saprolite					
at 150 cm	2.25	0	65	9	25
at 300 cm	2.00	0	66	11	24

Table 5.4 Amounts of iron extracted by dithionite-citrate and acid ammonium oxalate procedures from a discrete concretion.

	Dithionite-citrate,%		ammonium oxalate,%	
	of sample	of total Fe	of sample	of total Fe
Concretion				
Outer layer	8.83	86.1	0.14	1.4
Inner layer	32.63	75.3	0.71	1.6
Interior core	1.00	45.0	0.06	2.8
Soil matrix	2.89	66.1	0.35	9.2
Saprolite				
at 2 m depth	0.7	44.6	0.03	19.1
at 3 m depth	0.7	50.0	0.01	7.1

consists of hematite, goethite and ferric- and ferrous-containing silicate minerals. Mössbauer spectroscopy confirms the presence of goethite and the absence of hematite (within the limits of detection, <5% of the Fe) in the soil matrix and further indicates the presence of ferric- and ferrous-containing silicates. The saprolite contains goethite along with ferric- and ferrous-containing silicates. No hematite is detected in the saprolites. The ferrous-containing silicates constitute an appreciable portion (23-25%) of the iron in both the saprolite and the concretion core, but a much lesser portion of the iron in the soil matrix and concretion layers.

The Mössbauer spectroscopy results indicate that the iron oxides are well crystallized in the iron-rich inner layer but less crystalline in the core. The relative amounts of iron extracted by dithionite-citrate and acid ammonium oxalate procedures from the inner layer (32.63% and 0.71%, respectively) and the core (1.00% and 0.06%, respectively) support this conclusion (Table 5.4).

In summary, the iron oxide determinations are all consistent and indicate that hematite dominates over goethite in the core, they roughly balance in the inner layer and only goethite is present in the outer layer, the soil matrix and the saprolite.

5.2.6 "Life-cycle" of a concretion

The morphological evidence suggests that concretion formation commences in the upper portion of the saprolite, continues until somewhere between 100 and 50 cm depth, at which point degradation commences. By the time erosion has removed the overlying soil, and the layer in which they once existed is exposed at the surface, only fragments remain.

When the morphological, mineralogical and chemical evidence are brought together, a scenario for their "life-cycle" can be developed. Their life commences with hematite preferentially accumulating in the surface zone of shale fragments somewhere between 300 and 150 cm. Hematite also forms to a lesser extent in the core zone of the shale fragments. Goethite accumulation apparently commences somewhat later, but by 150 cm goethite-rich cutans are already forming in the fractures in the saprolite and goethite is also forming in the hematite-rich surface zone, where it ultimately accounts for approximately one half of the ferruginous material. As weathering and soil formation proceed, some of the concretions break up, some remain intact as individual concretions and some remain linked together as clusters. The intact concretions survive until erosion brings them nearer the surface.

The demise of the concretions appears to follow the pattern of breakup and complete loss of the goethite-rich inner layer. In this high rainfall area, where the water

table is seasonally recorded to approach the surface, it is postulated that, during periods of saturation, biological reduction of the ferric iron to the more mobile ferrous form leads to concretion breakdown and downward translocation of iron. The mobilized iron will accumulate as goethite and hematite in the lower part of the soil profile and the upper part of the saprolite when the drainage improves and oxidizing conditions return.

The balance of surface erosion, iron mobilization and precipitation at this site, is such that the iron accumulation zone remains between 0.3 to 2 meters below the surface, with the iron being recycled in this zone. Presumably at a more stable site, the depth of iron accumulation would be greater, or there might be no accumulation if the mobilized iron did not encounter oxidizing conditions during translocation. On a more erosive site, the concretions would survive at least partially intact until they arrived at the surface, where they would form a residual iron-rich surface unless removed during particularly heavy runoff. In either of these scenarios the iron would cease cycling. The presence of the concretions in this soil appears to derive from a balance of the processes of erosion, reduction, mobilization and reprecipitation.

5.3 Summary

Iron concretions found in the solum of pedon 2, a Typic

Dystrochrept, fine, illitic, thermic, have been investigated. The properties and genesis of pedon 2 have been described in the Chapter 4. The iron concretions in this pedon distribute discontinuously between approximately 30 and 110 cm depth, with the most intact and strongly developed concretions occurring between approximately 50 and 70 cm. Fragmented concretions are dispersed in the solum, with their size decreasing as the soil surface is approached. Some discrete concretionary bodies are also present (up to 4 cm across), but most occur as clusters of concretions solidly jointed together in polygonal structures up to 30 cm across.

Each individual unit in the concretion clusters has a soft core encased with an indurated crust. The discrete concretion is macroscopically similar, except for shape, to the individual units in the clusters. It consists of three concentric zones: a gray interior core, which is soft and fine textured; a dark reddish-brown indurated inner layer (equivalent to the crust of concretion units); and a reddish-yellow outer layer.

The indurated crusts, whether of concretion clusters or of discrete bodies, are greatly enriched in Fe (up to 62% Fe_2O_3), Mn and Zn, and are depleted in Si and Al relative to the outer layer, the surrounding soil matrix and the saprolites.

Mossbauer spectroscopy results indicate that hematite dominates over goethite in the core; they roughly balance in

the inner layer (crust); and only goethite is detectable in the outer layer, the soil matrix and the saprolite.

Thin section studies and chemical evidence suggest that the concretions commence their formation during the weathering of saprolite, are most prominently developed between 50 and 100 cm depth and mainly fragments remain above 30 cm. The iron forming these concretions appears to be cycled downward during their disintegration, to become involved again in the process. A life-cycle for the concretions, based on the balance of erosion, iron mobilization and reprecipitation at the site, is proposed.

CHAPTER 6 CONCLUSIONS

Two Typic Dystrochrepts and one Typic Halpudult have been investigated in the Lien-Hua-Chi area, in the mountains of Central Taiwan. These soils have developed from Tertiary sedimentary rocks, under a warm-temperate montane rain forest and a subtropical climatic regime.

The soils, their properties, and their genesis and classification may be summarized as:

(1) Typic Dystrochrept, fine, vermiculitic, thermic: this pedon, located in an upland position on a gentle 2% slope along a ridge top, is derived from Tertiary siltstones, although there is a lithological change to sandstones at 160 cm depth.

The soil is highly acidic (pH 4.0 in CaCl_2) with a base saturation less than 15% (by neutral ammonium acetate).

The soil is relatively immature with only small changes in soil weight, clay content and clay mineralogy having occurred during the course of pedogenesis. The relatively active pedogenic processes operating in the soil system are melanization (forming an organic-rich A1 horizon) and loosening (by increasing soil volume), with some indication of braunification (in situ iron transformation to develop a cambic Bw horizon).

The overall genesis operating in this pedon has produced an ochric epipedon and cambic horizons, yielding an A-Bw1-

Bw2-2C horizon sequence.

(2) Typic Dystrochrept, fine, illitic, thermic: this pedon, found on a steep (60% slope) and erosive terrain, is derived from Tertiary shales.

It is also a relatively young soil. The soil is highly acidic (pH 3.5 in CaCl_2) and has extremely low base saturation (about 10% by neutral ammonium acetate). Prominent hard iron concretions are distributed sporadically in the solum.

The predominant pedogenic processes are melanization (formation of organic C rich A11 and A12 horizons) and braunification (formation of a cambic Bw horizon). Translocation of Fe (from A to Bw and to BC horizons) has occurred and redistribution and local concentration of Fe has produced iron concretions.

The pedogenic processes in this pedon have produced an ochric epipedon and a cambic horizon, and have yielded an A11-A12-Bw-BC-2C horizon sequence.

The iron concretions, for which the term "shell concretions" is proposed, occur singly and in clusters up to 40 cm across, and are distributed discontinuously between 30 and 110 cm depth, with fragments of degraded ones distributed through the entire solum. Cross sections of the iron concretions reveal round to subangular polygonal iron-rich shells (commonly with an inner and outer layer) which encase a gray matrix. Evidence suggests that the concretions commence their formation during weathering of shale to saprolite, are

prominently developed between 50 and 100 cm depth and break down relatively rapidly to leave only fragments when erosion of overlying soil materials brings them to approximately 50 cm from the surface. Much of the iron forming these concretions appears to be cycled downward during their fragmentation, to become involved again in the process.

(3) Typic Halpudult, fine-loamy, siliceous, thermic: the pedon is located on a steep (69% slope) terrain and is derived from Tertiary sandstones. The sandstone parent material is not uniform with depth, possibly reflecting different depositional environments during its accumulation.

The pedon is highly acidic with an pH value about 3.5 (in CaCl_2). It has extremely low base saturation (about 8% by neutral ammonium acetate).

Major pedogenic processes that have operated in the soil are melanization, lessivage and translocation of sesquioxides. These processes, have led to the formation of an ochric epipedon and an argillic Bt horizon, and have produced an A-E-2Bt-3BC-3C horizon sequence.

These three pedons, located closely in space (within 2 km), developed under similar climate and native vegetation but under different conditions of topography and parent materials. The predominant pedogenic processes operating have differed and these differences are reflected in the pedons. In particular, the influence of parent material is a major factor explaining local differences in these soils.

The two Dystrochrepts are both derived from fine-textured parent materials and have many similarities. The major differences in soil forming factors are the different topographic positions (2% versus 60% slope) and the slightly coarser texture of the parent rock at site with 2% slope. The Dystrochrept at the more erosive, 60% slope, site appears to be in a relatively steady condition in which soil development is balanced by erosion and the result is little apparent change in the soil with time. This soil presumably will not become more strongly developed. The main differences between it and the Dystrochrept on the 2% site are the greater depth of B horizon development at the more stable site, a higher pH throughout (regardless of procedure) and presence of vermiculite rather than illite as the dominant clay mineral. The depth of B horizon development and the dominance of vermiculite may reflect the increased stability of the site allowing more change to have occurred. The higher pH is possibly because the solum has substantially more permanent charges and this more stable site is recently cleared and the decomposition of organic matter may have released some bases which result in higher base saturation. The observation that Dystrochrepts have developed at both sites is suggestive of them being the most common soil to be expected to develop on the fine-grained Tertiary sedimentary rocks in the mountains.

The Dystrochrept and the Hapludult pedons developed on

similar steep slopes ($>60\%$), about 120 m apart, within the same small watershed. They, however, have formed on different parent materials (shales and sandstones, respectively) and exhibit different properties in terms of texture, chemistry and clay mineralogy. The textural difference derives directly from the different parent rocks, and the coarser parent material for the Hapludult is undoubtedly a major factor in allowing the development of an argillic horizon in this pedon. The properties of parent materials on the unstable landscape, common in mountains of Central Taiwan, can lead to substantial differences in the soil development process. Presumably a more strongly developed Ultisol would form if the landscape was less erosive. The development of an Ultisol on this highly erosive site suggests that they should be the most common soil order developed on the coarse-textured Tertiary sedimentary rocks in the mountains.

The use of Soil Taxonomy to classify the studied pedons does not present any major difficulties, except for laborious analytical work, which actually provides benefits when the information gained is applied to interpretation for land use and management decisions. This is another example of the benefits of using Soil Taxonomy as a system of soil classification. It would be useful to discontinue use of the 1949 USDA soil classification in Taiwan and to conduct further soil investigations using the approach, principles and nomenclature of Soil Taxonomy.

It has been observed that Inceptisols developed on fine-textured sedimentary deposits while Ultisols developed on sandstones under the studied environmental conditions. It is presumed that these general observations hold for soils of other regions in Tawian with similar soil forming factors but this assumption deserves further investigation. If this generalization holds to be true, to an acceptable accuracy, it will facilitate future survey and classification of forest soils in the mountains of Central Taiwan.

The effects of parent materials and topography on soil formation are clearly demonstrated in this study. However, the persisting influence on these two and the other soil forming factors on soil genesis and classification needs to be studied. The soils on the Tertiary sedimentary rocks under different climates, native vegetation and topography need to be studied. In particular, the soils developed at higher elevations under coniferous forest cover deserve investigation, as might soils developed in areas dominated by bamboo.

The proposed scenario for the genesis of "shell concretions" is plausible but not has been well-developed. The detailed mechanisms by which iron is mobilized, transported and immobilized require detailed study as does their life span and their evolutionary history.

In summary, this research represents the first detailed study of the genesis of forest soil pedons in mountains of

central Taiwan. This is also the first attempt in Taiwan to classify forest soil pedons at the family level using Soil Taxonomy. The iron concretions found, in the solum of one of the Dystrichrepts derived from Tertiary shale, bear no similarity to other iron concretions reported in the soil science literature. The term "shell concretion" is proposed for these features, and a hypothesis as to their genesis and "life-cycle" has been proposed.

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APPENDIX

Appendix I: Analytical Data

Table I.1 Mechanical analysis (continued)

Pedon 2

Depth cm	Sand				Silt			Clay	
	2-1 mm	1-0.25 mm	0.25-0.05 mm	Total	50-20u	20-5u	5-2u	Total	< 2u
	%	%	%	%	%	%	%	%	%
0-10	1.54	1.32	7.82	10.69	23.24	17.13	5.21	45.59	43.72
10-20	2.33	1.71	7.05	11.09	20.32	17.78	4.51	42.61	46.29
20-30	1.87	2.03	6.56	10.46	21.08	18.12	5.52	44.72	45.18
30-40	1.96	1.93	4.99	8.88	18.25	19.70	7.41	45.36	45.76
40-50	2.92	2.92	6.82	12.66	29.57	17.84	5.64	41.06	46.28
50-60	6.41	5.05	10.95	22.41	19.18	14.64	5.60	39.42	38.16
60-70	3.44	3.29	8.94	15.67	17.82	16.74	6.27	35.32	41.81
70-80	4.06	3.51	6.91	14.48	17.18	17.03	7.41	41.61	42.91
80-90	4.47	3.61	5.74	13.82	18.66	17.95	6.51	43.11	43.06
90-100	3.97	3.41	6.71	14.10	19.65	17.41	6.16	43.23	43.24
100-110	3.27	2.55	6.54	12.37	17.94	19.98	6.23	44.15	43.48
110-120	3.56	3.92	6.46	13.94	20.40	15.82	9.72	45.93	40.13
120-130	6.60	6.85	8.82	22.27	21.96	18.69	5.89	46.55	31.18
130-140	2.91	2.81	5.62	11.34	19.26	20.79	8.30	48.35	40.30
140-150	3.25	3.20	5.37	11.83	18.58	20.35	8.38	47.31	40.86
150-160	3.36	3.96	11.82	19.14	25.38	19.74	8.51	53.64	27.21
160-170	3.75	2.43	12.18	18.37	24.40	19.08	7.10	50.58	31.05
170-180	4.66	2.94	10.85	18.45	20.78	19.26	7.15	47.19	34.36
180-190	5.28	3.57	17.00	25.86	20.62	17.25	5.58	43.46	30.68
190-200	2.81	2.86	16.08	21.76	21.76	17.84	6.08	45.68	32.56

Table I.1 Mechanical analysis (continued)

Pedon 3

Depth cm	Sand				Silt			Clay	
	2-1 mm	1-0.25 mm	0.25-0.05 mm	Total	50-20u	20-5u	5-2u	Total	< 2u
	%	%	%	%	%	%	%	%	%
0-10	0.70	15.33	41.91	57.94	10.74	12.09	3.65	26.48	15.58
10-20	0.81	15.08	43.37	59.27	13.31	8.63	4.16	26.10	14.63
20-30	0.63	14.18	43.33	58.13	10.06	10.22	4.17	24.45	17.41
30-40	0.61	13.85	44.17	58.64	12.47	7.82	2.76	23.06	18.30
40-50	1.16	14.19	42.23	57.58	10.71	9.31	2.99	23.02	19.40
50-60	1.52	12.57	41.89	55.97	11.42	9.76	3.43	24.61	19.41
60-70	2.57	12.97	40.64	56.18	8.32	10.04	3.01	21.37	22.45
70-80	6.68	18.75	32.32	57.75	7.57	7.94	2.56	18.07	24.18
80-90	6.76	22.05	32.35	61.16	7.80	7.17	2.45	17.42	21.42
90-100	9.77	25.02	30.42	65.21	7.04	6.38	2.16	15.59	19.20
100-110	10.02	29.82	29.77	69.61	6.90	4.99	1.48	13.37	17.02
110-120	11.14	32.63	29.27	73.03	5.80	5.25	1.06	12.10	14.86
120-130	8.10	34.22	28.97	71.28	4.43	6.87	1.38	12.68	16.04
130-140	9.49	32.68	27.50	69.67	4.79	7.34	1.46	13.60	16.73
140-150	9.13	34.02	27.62	70.79	2.99	7.00	1.45	11.44	17.77
150-160	11.31	31.09	27.64	70.04	8.23	3.50	1.28	13.01	16.94
160-170	10.75	33.42	26.61	70.78	4.24	4.33	1.67	10.24	16.71

Table I.2 Bulk density *

Depth cm	Pedon ₁ Mg/m ³	Pedon ₂ Mg/m ³	Pedon ₃ Mg/m ³
0-20	0.94	1.09	0.93 (0.92)
20-40	1.13	1.30	1.12 (1.13)
40-60	1.22	1.21	1.36 (1.12)
60-80	1.30	1.55	1.51 (0.99)
80-100	1.17	1.20	1.50 (0.90)
100-120	1.28	1.52	1.66 (1.29)
120-140	1.30	1.58	1.83 (1.48)
140-160	1.33	1.72	1.97 (1.56)
160-180	1.36	1.56	2.36 (1.85)

* Average values of 2-6 determinations; bulk density of fine earth fraction is shown in the parenthesis.

Table I.3 Soil reaction and exchange acidity

Depth	pH*			Exchange Acidity me/100g (phenolphthalein)
cm	H ₂ O	CaCl ₂ 0.1M	KCl 1M	
<u>Pedon 1</u>				
0-10	4.4	3.6	3.6	4.2
10-20	4.5	3.8	3.7	3.5
20-30	4.8	3.8	3.8	3.3
30-40	4.7	3.9	3.8	2.9
40-50	4.8	3.9	3.8	2.9
50-60	4.8	3.9	3.8	2.6
60-70	4.7	3.9	3.8	2.7
70-80	4.8	3.9	3.8	2.7
80-90	4.7	3.9	3.8	2.8
90-100	4.7	3.8	3.8	2.6
100-110	4.8	3.9	3.8	2.5
110-120	4.8	3.9	3.8	2.6
120-130	4.8	3.9	3.9	2.8
130-140	4.8	3.9	3.7	3.2
140-150	4.8	3.9	3.7	3.2
150-160	4.8	3.8	3.7	3.1
160-170	4.8	3.8	3.6	3.4
170-180	4.8	3.8	3.7	3.5
180-190	4.6	3.8	3.7	2.5

* Average values of two determinations.

Table I.3 (continued)

Depth cm	pH*			Exchange Acidity me/100g
	H ₂ O	CaCl ₂	KCl	
<u>Pedon 2</u>				
0-10	3.9	3.4	3.4	9.1
10-20	4.0	3.5	3.4	9.0
20-30	4.1	3.5	3.4	9.8
30-40	4.1	3.5	3.4	10.6
40-50	4.2	3.5	3.4	11.4
50-60	4.2	3.5	3.4	10.5
60-70	4.3	3.5	3.4	10.7
70-80	4.2	3.5	3.4	11.0
80-90	4.3	3.6	3.5	11.2
90-100	4.3	3.5	3.5	11.5
100-110	4.3	3.6	3.5	10.7
110-120	4.4	3.5	3.5	11.2
120-130	4.2	3.6	3.5	10.6
130-140	4.1	3.5	3.4	11.7
140-150	4.3	3.5	3.4	11.3
150-160	4.3	3.5	3.4	10.3
160-170	4.3	3.5	3.4	9.7
170-180	4.3	3.5	3.4	10.5
180-190	4.3	3.5	3.4	9.3
190-200	4.3	3.6	3.5	9.0
<u>Pedon 3</u>				
0-10	4.0	3.4	3.3	7.9
10-20	4.1	3.5	3.4	7.1
20-30	4.2	3.5	3.4	6.2
30-40	4.2	3.6	3.4	5.3
40-50	4.3	3.6	3.4	5.0
50-60	4.2	3.6	3.4	4.9
60-70	4.3	3.7	3.4	4.8
70-80	4.3	3.7	3.5	5.0
80-90	4.3	3.7	3.5	4.3
90-100	4.3	3.7	3.6	4.0
100-110	4.3	3.7	3.6	3.3
110-120	4.3	3.6	3.5	3.0
120-130	4.4	3.7	3.6	3.1
130-140	4.3	3.7	3.6	3.3
140-150	4.3	3.7	3.6	3.3
150-160	4.3	3.7	3.5	3.4
160-170	4.2	3.7	3.5	3.3

* Average values of two determinations.

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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Table I.4 Percent organic carbon content

Depth, cm	Pedon 1	Pedon 2	Pedon 3
0-10	3.39	2.14	1.49
10-20	1.67	1.33	0.76
20-30	1.30	1.17	0.54
30-40	1.14	0.80	0.27
40-50	0.96	0.55	0.38
50-60	0.76	0.28	0.37
60-70	0.73	0.24	0.34
70-80	0.74	0.26	0.44
80-90	0.60	0.30	0.35
90-100	0.57	0.58	0.24
100-110	0.48	0.30	0.23
110-120	0.37	0.33	0.27
120-130	0.40	0.29	0.12
130-140	0.32	0.46	0.17
140-150	0.30	0.44	0.36
150-160	0.38	0.22	0.37
160-170	0.41	0.42	0.23
170-180	0.32	0.33	-
180-190	0.27	0.36	-

Table I.5 Sodium chloride extractable cations, cation exchange capacity (CEC) and base saturation (BS).

Depth cm	Ca	Mg	K cmol(+)/kg	Al	CEC	BS %
<u>Pedon 1</u>						
0-10	0.56	0.10	0.17	1.67	5.03	16.5
10-20	0.27	0.03	0.15	1.33	3.95	11.4
20-30	0.24	0.01	0.24	1.00	3.79	12.9
30-40	0.27	0.01	0.07	0.83	3.25	10.8
40-50	0.23	0.01	0.07	1.17	3.21	9.7
50-60	0.20	0.01	0.08	1.00	2.89	10.3
60-70	0.27	trace	0.07	1.00	3.04	11.2
70-80	0.24	trace	0.06	1.00	3.00	10.0
80-90	0.11	trace	0.07	0.83	2.98	6.0
90-100	0.10	trace	0.03	0.83	2.73	4.8
100-110	0.10	trace	0.07	0.83	0.67	6.4
110-120	0.17	trace	0.06	0.83	2.83	8.1
120-130	0.17	trace	0.05	0.83	3.02	7.3
130-140	0.24	trace	0.06	1.17	3.50	8.6
140-150	0.17	trace	0.05	1.33	3.42	6.4
150-160	0.20	trace	0.07	1.17	3.37	8.0
160-170	0.20	trace	0.05	1.50	3.65	6.8
170-180	0.22	trace	0.05	1.17	3.77	7.2
180-190	0.11	trace	0.06	1.33	2.67	6.4

Table I.5 (Continued)

Depth cm	Ca	Mg	K cmol(+)/kg	Al	CEC	BS %
<u>Pedon 2</u>						
0-10	0.40	0.31	0.30	1.84	10.11	10.0
10-20	0.29	0.18	0.32	4.34	9.79	8.1
20-30	0.21	0.16	0.25	4.01	10.42	6.0
30-40	0.26	0.15	0.28	6.00	11.29	6.1
40-50	0.23	0.07	0.23	4.50	11.53	4.6
50-60	0.16	0.06	0.25	5.83	10.97	4.3
60-70	0.11	0.04	0.20	4.83	11.05	3.2
70-80	0.13	0.03	0.22	5.33	11.38	3.3
80-90	0.22	0.05	0.29	6.50	11.76	4.8
90-100	0.19	0.04	0.23	5.33	11.96	3.8
100-110	0.18	0.09	0.27	4.83	12.14	4.4
110-120	0.08	0.04	0.30	5.83	11.62	3.6
120-130	0.04	0.03	0.28	5.17	10.95	3.2
130-140	0.10	0.03	0.24	6.33	12.07	3.1
140-150	0.25	0.04	0.27	6.67	11.86	4.7
150-160	0.04	0.03	0.26	4.67	10.63	3.1
160-170	0.04	0.01	0.17	3.84	9.92	2.2
170-180	0.08	0.02	0.24	5.50	10.84	3.1
180-190	0.14	0.03	0.25	4.83	9.72	4.3
190-200	0.29	0.07	0.27	5.17	9.63	6.5
<u>Pedon 3</u>						
0-10	0.28	0.05	0.13	4.00	8.36	5.5
10-20	0.17	0.02	0.09	3.83	7.48	5.1
20-30	0.19	0.02	0.07	3.50	6.58	4.3
30-40	0.14	0.01	0.07	2.67	5.52	4.0
40-50	0.14	0.01	0.07	3.00	5.22	4.2
50-60	0.21	0.06	0.07	2.50	5.14	4.7
60-70	0.16	trace	0.06	2.83	5.02	4.4
70-80	0.33	trace	0.07	2.17	5.40	7.4
80-90	0.30	trace	0.07	2.17	4.67	7.9
90-100	0.14	0.02	0.05	1.67	4.31	7.2
100-110	0.23	trace	0.05	2.17	3.58	7.8
110-120	0.18	trace	0.04	1.83	3.32	6.6
120-130	0.20	trace	0.05	1.83	3.35	7.5
130-140	0.23	trace	0.05	2.17	3.58	7.8
140-150	0.18	trace	0.05	1.67	3.53	6.5
150-160	0.05	trace	0.07	2.33	3.62	6.1
160-170	0.10	trace	0.06	2.33	3.46	4.6

Table I.6 Neutral 1M NH_4OAc extractable cations, cation exchange capacity (CEC) and base saturation (BS).

Depth cm	Ca	Mg	K cmol(+)/kg	Na	Al	CEC	BS %
<u>Pedon 1</u>							
0-10	0.40	0.10	0.36	0.12	1.67	5.18	18.9
10-20	0.19	0.04	0.22	0.08	1.11	4.03	13.2
20-30	0.23	0.03	0.28	0.14	1.22	3.98	17.1
30-40	0.24	0.02	0.15	0.03	1.00	3.34	13.2
40-50	0.28	0.01	0.10	0.07	1.11	3.36	13.7
50-60	0.24	0.01	0.10	0.06	1.11	3.01	13.6
60-70	0.20	0.01	0.10	0.02	1.33	3.03	10.9
70-80	0.15	0.01	0.10	0.05	1.22	3.01	10.3
80-90	0.22	0.01	0.12	0.04	0.78	3.19	12.2
90-100	0.17	0.01	0.10	0.03	0.89	2.91	10.7
100-110	0.17	0.01	0.09	0.01	0.56	2.78	10.7
110-120	0.16	0.01	0.08	0.01	0.67	2.86	9.1
120-130	0.14	0.01	0.08	0.01	0.11	3.04	7.9
130-140	0.27	0.01	0.08	0.01	0.22	3.56	10.1
140-150	0.28	0.01	0.09	0.03	0.11	3.61	11.4
150-160	0.31	0.01	0.09	0.10	0.33	3.61	14.1
160-170	0.32	0.01	0.09	0.05	0.22	3.87	12.1
170-180	0.21	0.01	0.10	0.01	0.22	3.83	8.6
180-190	0.15	0.01	0.08	0.01	0.22	2.76	9.4
<u>Pedon 2</u>							
0-10	0.58	0.23	0.59	0.06	3.00	10.56	13.8
10-20	0.38	0.13	0.38	0.03	2.66	9.92	9.3
20-30	0.30	0.11	0.44	0.03	3.00	10.68	8.2
30-40	0.33	0.09	0.56	0.04	4.11	11.32	6.4
40-50	0.51	0.07	0.38	0.06	4.33	12.42	8.2
50-60	0.38	0.07	0.36	0.07	4.00	11.38	7.7
60-70	0.31	0.06	0.36	0.08	4.88	11.51	7.0
70-80	0.24	0.03	0.33	0.01	3.55	11.61	5.3
80-90	0.44	0.04	0.44	0.01	3.44	12.13	7.7
90-100	0.20	0.04	0.38	0.01	2.89	12.13	5.2
100-110	0.57	0.05	0.36	0.02	3.19	11.70	8.5
110-120	0.15	0.04	0.33	0.01	3.55	11.73	4.5
120-130	0.12	0.03	0.33	0.01	3.89	11.09	4.4
130-140	0.16	0.03	0.31	0.01	3.11	12.20	4.2
140-150	0.32	0.04	0.36	0.04	3.55	12.06	6.3
150-160	0.14	0.04	0.36	0.07	2.44	10.91	5.6
160-170	0.26	0.04	0.28	0.01	2.11	10.29	5.7
170-180	0.16	0.04	0.31	0.01	1.89	11.02	4.7
180-190	0.25	0.04	0.33	0.03	1.89	9.95	6.5
190-200	0.34	0.06	0.33	0.01	1.67	9.72	7.4

Table I.6 Neutral 1M NH_4OAc extractable cations, cation exchange capacity (CEC) and base saturation (BS). (Continued)

Depth cm	Ca	Mg	K	Na	Al	CEC	BS %
Pedon 3							
0-10	0.31	0.04	0.14	0.02	7.10	8.41	6.1
10-20	0.30	0.03	0.10	0.03	5.00	7.56	6.1
20-30	0.26	0.02	0.09	0.03	3.00	6.60	6.1
30-40	0.22	0.02	0.10	0.04	1.67	5.66	6.4
40-50	0.22	0.02	0.11	0.06	1.44	5.41	7.6
50-60	0.24	0.01	0.11	0.03	2.00	5.29	7.4
60-70	0.27	0.01	0.10	0.01	1.67	5.19	7.5
70-80	0.46	0.02	0.11	0.03	2.00	5.62	11.0
80-90	0.26	0.01	0.08	0.02	1.56	4.67	7.9
90-100	0.40	0.02	0.10	0.01	1.89	4.53	11.7
100-110	0.33	0.01	0.08	0.01	1.11	3.73	11.5
110-120	0.21	0.01	0.08	0.02	1.11	3.32	9.6
120-130	0.34	0.03	0.08	0.02	1.00	3.57	13.2
130-140	0.27	0.01	0.08	0.01	1.00	3.67	10.1
140-150	0.36	0.01	0.12	0.03	1.22	3.82	13.6
150-160	0.19	0.01	0.09	0.01	1.22	3.70	8.1
160-170	0.24	0.01	0.11	0.01	1.22	3.67	10.1

Table I.7 Dithionite extractable iron, aluminum, manganese and silicon content

Depth cm	Fe	Al	%	Mn	Si
<u>Pedon 1</u>					
0-10	2.30	0.34		0.004	0.07
10-20	1.54	0.36		0.003	0.07
20-30	2.15	0.32		0.013	0.07
30-40	2.37	0.30		0.003	0.07
40-50	2.95	0.32		0.008	0.09
50-60	3.35	0.30		0.025	0.14
60-70	3.33	0.30		0.007	0.09
70-80	3.14	0.30		0.005	0.10
80-90	3.57	0.34		0.005	0.13
90-100	3.54	0.34		0.007	0.11
100-110	2.86	0.32		0.005	0.09
110-120	3.16	0.33		0.006	0.09
120-130	2.61	0.30		0.009	0.08
130-140	2.56	0.33		0.005	0.09
140-150	2.65	0.32		0.004	0.10
150-160	2.82	0.27		0.005	0.07
160-170	2.78	0.30		0.004	0.11
170-180	2.99	0.34		0.002	0.09
180-190	2.96	0.32		0.007	0.10
190-200	2.76	0.29		0.006	0.09
<u>Pedon 2</u>					
0-10	1.44	0.76		0.003	0.05
10-20	2.16	0.51		0.002	0.05
20-30	1.93	0.37		0.002	0.06
30-40	2.07	0.36		0.002	0.05
40-50	1.63	0.31		0.002	0.05
50-60	2.13	0.41		0.002	0.05
60-70	1.25	0.26		0.002	0.05
70-80	3.00	0.56		0.003	0.05
80-90	2.82	0.87		0.003	0.05
90-100	2.68	0.72		0.003	0.06
100-110	2.59	0.66		0.003	0.06
110-120	1.36	0.36		0.002	0.06
120-130	1.57	0.36		0.002	0.06
130-140	2.51	0.68		0.002	0.07
140-150	2.25	0.76		0.002	0.07
150-160	2.83	0.51		0.002	0.07
160-170	3.65	0.92		0.002	0.07
170-180	3.16	0.81		0.001	0.07
180-190	2.19	0.35		0.001	0.07

Table I.7 Dithionite extractable iron, aluminum, manganese and silicon content (continued)

Depth cm	Fe	Al	%	Mn	Si
<u>Pedon 3</u>					
0-10	0.58	0.15		0.002	0.12
10-20	0.57	0.13		0.002	0.10
20-30	0.62	0.12		0.002	0.11
30-40	0.50	0.13		0.002	0.10
40-50	0.45	0.14		0.002	0.10
50-60	0.49	0.11		0.002	0.10
60-70	0.76	0.13		0.002	0.11
70-80	0.91	0.12		0.002	0.10
80-90	0.78	0.13		0.002	0.10
90-100	0.52	0.13		0.001	0.11
100-110	0.20	0.12		0.002	0.09
110-120	0.31	0.09		0.001	0.10
120-130	0.52	0.14		0.002	0.11
130-140	0.84	0.12		0.002	0.12
140-150	0.82	0.12		0.002	0.13
150-160	0.86	0.10		0.002	0.11
160-170	0.92	0.11		0.002	0.11

Table I.8 Oxalate extractable iron, aluminum, manganese and silicon content

Depth, cm	%, Fe	%, Al	%, Mn	%, Si
<u>Pedon 1</u>				
0-10	0.80	0.30	0.003	0.01
10-20	0.73	0.28	0.002	0.01
20-30	0.69	0.28	0.002	0.02
30-40	0.52	0.26	0.002	0.01
40-50	0.33	0.26	0.008	0.01
50-60	0.25	0.27	0.017	trace
60-70	0.25	0.25	0.004	trace
70-80	0.25	0.24	0.004	trace
80-90	0.21	0.24	0.003	trace
90-100	0.24	0.24	0.004	trace
100-110	0.29	0.25	0.004	trace
110-120	0.21	0.24	0.002	trace
120-130	0.12	0.23	0.005	trace
130-140	0.29	0.23	0.007	trace
140-150	0.17	0.24	0.003	trace
150-160	0.16	0.22	0.004	trace
160-170	0.20	0.21	0.004	trace
170-180	0.20	0.22	0.007	trace
180-190	0.21	0.22	0.005	trace
190-200	0.37	0.20	0.004	trace
<u>Pedon 2</u>				
0-10	0.53	0.45	0.001	0.01
10-20	0.51	0.37	0.001	trace
20-30	0.50	0.33	trace	trace
30-40	0.43	0.33	trace	trace
40-50	0.41	0.30	trace	trace
50-60	0.39	0.34	trace	0.02
60-70	0.37	0.35	trace	0.03
70-80	0.37	0.36	trace	trace
80-90	0.37	0.36	trace	trace
90-100	0.32	0.34	trace	0.01
100-110	0.28	0.34	trace	0.02
110-120	0.19	0.26	trace	0.01
120-130	0.15	0.23	trace	trace
130-140	0.14	0.21	trace	trace
140-150	0.16	0.22	trace	trace
150-160	0.14	0.22	trace	0.01
160-170	0.14	0.18	trace	0.01
170-180	0.13	0.17	trace	0.01
180-190	0.10	0.13	trace	0.01

Table 1.8 Oxalate extractable iron, aluminum, manganese and silicon content (Continued)

Depth, cm	%, Fe	%, Al	%, Mn	%, Si
<u>Pedon 3</u>				
0-10	0.22	0.12	trace	0.05
10-20	0.18	0.12	trace	0.05
20-30	0.15	0.11	trace	0.04
30-40	0.12	0.08	trace	0.05
40-50	0.10	0.07	trace	0.04
50-60	0.08	0.07	trace	0.05
60-70	0.06	0.07	trace	0.05
70-80	0.06	0.08	trace	0.04
80-90	0.04	0.05	trace	0.03
90-100	0.04	0.05	trace	0.04
100-110	0.02	0.04	trace	0.03
110-120	0.02	0.03	trace	0.04
120-130	0.02	0.04	trace	0.05
130-140	0.04	0.04	trace	0.05
140-150	0.02	0.02	trace	0.04
150-160	0.06	0.03	trace	0.04
160-170	0.02	0.04	trace	0.04

Table I.9 Pedon 1: total elemental analysis of fine plus very fine sand fraction
(0.25-0.05 mm)

Element	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	100-120 cm	120-140 cm	140-160 cm	160-180 cm	190 ⁺ cm
SiO ₂ , %	97.70	98.12	98.04	98.37	98.00	98.19	97.77	98.93	97.61	96.96
Al ₂ O ₃ , %	0.58	0.38	0.43	0.41	0.42	0.39	0.38	0.40	0.45	0.97
Fe ₂ O ₃ , %	0.52	0.43	0.43	0.54	0.53	0.62	0.62	0.68	0.67	0.47
MgO, %	0.05	0.03	0.02	0.05	0.08	0.06	0.08	0.04	0.01	0.04
CaO, %	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Na ₂ O, %	0.00	0.00	0.00	0.17	0.00	0.00	0.01	0.00	0.00	0.00
K ₂ O, %	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.21
TiO ₂ , %	0.09	0.09	0.10	0.09	0.10	0.10	0.10	0.10	0.10	0.11
P ₂ O ₅ , %	0.04	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01
MnO, %	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00
S, %	0.00	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00
Ba, ppm	42	27	47	38	40	49	51	47	43	49
Cr, ppm	431	371	358	462	406	536	496	<10	<10	385
Zr, ppm	147	163	180	157	177	169	207	176	186	231
Sr, ppm	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Rb, ppm	<10	<10	<10	<10	<10	<10	13	<10	<10	<10
Y, ppm	<10	<10	11	<10	<10	<10	<10	<10	10	12
Nb, ppm	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Zn, ppm	59	41	31	18	18	13	24	19	28	49
Ni, ppm	<10	<10	<10	11	11	12	10	11	<10	13
V, ppm	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
LOI*, %	0.51	0.17	0.18	0.12	0.12	0.12	0.12	0.13	0.48	

* LOI= Loss on ignition.

Table I.9 Pedon 2: total elemental analysis of fine plus very fine sand fraction
(0.25-0.05 mm)

Element	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	100-120 cm	120-140 cm	140-160 cm	160-180 cm	180-200 cm
SiO ₂ , %	86.38	86.95	76.02	79.08	77.13	75.21	75.48	77.16	80.51	79.73
Al ₂ O ₃ , %	6.96	5.15	9.35	8.17	8.38	9.59	11.41	11.27	9.05	9.78
Fe ₂ O ₃ , %	0.73	3.19	5.41	5.24	7.10	6.99	4.64	3.71	3.15	2.92
MgO, %	0.45	0.31	0.73	0.52	0.47	0.48	0.52	0.48	0.44	0.53
CaO, %	0.04	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02
Na ₂ O, %	0.11	0.23	0.20	0.26	0.25	0.33	0.30	0.25	0.45	0.00
K ₂ O, %	1.59	1.19	2.32	1.93	1.91	2.13	2.46	2.43	2.03	2.16
TiO ₂ , %	1.04	0.31	0.34	0.36	0.37	0.44	0.54	0.54	0.46	0.48
P ₂ O ₅ , %	0.01	0.06	0.11	0.10	0.10	0.10	0.12	0.09	0.04	0.06
MnO, %	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01
S, %	0.01	0.01	0.00	0.00	0.01	0.02	0.01	0.01	0.01	0.01
Ba, ppm	202	166	262	220	219	251	280	296	251	212
Cr, ppm	35	505	313	423	338	322	302	234	230	219
Zr, ppm	447	117	125	121	123	132	157	167	150	152
Sr, ppm	44	12	20	17	18	22	30	27	19	19
Rb, ppm	82	66	143	108	105	113	132	127	107	116
Y, ppm	35	14	17	18	18	21	21	24	18	22
Nb, ppm	28	<10	<10	<10	<10	11	<10	10	<10	<10
Zn, ppm	29	40	69	56	62	62	60	57	50	64
Ni, ppm	<10	23	65	19	32	13	<10	<10	<10	<10
V, ppm	30	27	56	38	46	67	42	55	31	40
LOI, %	1.59	1.59	3.00	2.59	3.08	3.54	3.23	2.96	2.43	2.58

Table I.9 Pedon 3: total elemental analysis of fine plus very fine sand fraction
(0.25-0.05 mm)

Element	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	100-120 cm	120-140 cm	140-160 cm	180 ⁺ cm
SiO ₂ , %	96.84	96.81	97.24	97.34	97.38	98.20	97.10	97.27	97.56
Al ₂ O ₃ , %	0.82	0.85	0.88	1.14	1.19	0.77	0.81	0.86	0.95
Fe ₂ O ₃ , %	0.58	0.52	0.61	0.65	0.40	0.52	0.81	0.69	0.53
MgO, %	0.03	0.00	0.03	0.03	0.08	0.15	0.09	0.06	0.10
CaO, %	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Na ₂ O, %	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K ₂ O, %	0.16	0.17	0.18	0.25	0.27	0.17	0.18	0.19	0.21
TiO ₂ , %	0.16	0.14	0.15	0.15	0.10	0.06	0.08	0.09	0.10
P ₂ O ₅ , %	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00
MnO, %	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S, %	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Ba, ppm	48	49	64	71	68	48	38	43	43
Cr, ppm	471	415	438	426	303	403	464	463	413
Zr, ppm	232	189	182	206	155	97	120	122	141
Sr, ppm	<10	<10	<10	<10	<10	<10	<10	<10	<10
Rb, ppm	<10	<10	<10	<10	<10	<10	<10	<10	<10
Y, ppm	13	11	13	13	13	<10	10	<10	10
Nb, ppm	<10	<10	<10	<10	<10	<10	<10	<10	<10
Zn, ppm	37	57	17	16	20	20	15	14	11
Ni, ppm	<10	<10	13	21	19	19	31	11	<10
V, ppm	<10	<10	<10	<10	<10	<10	<10	<10	<10
LOI, %	0.13	0.18	0.17	0.20	0.24	0.16	0.17	0.18	0.44

Table 1.10 Pedon 1: total elemental analysis of fine earth fraction.

Element	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	100-120 cm	120-140 cm	140-160 cm	160-180 cm	180 ⁺ cm
SiO ₂ , %	64.79	69.50	70.35	66.86	69.81	70.88	68.04	68.73	71.27	83.82
Al ₂ O ₃ , %	12.22	13.22	13.64	13.45	14.11	14.41	15.13	15.17	14.21	8.59
Fe ₂ O ₃ , %	4.86	5.29	5.45	5.58	5.66	5.51	5.58	5.69	5.52	3.43
MgO, %	0.40	0.41	0.39	0.40	0.40	0.38	0.37	0.35	0.32	0.25
CaO, %	0.03	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.01
Na ₂ O, %	0.00	0.06	0.02	0.00	0.30	0.37	0.00	0.00	0.09	0.09
K ₂ O, %	1.23	1.31	1.31	1.24	1.28	1.29	1.42	1.48	1.39	1.09
TiO ₂ , %	0.80	0.86	0.88	0.86	0.89	0.89	0.85	0.84	0.80	0.43
P ₂ O ₅ , %	0.08	0.05	0.05	0.05	0.05	0.03	0.05	0.03	0.02	0.01
MnO, %	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
S, %	0.00	0.01	0.01	0.00	0.01	0.00	0.02	0.01	0.00	0.00
Ba, ppm	205	194	207	209	185	188	212	234	222	123
Cr, ppm	87	71	83	84	83	100	76	81	77	57
Zr, ppm	285	343	340	324	344	341	347	326	327	228
Sr, ppm	38	44	39	40	40	43	45	47	43	31
Rb, ppm	81	91	89	86	90	88	90	99	94	58
Y, ppm	30	33	33	31	33	29	32	30	30	21
Nb, ppm	10	16	15	12	13	14	16	15	12	<10
Zn, ppm	54	54	51	53	67	66	67	75	65	37
Ni, ppm	55	16	19	15	18	84	8	29	28	<10
V, ppm	88	103	101	103	102	114	111	103	98	48
LOI, %	9.70	7.318	6.62	6.45	6.48	6.029	6.272	6.078	5.66	

Table I.10 Pedon 2: total elemental analysis of fine earth fraction.

Element	0-20	20-40	40-60	60-80	80-100	100-120	120-140	140-160	160-180	180-200	200+
	cm	cm	cm	cm	cm	cm	cm	cm	cm	cm	cm
SiO ₂ , %	63.21	63.83	61.98	63.50	62.31	62.79	64.19	64.25	65.77	65.47	62.63
Al ₂ O ₃ , %	15.88	17.84	17.97	18.09	18.38	18.79	18.73	18.69	17.36	17.19	17.63
Fe ₂ O ₃ , %	4.34	4.53	6.71	5.93	6.47	5.52	4.67	4.78	5.37	5.33	5.86
MgO, %	0.64	0.64	0.72	0.65	0.77	0.75	0.69	0.65	0.65	0.60	0.62
CaO, %	0.04	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.03
Na ₂ O, %	0.31	0.38	0.11	0.35	0.64	0.26	0.22	0.41	0.22	0.25	0.07
K ₂ O, %	3.10	2.56	3.63	3.66	3.68	3.78	0.75	3.76	3.44	3.39	3.46
TiO ₂ , %	0.72	0.74	0.68	0.70	0.71	0.72	0.72	0.75	0.70	0.71	0.70
P ₂ O ₅ , %	0.07	0.06	0.06	0.06	0.07	0.08	0.05	0.05	0.07	0.04	0.08
MnO, %	0.01	0.01	0.03	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.02
S, %	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01
Ba, ppm	351	366	424	415	401	387	411	402	373	360	382
Cr, ppm	66	56	61	58	63	68	55	57	60	57	54
Zr, ppm	253	242	217	241	233	230	221	243	268	296	257
Sr, ppm	46	48	53	55	53	50	52	54	47	48	49
Rb, ppm	196	207	208	206	202	205	206	207	186	188	200
Y, ppm	29	32	29	32	32	33	33	37	32	35	34
Nb, ppm	14	18	15	16	15	14	17	15	14	13	14
Zn, ppm	56	52	70	65	68	70	57	14	40	65	63
Zi, ppm	<10	<10	12	40	<10	<10	<10	<10	0	20	27
V, ppm	68	88	95	82	80	78	92	87	85	42	84
LOI, %	8.37	8.22	6.19	5.99	6.04	6.19	6.10	5.67	5.52	58	6.75

Table I.10 Pedon 3: total elemental analysis of fine earth fraction.

Element	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	100-120 cm	120-140 cm	140-160 cm	180 ⁺ cm
SiO ₂ , %	78.01	85.58	79.18	83.48	80.52	81.53	89.02	84.37	79.92
Al ₂ O ₃ , %	5.73	6.93	8.62	8.92	8.20	6.16	6.43	6.50	6.32
Fe ₂ O ₃ , %	1.05	1.31	1.34	1.69	1.34	0.92	1.30	1.28	1.20
MgO, %	0.19	0.22	0.24	0.20	0.20	0.12	0.18	0.15	0.17
CaO, %	0.02	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.01
Na ₂ O, %	0.00	0.00	0.35	0.00	1.67	0.73	0.53	0.00	0.06
K ₂ O, %	0.88	1.05	1.10	1.50	1.47	1.12	1.20	1.19	1.18
TiO ₂ , %	0.38	0.41	0.43	0.37	0.25	0.17	0.19	0.19	0.18
P ₂ O ₅ , %	0.03	0.00	0.02	0.00	0.01	0.01	0.00	0.01	0.02
MnO, %	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S, %	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00
Ba, ppm	146	162	112	178	162	144	152	176	149
Cr, ppm	32	37	58	49	26	15	21	30	32
Zr, ppm	268	326	221	269	172	104	127	135	134
Sr, ppm	24	24	29	28	20	11	12	13	12
Rb, ppm	47	63	55	85	73	55	56	61	62
Y, ppm	20	20	20	21	15	14	14	14	14
Nb, ppm	<10	<10	<10	<10	<10	<10	<10	<10	<10
Zn, ppm	22	26	49	37	53	35	41	24	28
Zi, ppm	<10	<10	<10	44	<10	<10	11	14	<10
V, ppm	6	22	63	37	23	<10	16	19	24
LOI, %	3.445	2.77	2.67	2.80	3.27	1.87	1.86	2.00	1.81

Table I.11 Contents of zirconium, potassium in
0.05-0.2 mm sand fraction.

Depth	Zr	K
cm	ug/g	mg/g
<u>Pedon 1</u>		
0-20	147	0.6
20-40	163	0.5
40-60	180	0.5
60-80	157	0.5
80-100	177	0.5
100-120	169	0.5
120-140	207	0.5
140-160	176	0.5
160-180	186	0.6
180-200	231	1.7
<u>Pedon 2</u>		
0-20	-	-
20-40	117	15.9
40-60	125	19.3
60-80	121	16.0
80-100	123	15.8
100-120	132	17.6
120-140	157	20.4
140-160	167	20.1
160-180	150	16.8
180-200	152	17.9
<u>Pedon 3</u>		
0-20	232	1.3
20-40	189	1.4
40-60	182	1.5
60-80	206	2.3
80-100	155	2.2
100-120	97	1.4
120-140	120	1.5
140-160	122	1.6
160-180	141	1.7

Appendix II: Quantitative evaluation

Appendix II Quantitative evaluation of pedon 1

A column of original soil materials one square cm in cross-section was used as the basis for quantitatively evaluating gains or losses of soil volume, soil weight, and weight changes of the mobile components of pedon 1 profile.

In order to better understand the calculations carried out for Table II.1, the 0-20 cm layer of pedon 1 soil is used here to illustrate the calculation procedures.

The calculations are made based on assumptions that the initial least weathered (or reference) materials are located at 140-180 cm from the surface. These materials have the following average properties:

- a. Bulk density of fine earth fraction (Figure 4.2)
= 1.345 Mg/m³
- b. Clay content (Table I.1)
= 37.75%
- c. Dithionite-citrate-extractable Fe (Table I.7)
= 2.81%
- d. Dithionite-citrate-extractable Al (Table I.7)
= 0.31%

The calculation procedures are:

- (1) Present volume (cc/layer)
= 20 cc
- (2) Present bulk density (g/cc) : from table 1.2.
= 0.94
- (3) Present wt of soil (g/layer)
= present volume of soil (cc/layer)
X present bulk density (g/cc)
= 20 X 0.94
= 18.80
- (4) Present index mineral (mg/g) : calculated
= 0.147
from Table 1.11,
for Zr content.
- (5) Original bulk density (g/cm³) : see figure 4.2, for
= 1.345
assumed trend of bulk
density in parent
material.

- (6) Present wt. of index mineral (mg/layer) : Table I.11
 = index mineral (mg/g) X present wt. of soil
 = 0.147 X 18.80
 = 2.76
- (7) Original wt. of index mineral (mg/layer) : obtain
 = assumed original index mineral (mg/g) assumed
 X assumed original bulk density (g/cc) original
 X present volume (cc) Zr content
 = 0.160 X 1.345 X 20 from Figure
 = 4.30 4.1
- (8) Correction factor
 Present wt of index mineral (mg/layer)
 =
 = $\frac{\text{original wt of index mineral (mg/layer)}}{\text{original wt of index mineral (mg/layer)}}$
 = 2.76/4.30
 = 0.64
- (9) Present wt of clay (g/layer)
 = percent of clay (calculated from Table I.1)
 X present wt of soil (g/layer)
 = 33.65 % X 18.80
 = 6.33
- (10) Original volume (cc/layer)
 = present volume (cc/layer) X correction factor
 = 20 X 0.64
 = 12.8
- (11) Original wt of soil (g/layer)
 = original bulk density (g/cc) X original vol. (cc/layer)
 = 1.345 X 12.8
 = 17.2
- (12) Original wt of clay (g/20cc)
 = Average present wt of clay of reference horizon (g/20cc)
 X assumed original bulk density of of reference horizon
 X present volume
 = 37.75% X 1.345 X 20
 = 10.15
- (13) Original wt of clay (g/layer)
 = original wt of clay (g/20cc) X correction factor
 = 10.15 X 0.64
 = 6.50
- (14) Changes in wt of soil (g/layer)
 = present wt of soil (g/layer)
 - original wt of soil (g/layer)
 = 18.8 - 17.2
 = +1.6

- (15) Changes in wt of soil (%)

$$= \frac{\text{changes in wt of soil (g/layer)}}{\text{original wt of soil (g/layer)}} \times 100$$

$$= 1.6/17.2 \times 100$$

$$= 9.30$$
- (16) Changes in wt of clay (g/layer)

$$= \text{present wt of clay (g/layer)} - \text{original wt of clay (g/layer)}$$

$$= 6.33 - 6.50$$

$$= -0.17$$
- (17) Changes in wt of clay (%)

$$= \frac{\text{changes in wt of clay (g/layer)}}{\text{original wt of clay (g/layer)}} \times 100$$

$$= -0.17/6.50 \times 100$$

$$= -2.6$$
- (18) Changes in volume of soil (cc/layer)

$$= \text{present volume (cc/layer)} - \text{original volume (cc/layer)}$$

$$= 20.0 - 12.8$$

$$= 7.2$$
- (19) Changes in volume of soil (%)

$$= \frac{\text{changes in volume of soil (cc/layer)}}{\text{original volume of soil (cc/layer)}} \times 100$$

$$= 7.2/12.8 \times 100$$

$$= 56$$
- (20) Present wt of dithionite extractable Fe (mg/layer)

$$= \text{Fe (\%)} \times \text{present bulk density (g/cc)} \times \text{present volume (cc/layer)} \times 10$$

$$= 1.92\% \times 0.94 \times 20 \times 10$$

$$= 361$$
- (21) Present wt of dithionite extractable Al (mg/layer)

$$= \text{Al (\%)} \times \text{present bulk density (g/cc)} \times \text{present volume (cc/layer)} \times 10$$

$$= 0.35\% \times 0.94 \times 20 \times 10$$

$$= 65.8$$
- (22) Original wt of dithionite extractable Fe (mg/20cc)

$$= \text{Average present \% of Fe of reference horizon (mg/20cc)} \times \text{assumed original bulk density of reference horizon} \times \text{present volume (cc)} \times 1000$$

$$= 2.81 \times 1.345 \times 20 \times 1000$$

$$= 756$$

- (23) Original wt of dithionite extractable Fe (mg/layer)
 = original wt of Fe (mg/20cc) X correction factor
 = 756 X 0.64
 = 483
- (24) Original wt of dithionite extractable Al (mg/20cc)
 = Average present % of Al of reference horizon (mg/20cc)
 X assumed of original bulk density of reference horizon
 X present volume (cc) X 1000
 = 0.31 % X 1.345 X 20 X 1000
 = 83.4
- (25) Original wt of dithionite extractable Al (mg/layer)
 = original wt of Al (mg/20cc) X correction factor
 = 83.4 X 0.64
 = 53.4
- (26) Changes in wt of dithionite extractable Fe (mg/layer)
 = present wt of Fe (mg/layer)
 - original wt of Fe (mg/layer)
 = 361 - 483
 = -122
- (27) Changes in wt of dithionite extractable Fe (%)
 changes in wt of Fe (mg/layer)
 = $\frac{\text{changes in wt of Fe (mg/layer)}}{\text{original wt of Fe (mg/layer)}} \times 100$
 = -122/483 X 100
 = -25
- (28) Changes in wt of dithionite-extractable Al (mg/layer)
 = present wt of Al (mg/layer)
 - original wt of Al (mg/layer)
 = 65.8 - 53.4
 = 12.4
- (29) Changes in wt of dithionite extractable Al (%)
 changes in wt of Al (mg/layer)
 = $\frac{\text{changes in wt of Al (mg/layer)}}{\text{original wt of Al (mg/layer)}} \times 100$
 = 12.4/53.4 X 100
 = 23

Table II.1 Quantitative evaluation of pedon 1.

Horizon	Depth cm	Present volume	Present bulk density	Present wt. of soil	Index mineral Zr content in 0.25-0.05 mm fraction	Original bulk density	wt. of index mineral	
		g/cc	g/layer	g/layer	mg/g	g/cc	present mg/layer	original mg/layer
		(1)	(2)	(3)	(4)	(5)	(6)	(7)
A	0-20	20	0.94	18.80	0.147	1.345	2.76	4.30
Bw1	20-40	20	1.13	22.60	0.163	1.345	3.68	4.41
"	40-60	20	1.22	24.40	0.180	1.345	4.39	4.46
Bw2	60-80	20	1.30	26.00	0.157	1.345	4.08	4.57
"	80-100	20	1.17	23.40	0.177	1.345	4.14	4.65
"	100-120	20	1.28	25.60	0.169	1.345	4.33	4.73
BC	120-140	20	1.30	26.00	0.207	1.345	5.38	4.83
"	140-160	20	1.33	26.60	0.176	1.345	4.68	4.92
"	160-180	20	1.36	27.20	0.186	1.345	5.06	5.00

(2) from table I.2.

(3) = (2) X (1)

(4) = Zr content in the 0.25 - 0.05 mm sand fraction (from Table I.11)

(5) from figure 4.2, assumed original bulk density trend

(6) = (4) X (3)

(7) = (assumed original index mineral) X (5) X (1)

Table II.1 (Continued)

Horzion	Depth cm	correc- tion factor	Present wt. of clay g/layer	Original volume cc/layer	Original wt. of soil g/layer	Original wt. of clay		Changes in wt. of soil	
						g/20cc	g/layer	g/layer	%
		(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
A	0-20	0.64	6.33	12.8	17.2	10.15	6.50	+1.6	+9.3
Bw1	20-40	0.83	7.70	16.6	22.3	10.15	8.42	+0.3	+1.3
"	40-60	0.98	8.76	19.6	26.4	10.15	9.95	-2.0	-7.6
Bw2	60-80	0.89	9.38	17.8	23.9	10.15	9.03	+2.1	+8.8
"	80-100	0.90	8.47	18.0	24.2	10.15	9.14	-0.8	-3.3
"	100-120	0.92	9.10	18.4	24.9	10.15	9.34	+0.7	+3.0
BC	120-140	1.11	9.89	22.0	29.6	10.15	11.27	-3.6	-12.2
"	140-160	0.95	10.44	19.0	25.6	10.15	9.64	+1.0	+0.4
"	160-180	1.01	9.75	20.2	27.2	10.15	10.25	0	0

(8) = (6)/(7)
 (9) = (% of clay, Table I.1) X (3)
 (10) = (1) X (8)
 (11) = (5) X (10)
 (12) = as described in the example
 (13) = (12) X (8)
 (14) = (3) - (11)
 (15) = (14)/(11) X 100

Table II.1 (Continued)

Horzion	Depth cm	Changes in wt. of clay		Changes in volume of soil		Present wt. of Fe-d		Present wt. of Al-d		Original wt. of Fe-d	
		g/layer	%	mg/layer	%	mg/layer	(19)	mg/layer	(21)	mg/20cc	mg/layer
		(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)		
A	0-20	-0.17	-3	+7.2	+56	361	65.8	756	483		
Bw1	20-40	-0.72	-9	+3.4	+20	511	70.1	756	627		
"	40-60	-1.19	-12	+0.4	+2	769	75.6	756	741		
Bw2	60-80	+0.35	+4	+2.2	+12	842	78.0	756	673		
"	80-100	-0.67	-7	+2.0	+11	833	79.6	756	680		
"	100-120	-0.24	-3	+1.6	+9	771	84.5	756	696		
BC	120-140	-1.38	-12	-2.2	+10	673	83.2	756	839		
"	140-160	+0.30	+8	+0.8	+4	729	79.8	756	718		
C	160-180	-0.36	-4	-0.2	-1	786	87.0	756	764		

(16) = (9) - (13)

(17) = (16)/(13) X 100

(18) = (1) - (10)

(19) = (18)/(10) X 100

(20) = (Fe-d % from table I.7) X (3) X 10

(21) = (Al-d % from table I.7) X (3) X 10

(22) = as described in the example

(23) = (22) X (8)

Table II.1 (Continued)

Horizon	Depth	Original		Changes in		Changes in	
		wt. of Al-d	wt. of Fe-d	wt. of Al-d	wt. of Fe-d	wt. of Al-d	wt. of Fe-d
		mg/20cc	mg/layer	mg/layer	%	mg/layer	%
		(24)	(25)	(26)	(27)	(28)	(29)
A	0-20	83.4	53.4	-122	-25	+12.4	+23
Bw1	20-40	83.4	69.2	-116	-19	+0.9	+1
"	40-60	83.4	81.7	+28	+4	-6.1	-7
Bw2	60-80	83.4	74.2	+169	+25	+3.8	+5
"	80-100	83.4	75.1	+153	+23	+4.5	+6
"	100-120	83.4	76.7	+75	+11	+7.8	+10
BC	120-140	83.4	92.6	-166	-20	-9.4	-10
"	140-160	83.4	79.2	+11	+2	+0.6	+1
C	160-180	83.4	84.2	0	+3	+2.8	+3

(24) = as described in the example

(25) = (24) X (8)

(26) = (20) - (23)

(27) = (26)/(23) X 100

(28) = (21) - (25)

(29) = (28)/(25) X 100

Appendix III: Thin Section Studies

Pedon 1: Typic Dystrochrept, fine, vermiculitic, thermic	A-33
Horizon: A, 0-10 cm	A-33
Horizon: Bw1, 45-50 cm	A-35
Horizon: BC, 140 cm	A-37
 Pedon 2: Typic Dystrochrept, fine, illitic, thermic ..	A-39
Horizon: A, 0-10 cm	A-39
Horizon: Bw, 50 cm	A-41
 Pedon 3: Typic Hapludult, fine-loamy, siliceous, thermic	A-44
Horizon: A, 0-10 cm	A-44
Horizon: Bt, 70 cm	A-46

Appendix III Thin Section Studies

Pedon 1: Typic Dystrochrept, fine, vermiculitic, thermic

Horizon: A₁ 0-10 cm

1. Microstructure

(A) Types: Crumb, granular and vughy structures.

(B) Peds

- (a) Crumb: strongly-developed; 50 % of the area; mainly 0.3-2.5 mm (ultrafine to medium); surface (5X) of finer crumbs is generally rough and larger ones undulating; unaccommodated; random basic distribution.
- (b) Granular: strongly-developed; 10% of the area; generally < 500 μ m in diameter; undulating to rough surface; un-accommodated; random basic distribution.
- (c) Vugh: numerous irregularly shaped vughs break the continuity of the fine material; channels average 100 μ m width; occasional chambers present.

(C) Voids: Total porosity (< 30 μ m) approx. 20%

- (a) Inter-aggregate pores mainly consist of compound packing voids (20% of the area); width is generally < 250 μ m; mainly rough walls; random arrangement; these voids vary with size ranging from 25 μ m to 2 mm across, most occur as 100 μ m across; irregular shape with rough to undulating surface.
- (b) Intra-aggregate pores consist of irregular meso- (ca. 25 mm) to micro (ca. 0.25 mm) vughs; occupy < 5% of the area.

2. Basic Mineral Components:

coarse/fine limit at 10 μ m = 20 : 80

(A) Coarse material:

- (a) Quartz: the predominant fraction of coarse material; wide range of size (10-1000 μ m), of which 60% of quartz grains have the size between 150-300 μ m in diameter; poorly sorted; mainly smooth, subround to subangular; random basic distribution.
- (b) Muscovite: trace amount; size approx. 50-100 μ m; smooth, round to subround; well sorted.
- (c) Zircon: trace amount; size ca. 50 μ m; smooth, subround to euhedral, random basic distribution.

- (d) Tourmaline: trace amount; size ca. 20 μm ; smooth, subround; random basic distribution.
- (B) Fine material: brownish yellow (10YR 6/8) clay to fine silt material containing some optically amorphous iron oxides.

3. Basic Organic Components

Coarse/fine limit at 10 μm

- (A) Coarse fraction: occupies 5% of the area.

Mainly consists of plant residues: cross section of living roots (0.3-0.6 mm in diameter) with all cells visible; some longitudinal sections of living roots (4 mm long) are also visible; others are dark brown to black, partially decomposed and fragmented plant tissues (mainly cell walls of roots); their size varies widely from 10 μm to 3 mm.

Some single and 4-5 clusters of circular shaped (cross-sectional view, ca. 90 μm across) or oval shaped (longitudinal sectional view, ca. 120 μm at long-axis) plant organs (most likely spores of fern?) are randomly distributed. These plant organs enclosed in a multilayered cell wall case, ca. 300 μm in diameter, which may be clearly recognizable or partially to completely decomposed.

- (B) Fine fraction

If present, occurs mainly as a component of micromass which it impregnated. Fine material is yellowish brown with a diffuse boundary and is isotropic.

4. Groundmass

c/f limit of 10 μm : ratio of 25 : 75

Coarse material is randomly distributed.

The fine material is undifferentiated b-fabric with single to double spaced porphyric.

5. Pedofeatures

- (A) Textural: Very thin (approx. 10 μm thick) discontinuous limpid clay coating on the surface of silt and sand grains, no particular side is preferentially coated.
- (B) Amorphous and cryptocrystalline: Brown to dark brown, impregnative, isotropic materials randomly distributed with round, subround and irregular shapes; size ranging from < 5 μm to 400 μm .

Horizon: Bw1, 45-50 cm

1. Microstructure

(A) Types: crumb, granular and subangular blocky

(B) Peds:

(a) Granular: strongly developed; 10% of the area; 0.1 mm in diameter; smooth surface; unaccommodated; random basic distribution.

(b) Crumb: moderately developed; 20% of the area; 1.0 mm in diameter; undulating to rough surface; partially to unaccommodated; random basic distribution.

subangular blocky: moderately developed; 50% of the total area; accommodated to partially accommodated; random basic distribution.

(C) Voids:

(a) Inter-aggregates: these pores, associated with crumbs and/or granular peds, consist of compound packing voids; 10% of the area; width is approx. 300 μ m; mainly undulating to rough walls; partially to unaccommodated; pores, associated with subangular blocky structures consist of planar voids; their width ranging from 50-100 μ m; accommodated.(b) Intra-aggregates: pores consist of channels approx. 10 μ m wide; unaccommodated; random distribution.Vughs: 250-750 μ m; undulating wall surface; 2% of the area; irregular shape; total estimated porosity : 5-10%.

2. Basic mineral components:

c/f limit at 10 μ m = 25 : 75

(A) coarse material: single mineral grains all are randomly distributed.

(a) Quartz: is predominant coarse material; size ranges widely from 10 μ m to 1.25 mm; poorly sorted; the larger ones (> 100 μ m in diameter) are rounded to subrounded; the smaller ones (< 100 μ m in diameter) are subangular blocky; 25% of total thin section; mica and fluid inclusions.(b) mica, tourmaline and zircon: trace amount; 10-40 μ m.(c) chert: some round to subround chert fragments approx 175 μ m in diameter are randomly distributed; presumably siliceous material.

(B) Fine material: brownish yellow (10 YR 6/8) clay to fine silt material impregnated with optically amorphous iron-oxides (presumably goethite).

The fine material is isotropic.

3. Basic Organic components

c/f limit at 10 μm = 90:10

(A) Coarse material:

Plant residues, mainly living roots (300 μm in diameter, 2 mm long) with all cells visible; others are dark brown to black partially-decomposed plant tissues (up to 2.5 mm across) with cell walls visible. Some amorphous isotropic organic materials with wide range of size (10 μm to 200 μm) and variable shapes. Faunal dropping of 60 X 75 μm .

Some oval shaped plant residues, 90 X 125 μm^2 with well preserved internal organization are identical to those found in upper horizon but with less abundance.

(B) Fine material:

occurs mainly as a component of micromass which it impregnates; fine material is yellowish brown with diffuse boundary and is isotropic.

4. Groundmass

Coarse to fine limit of 10 μm = 25:75

The coarse material is random fabric

The fabric of micromass is undifferentiated

The c/f related distribution is mainly double spaced porphyric.

5. Pedofeatures

(A) Textural: rare and very thin (approx. < 10 μm) discontinuous limpid clay coatings on the surfaces of some silt and sand particles, with no particular side preferentially coated.

(B) Amorphous and crypocrystalline:

The soil matrix is uniformly impregnated with brownish yellow amorphous material (presumably hydrous iron oxides).

(C) Excrements:

Ellipisoids are located within the voids of plant (leaves) residues. The size varies very little, approx. 90 μm and 125 μm for short and long axis respectively. The surface is smooth to undulating (40 X). The color (PPL) varies from brownish red to dark brown. The excrements mainly coalesce to dense, undifferentiated masses.

Horizon: BC, 140 cm

1. Microstructure: Apedal soil material, without clod or fragments, dominated by channel structure and with minor vughs structure.
 - (A) Channel structure: channels have wide range of width (100-800 μm) and straight with smooth to undulating walls (5 X); 5% of total area; strongly oriented and parallel; Random and parallel distribution.
 - (B) Vughs structure: Elongated; sizes vary widely up to 2 mm across; subround to angular; undulating to rough wall; occupy 2% of total area; random basic distribution.
Total porosity estimated as 5-10 % of total thin section.
2. Basic Mineral Component.
c/f limit at 10 μm ; ratio of 25: 75
 - (A) Coarse material : consists of single mineral grains which are almost entirely quartz grains with trace amount of zircon and tourmaline.
 - (a) Quartz: size varies widely ranging from 10 to 750 μm ; unsorted; random distribution; sub-round to subangular; approx. 100% of total coarse fraction and 20% of total area; fluid inclusions.
 - (B) Other minerals including trace amount of mica, zircon and tourmaline; size approx. 10-40 μm , random distribution.
 - (C) Fine material: clay to fine silt; reddish yellow (7.5 YR 6/8); striated b-fabric.
3. Basic organic compounnts: absent
4. Ground mass:
Medium cross striated b-fabric
The c/f related distribution is many single to double spaced porphyric.
5. Pedofeatures:
 - (A) Textural: most coarse materials (mainly quartz grains) and some voids have coatings of clay; their thickness varies from 10 to 80 μm .
The coatings are usually continuous along sides of quartz grains.
 - (B) Amorphous and Cryptocrystalline: brown to dark brown isotropic pure nodules range from 10 to 700 μm in size; shapes vary (round to elongate); boundaries sharp; edges smooth to undulating;

very few grains have reddish coatings, presumably Fe-oxides.

Pedon 2: Typic Dystrochrept, fine, illitic, thermic

Horizon: A, 0-10 cm

1. Microstructure:

(A) Types: Crumb, granular and subangular blocky.

(B) Peds:

- (a) Crumb: strongly to moderately developed; mainly 1.25 mm; surface (5 X) is generally rough; unaccommodated; random basic distribution.
- (b) granular: strongly developed (10 % of total structures); mainly 0.1 mm; surface (5 X) is undulating to smooth; clustered basic distribution.
- (c) subangular blocky: moderately developed; 40% of total area; size ranging from 0.3 mm to mm; surface (5 X) undulating to smooth; accommodated; random.

(C) Voids:

- (a) Inter-aggregate voids consist mainly of compound packing voids and some planar voids.
 - (i) compound packing voids between crumbs granules, and plant fragments; wide range of size from 50 to 500 μ m; 10% of the area; irregular shapes; random arrangement.
 - (ii) planar voids: separating subangular blocky peds; 5% of the area; width 20-250 μ m; undulating to smooth and curved walls.
 - (iii) occasional channels, chambers are present; they occupy < 2% of the area; channels are 250 μ m wide and chambers are 250 μ m in diameter; both are random distributed.
- (b) Intra-aggregate pores: packing voids within aggregates and between partially fused aggregates; irregular shape; size mainly 50 μ m; undulating (5 X) walls; < 2% of the area.

2. Basic mineral components

c/f limit at 10 μ m; ratio of 25:75.

(A) Coarse fraction:

- (a) single mineral grains: all mineral grains are randomly distributed.
- (b) Quartz: the majority of grains averages approx. 25 μ m (> 90% of total coarse frac-

- tion; 25% of thin section area) but large ones up to 750 μm are present; well-sorted; round to subangular blocky with smooth surface; mica (ca. 5 μm) and fluid inclusions.
- (c) mica: mainly acicular grains with sizes 100-140 μm long, 10-20 μm wide; well-sorted; < 2% of total coarse fraction.
 - (d) Zircon: trace amount; 20 X 40 μm , euhedral or subangular blocky; well-sorted.
 - (e) Chert fragments: trace amount; size 200-400 μm in diameter; round to subround with smooth surface (5 X); presumably siliceous material; occasional irregular shaped quartz of < 50 μm in size were included.
 - (f) shale fragments; trace amount; smaller than 400 μm across; subangular blocky with smooth surface.

(B) Fine fraction:

Clay to fine silt materials; speckled yellowish brown.

3. Basic Organic Components:

c/f limit at 20 μm = ratio of 20:80

- (A) Coarse organic material: plant residues; root sections up to 1.1 mm in diameter and up to 4 mm long; some are living roots with all cells visible, others are plant residues at various stages of decomposition.

- (B) Fine material:

occurs mainly as components of micromass which it impregnates; it is yellowish brown to reddish brown and isotropic.

4. Groundmass:

c/f limit at 10 μm

speckled b-fabric.

Fine material occurs as partial to complete thin coats on grains with single spaced porphyric related distribution.

5. Pedofeatures:

- (A) Textural: impurity clay containing contrasted particles of fine to coarse silt-size; thin (< 10 μm) discontinuous laminated clay coatings around the sides of quartz grains and surfaces of some voids, no particular side is preferentially coated.

- (B) Amorphous and cryptocrystalline: impregnative amorphous and crypto-crystalline materials with orange in color (PPL); some fragments of iron concretions, occupying 5% of the total area, are

hypo-coatings and quasi-coatings of planar voids; detailed description of iron-concretions is described under the code name TS 8576 thin section.

- (C) Excrement: dark brown coalesced dense to very dense excrements occupy <1% of the area; size approx. 40 μm in diameter. The surface ranges from rough for dense excrements to smooth for very dense ones; most of them occur in the chambers of decayed leaf residues and some found in the voids or soil matrix.

Horizon: Bw 50 cm

1. Microstructure

(A) Types: crumbs, subangular blocky

(B) Peds:

(a) Crumbs: strongly to moderately developed; <1% of total thin section area; size varies widely from <50 μm to >3 mm, most being 250 μm across; undulating surface with faces of the crumbs are mainly unaccommodated; clustered basic distribution.

(b) Subangular blocky: moderately developed; over 50% of total thin section area; mostly fine (1-5 mm across); surfaces are smooth with accommodated faces; random basic distribution.

(C) Voids: total porosity <10% of total thin section area

(a) Inter-aggregate voids consist mainly of compound packing voids, vughs and some planar voids.

(i) compound packing voids: occurring between crumbs; wide range of size, 50 μm to 1.3 mm; irregular shapes; <1% of total thin section area; undulating walls; larger sizes are mostly vertical.

(ii) vughs: irregular shaped, elongated (mostly 0.5 mm wide); undulating walls; <10% of total thin section area.

(iii) planar voids: separating subangular blocky voids; mostly 0.25 mm wide with smooth walls and cracked patterns; <0.1% of total thin section area.

(b) Intra-aggregate pores: voids within crumbs and subangular blocky peds; irregular shapes; usually 50 to 200 μm in size; random basic distribution.

2. Basic Mineral Components

c/f limit at 10 μm : ratio of 25: 75

(A) Coarse fraction:

(a) Single grain minerals: all mineral grains are randomly distributed.

(i) Quartz: the majority of grain size; 10% of total area; size varying from 10 μm to 120 μm with average of 30 μm across; moderately sorted; mostly are angular to subangular block, with some smaller ones being round; open porphyric related distribution.

(ii) mica: acicular shape; mostly <300 μm long and 20 μm wide; smooth surface; poorly sorted; occasional large mica rectangular flakes (up to 350 X 250 μm) with foliated fractures.

(iii) Zircon: subround to oblate; <30 μm across; trace amount; random basic distribution.

(b) Chert: mainly round to subround with occasional oblate shape; surface smooth; size variable, most are <500 μm across; grayish (PPL); <1% of total area; moderately sorted.

(d) shale fragments: round, subround to oblate; size varies up to 4 μm across; smooth to undulating; colour varies from brownish-yellow to yellowish-gray: 5% of total area;

(B) Basic Organic Components

None organic components were readily observed.

3. Groundmass

The c/f (limit at 10 μm) related distribution is open porphyric. The b-fabric of the micromass is speckled.

4. Pedofeatures

(A) Textural

(i) silt and clay laminated coatings on voids, concretion fragments and a few quartz grains; reddish-brown (PPL); <70 μm thick; <1% of the total area;

(ii) continuous clay laminations on the peripheries of chert fragments; yellowish (PPL); <40 μm .

(B) Depleted

(i) some shale fragments (or saprolites) show depletion in iron-oxides hence lighter colour than those of others embedded in the

micromass, i.e. yellow vs yellow-brown.
(ii) loss of coloration also occurs in the cores

of iron-concretion fragments (detail description in Chapter 5).

- (C) Iron concretion fragments at various stage of decomposition: irregular shape, most being oblate; variable sizes, from 8 X 3 mm to < 10 μ m across; moderately sorted; random distribution (more detail refers to Section 5.2.3 of Chapter 5).

Pedon 3: Typic Hapludult, fine-loamy, siliceous, thermic**Horizon: A, 0-10 cm****1. Microstructure:****(A) Types: crumb, subangular blocky****(B) Peds**

- (a) Crumb: strongly to moderately developed; sizes vary, being mostly 1-3 mm across; surface is generally smooth; unaccommodated; random basic distribution.**
- (b) subangular blocky: moderately developed; sizes vary, average 5 mm across; surface is smooth to undulating; partially accommodated; clustered basic distribution.**

(C) Voids:

- (a) Inter-aggregate voids consist mainly of compound packing voids and some planar voids.**
 - (i) compound packing voids occurring between peds; wide range of width up to 5 mm wide, with varying length; about 10% of the area; undulating to smooth walls.**
 - (ii) planar voids: separating subangular blocky peds; <1% of the area; width < 50 μ m; undulating walls; partially accommodated.**
 - (iii) Vughs: irregular shaped; more-or-less equant; mostly 3 mm; 5% of the area; rough to smooth walls; random distribution.**

2. Basic Mineral Components**c/f limits at 10 μ m = ratio of 60 : 40****(A) Coarse fraction:****(a) Single mineral grains:**

- (i) Quartz: size varying widely up to 0.5 mm across; poorly sorted; shapes vary widely, mainly blocky and lenticular; about 60% of total area; random distribution.**
- (ii) mica: mainly acicular grains with size 60-120 μ m; well-sorted; <1% of coarse fraction; random distribution.**
- (iii) Zircon: trace amount; 30 X 20 μ m; random distribution.**

(b) Rock fragments of sandstones, consist predominately of quartz grains, are occasionally presented; blocky; 0.7 mm across; random distribution.

- (B) Fine fraction:
Brownish (PPL) fine material containing numerous micro-contrasted (dark brown to black) particles of variable size.

3. Basic Organic Components:

c/f limit at 20 μm :

- (A) Coarse fraction-occupies 5% of area
 - (1) vascular plant residues: sections of living and partially decomposed roots, up to 400 μm across and 5 mm long; with cells and cell walls visible.
 - (2) occasional animal droppings; globular-shape; approximate 25-35 μm across; dark brown (PPL) in colour, in the cavities of decomposed plant tissues (epidermis).
 - (3) amorphous coarse organic matter; randomly distributed; up to 250 μm across; light brown to black (PPL); isotropic.
- (B) Fine fraction
Fine organic material dispersed in the micromass, yellow brown to dark brown (PPL) and isotropic.

4. Groundmass:

c/f limit at 10 μm

Coarse material is randomly distributed;
Speckled b-fabric;
Close porphyric related distribution.

5. Pedofeatures:

- (A) Textural: silt and clay coatings are found only on the surface of a few quartz grains and roots; approximately <10 μm thick; no particular side is preferentially coated; colour is similar to the fine materials (clays) in micromass.
- (B) Amorphous: impregnative amorphous materials with dark brown colour (PPL); sizes vary from <20 μm to approximate 300 μm ; most are rounded with a few subrounded; occupy <1% of the area.
- (C) Excrement: globular shape; averaged 30 μm across; dark brown; in the chamber of decayed plant tissue.

Horizon: Bt, 70 cm

1. Microstructure:

(A) Types:

Weakly developed subangular blocky to structureless; surface is undulating to rough; partially accommodated.

(B) Voids

(a) Inter-aggregate voids are mainly compound packing voids occurring between peds and between ped and rock fragment; irregular width, up to 0.8 mm; approximate <5% of the area; surface rough to undulating.

(b) Vughs: irregular shapes; <1% of the area; size varying up to 750 μm across; wall rough to undulating.

2. Basic Mineral Components

c/f limit at 20 μm = ratio of 50 : 50

(A) Coarse fraction:

(a) Single mineral grains

(1) Quartz: the predominant fraction of coarse material; wide range of size (10-1500 μm), with most being between 200-350 μm ; poorly sorted; subround to subangular with smooth surface; about 50% of total area or >90% of total coarse fraction; with zircon inclusions.

(2) Mica: trace amount; acicular; 80 X 10 μm ; surface smooth.

(3) Zircon: trace amount; size varies from <10 to 50 μm , with occasional size about 50 X 150 μm ; subround to subangular blocky; smooth surface; random distribution.

(b) Compound grains and rock fragments: size varies up to 8 X 4 mm; poorly sorted; elongated shape; smooth boundary; 40% of total coarse fraction; random distribution; consist of mainly quartz grains with trace amount of zircon.

(B) Fine fraction: yellowish-brown (PPL) clay to fine silt material containing randomly distributed orange-brown dotted particles of variable size (all <5 μm).

3. Basic Organic Components:

c/f limit at 10 μm

(A) Coarse fraction: <1% of total area.

plant residues: mainly living plant roots; 100-500 μm in diameter, up to 6 mm long; internal

structure is well-preserved with individual cells visible (PPL, 40x); brown colour (PPL);

(B) Fine fraction:

occurs mainly as a component of micromass which it impregnates; fine material is yellowish-brown to reddish-brown (PPL).

4. Groundmass

The coarse material is random fabric;

The fabric of micromass is striated b-fabric (XPL);

The c/f related distribution is mainly single spaced porphyric.

5. Pedofeatures

(A) Textural:

(1) mostly thin (approximate 15 μm) discontinuous limpid clay coatings on the surface of mainly quartz grains and some on walls of voids, with no particular side preferentially coated; some local thick coatings (up to 125 μm) also occur on the surface of quartz particles; the colour of coatings is brownish-yellow (PPL).

(B) Amorphous:

Dark brown, either densely or loosely, isotropic ferruginous infillings in rock fragments; infillings on the peripheries of rock fragments approximate 200 μm thick; these occur occasionally and <1% of total area.

END

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FIN