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SOIL PROPERTIES, TOPOGRAPHY AND QUATERNARY SUBSTRATUM IN THE EDGE OF THE RED RIVER DELTA, VIETNAM

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Abstract

The Red River delta, the second biggest delta in Vietnam, plays an important role in the agriculture of Vietnam but it is facing the loss of agricultural land by urbanization and industrialization. The research wants to illustrate the relationship between soil attributes, Quaternary sediments and geomorphology in Quaternary in a specified study area within the Red River delta. The landuse change, which is evaluated for the period 1987 – 2003, and the relationship between pedology and geology are used to provide idea for landuse planning.

The paleochannel systems in the study area are classified into the Day River, Red River and Tich River system. The Day River and the Red River paleochannel system 1 is the youngest. The minimum age of the Red River paleochannel system 2 is around 1200 years according to luminescence ages. The maximum age of Red River paleochannel system 3 is 5166 ± 92 year cal. B.P. determined by radiocarbon dating.

From the relationship between soil properties, geomorphology and geology in the study area, it is concluded that: 1- the pH and grain size distribution relate to the geological formation and geomorphology. 2- The change of the bulk and clay mineral amounts in the top soil layer corresponds with relative soil age and the degree of weathering level. 3- Plinthic Ferrasols formed in the F4 and F5 formation or on erosion hill slopes, erosion terrace II and erosion plains. Ferralic Fluvisols developed in the F3 formation or terrace I. Umbric and Ochric Fluvisols formed in the F1 and F2 formation or on alluvial accumulation. Soils with gleyic properties formed in depressions and in the floors of the paleochannels.

During lateritization in the study area accumulated dominantly iron oxides in laterite profiles. In the Quaternary formations, laterite highly developed in the foothills within formation F4 and the terrace I of formation F3.

The landcover/landuse change from 1987 to 2003 occurred with a different degree in different geological formations and soil types. A significant landcover/landuse change in Plinthic Ferrasols from shrub areas to artificial forest and vegetable was noticed.

Land-use planning in the study area should aim at conserving the agricultural land in fluvial terrain especially with respect to the paddy rice areas outside the artificial dyke (F2 formation). The hill areas and foothills are suitable for factories and industrial zone. The landuse in the foothills and hill areas should be converted from artificial forest (Acacia and Eucalyptus tree) to agro-forest combination models.

Abstraktum

Das Delta des Roten Flusses, das zweitgrößte Delta in Vietnam, spielt eine wichtige Rolle für die Landwirtschaft Vietnams. Durch Urbanisierung und Industrialisierung sind die landwirtschaftlichen Nutzflächen in den letzten Jahren jedoch zurückgegangen. Die vorliegende Arbeit untersucht den Zusammenhang zwischen Bodeneigenschaften, Quartären Sedimenten und der Geomorphologie in einem Teilarbeitsgebiet des Deltas des Roten Flusses. Veränderungen der landwirtschaftlichen Nutzung zwischen 1987 und 2003 werden evaluiert und die Zusammenhänge zwischen Pedologie und Geologie im Arbeitsgebiet werden verwendet um eine Empfehlung für die zukünftige landwirtschaftliche Nutzung zu geben.

Mehrere Paläoflusssysteme im Arbeitsgebiet wurden dem Day River, dem Roten Fluss und dem Tich River zugeordnet. Das Paläoflusssystem I des Roten Flusses und des Day Rivers ist das jüngste. Das Paläoflusssystem 2 des Roten Flusses ist ca. 1200 Jahre alt. Ein weiteres Paläoflusssystem des Roten Flusses entstand vor maximal 5166 ± 92 Jahren B.P.

Der Vergleich der Bodeneigenschaften, der Geomorphologie und der Geologie lässt folgende Rückschlüsse zu:
1. der pH-Wert und die Korngröße hängen von der geologischen Formation und der Geomorphologie ab. 2. Die Mineral und speziell die Tonmineralzusammensetzung korreliert mit dem relativen Alter des Boden und dem Verwitterungsgrad. 3. Plinthic Ferralsols entstanden auf den geologischen Formationen F4 und F5 und auf den Erosionshängen, der Erosionsterrasse II und den Erosionsflächen.

Ferralitische Fluvisole entstanden in der Formation F3 und der Terrasse I. Auf den Formationen F1 und F2 und den Auen entstanden Umbric und Ochric

Fluvisole. In Senken und in den Paläoflusssystemen entstanden Böden mit Gley-Characteristika.

Bei der Lateritisierung wurde nur Eisenoxide akkumuliert. Intensiv entwickelte Laterite entstanden auf den Fußflächen des Hügellandes der Formation F4 und auf Terrasse I der Formation F3.

Veränderungen der landwirtschaftlichen Nutzung von 1987 bis 2003 traten auf den unterschiedlichen Formation in unterschiedlicher Ausprägung auf. Eine signifikante Veränderung trat auf den Plinthic Ferrasols auf, wo Buschland in Flächen für Forst und Gemüseanbau umgewidmet wurde.

Für die zukünftige Entwicklung wird ein Erhaltung der landwirtschaftlichen Nutzflächen, im besonderen des Reisanbau, in den fluvial geprägten Gebieten außerhalb der Dämme (Formation F2) empfohlen. Das Hügelland und dessen Fussflächen erscheint für die Errichtung von Fabriken und Industriezonen geeignet. Akazien- und Eucalyptus-walder im Hügelland sollten in Kombination mit Landwirtschaft genutzt werden.

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LIST OF ABBREVIATIONS

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AD	After Christ
B.P	Before Present (before 1950)
Cal. B.P.	Calibrated Before Present
CEC	Cation Exchange Capacity
DEM	Digital Elevation Models
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic Information System
NDVI	Normalized Difference Vegetation Index
OSL	Optical Stimulated Luminescence
RSQ	The square of the Pearson product moment correlation coefficient
SAM	Spectral Angle Mapper
SWIR	Short-wave infrared
UNESCO	United Nations Educational Scientific and Cultural Organization
XRD	X-ray diffraction
WGS-84	World Geodetic System 1984
WRB	World Reference Base

1 Introduction

1.1 Problem statement

The Red River delta, the second biggest delta in Vietnam, plays an important role in the agriculture of Vietnam. The agricultural cultivation in the Red River delta guarantees the food security and rice exportation of Vietnam. As shown by Mussgnug (2006), the Red River delta provides food and livelihood for about 20% of Vietnam's population. However, the Red River delta is facing the issue of reduction in cultivated land. According to Department of Cultivation - Ministry of Agriculture and Rural Development (MARD), during 2002-2007, the Red River delta lost 7.500 ha yr^{-1} paddy land as a result of urbanization and industrialization. This figure is double the average loss of paddy land per year in the whole country (Yen, 2008).

In Vietnam, as in many other developing countries, the need to raise the production efficiency of agricultural land is an urgent issue. To reach this goal, the knowledge of the soil properties, variation and distribution and the role of parent material and topography are indispensable. This issue in the world as shown by McFadden and Knuepfer (1990) that "during much of the twentieth century, geology and pedology have generally evolved along nearly separate path-way". In the article, they also discussed that re-integration of these two disciplines began slowly in the late 1950s and early to middle 1960s. In the Red River delta, most studies deal with soil, geology or geomorphology separately (Fridland, 1959; Ky, 1973; Vietnam Soil Science Society, 1996; Bieu et al., 1998; Lam, 2000, 2001, 2005; Phach, 2001; National Institute of Agricultural Planning and Projection, 2004; Hanebuth et al., 2006; Borges et al., 2007; Funabiki et al., 2007). Therefore, to gain a better understanding of the interactions between pedology, geomorphology and geology, more research applying an interdisciplinary approach is needed.

1.2 Aim of the study

The research wants to illustrate the relationship between soil attributes, Quaternary sediments and geomorphology in Quaternary in a specified study area within the Red River delta. The landuse change, which is evaluated for the period 1987 – 2003, and the relationship between pedology and geology are used to provide new ideas for landuse planning.

1.3 General description of study area

The study area is situated 30 km to the north-west of Hanoi, alongside the Red River bank (Figure 1.1). In the study area, there are two main rivers. There area the Red River in the northern part and the Day River - a tributary of the Red River – in the western part (Figure 1.2). The parameters of material in the Red River water are pH value 7-7.5, CaO+MgO 2-2.5 %, Na_2O+MgO 2-3 %, P_2O_5 0.4 – 0.6%, N 0.2-0.3 %. The amount of matter in the Red River water reaches to 900 – 1300 g/m^3 in the monsoon and 500 g/m^3 in dry season (measured at Sontay station – northwest of the study area) (Vietnam Soil Science Society,1996). A further small river, the Tich, located in the western part of the study area, originates in the Bavi Mountain (15 km SW of the study area).

As pointed out by Lap (1979, p.162), the Red River delta's boundary "runs straight along the Bavi mountain". The study area is located in a transition area between the Red River delta and the mountainous area. The economic and social development strategy from present to 2020 in the area aims to increase the economic value of the cultivated land by converted crops framework (People's Committee of Hatay province). The geology and pedology data is need to create converted model.

Since 01 August 2008, the area is annexed into Hanoi territory. The north-western direction has been one of the guidelines of development orientation in conjunction with Hanoi urban planning. Clearly, urbanization of this area will be increased in the near future.

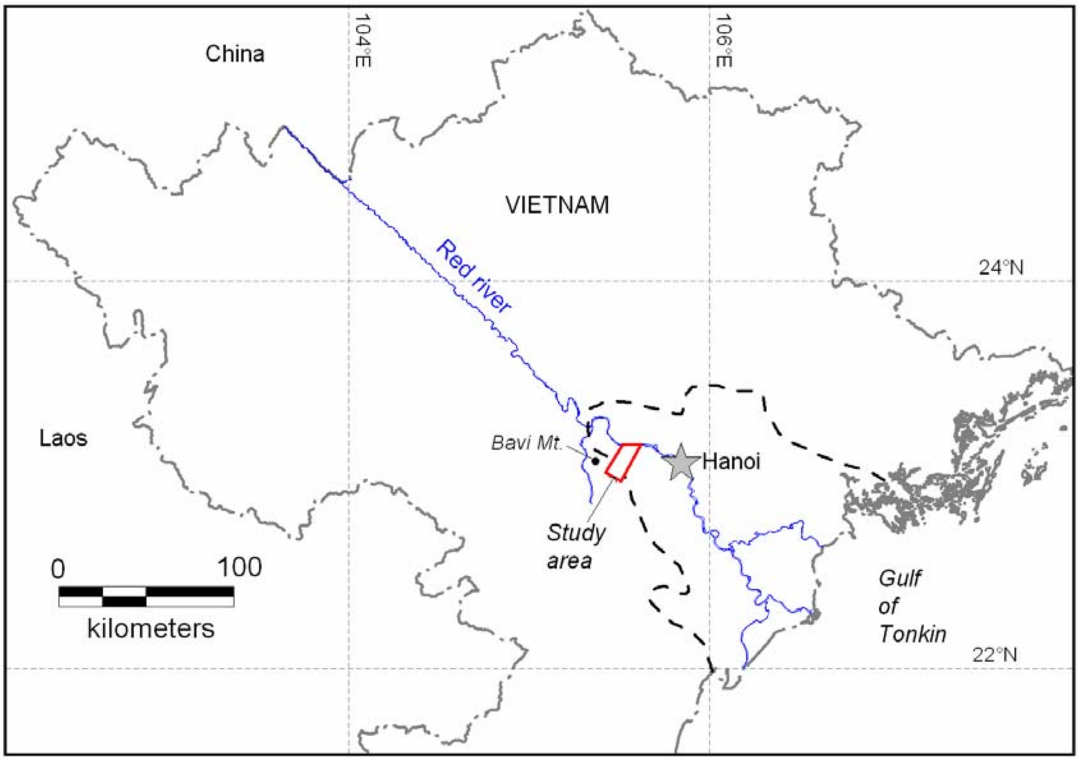

Figure 1.1: Location map showing North of Vietnam with Hanoi capital and the Red River. The red trapezium highlights the study area. The black dash-line is the border of the Red River delta (Huyen et al., 1997). Coordinate is latitude/longitude.

1.3.1 Geology and relief

The altitude within the study area decreases from the North to the South and the West to the East (Figure 1.2). The altitude inside the dyke is quite higher than outside the dyke. And, the altitude relief in the Day River valley is higher than in the surrounding. Based on the altitude histogram from a Digital Elevation Model (DEM) which interpolated from 1:50.000 topographic maps, the altitude relief can be divided into 5 levels, videlicet below 8 m, 8 to 15 m, 15 to 20m, 20 to 40m and higher 40m. Fluvial terraces exist in the area comprising two levels. The altitude of terrace level I in the study area is from 10 to 12 m. Terrace level 2 is in 20 - 30 m. The geological formations are shown in Figure 1.3.

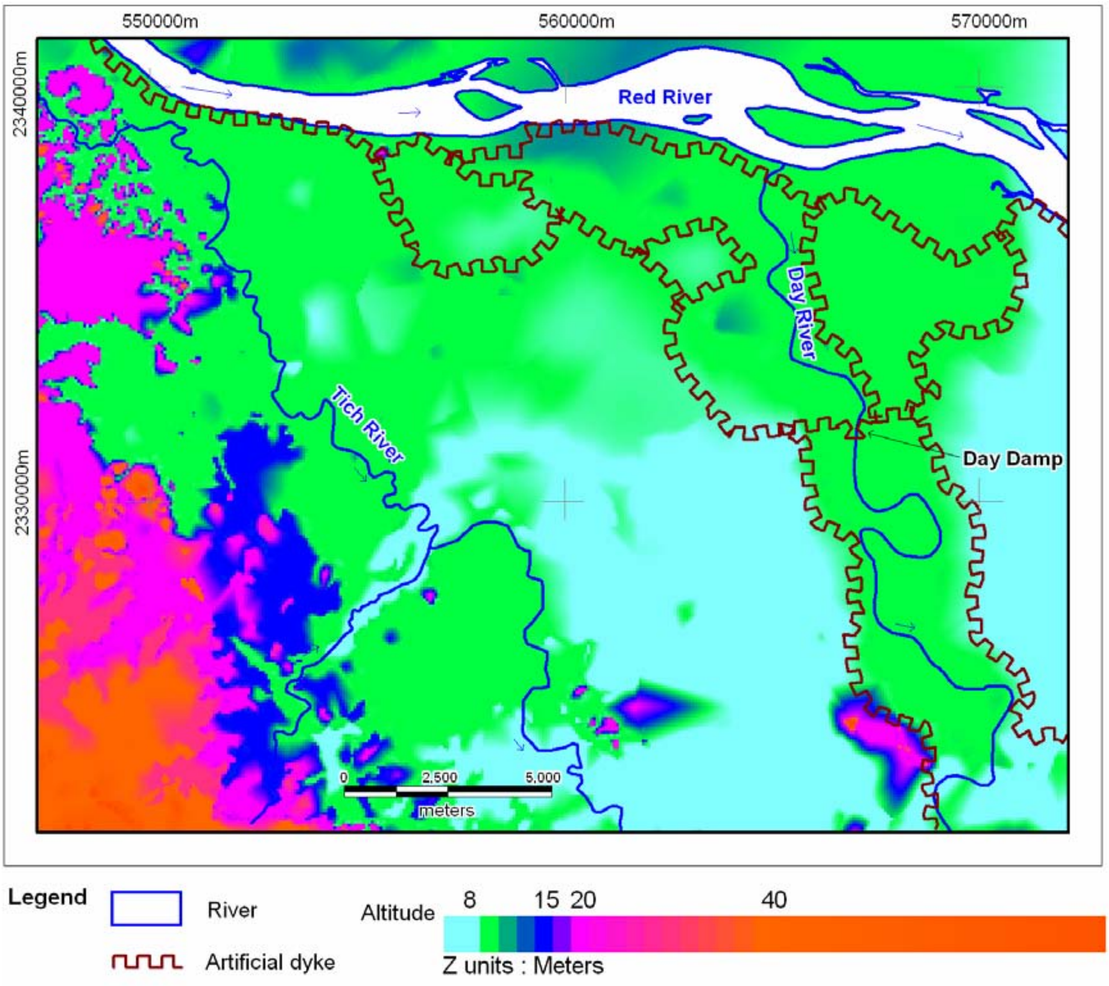

Figure 1.2: Map of the Digital Elevation Model (DEM) of the study area. The DEM was interpolated from the topographic map 1:50.000. Coordination is UTM-WGS-84. The figure shows the fluvial terrain inside dyke is higher than most of fluvial terrain outside the dyke. The figure also describes the altitude of fluvial terrain outside the dyke decrease from the north to the south

According to Nghi and Toan 1991; Nghi et al., 1991; Dy et al., 1995; Nghinh et al., 1991; Toan et al., 2000, the Quaternary in the Red River delta comprises 5 sedimentation phases corresponding to the five geological formations. In the study area, there are only three Quaternary formations with age Q_{IV}^3, Q_{III}, Q_{II-III}^1. In Figure 1.3, the upper part of Q_{IV}^3 formation is abbreviated as F1. The lower part is F2. Q_{III} formation as F3, and Q_{II-III}^1 formation as F4. Older formations are combined into one pre-Quaternary formation which named F5. Table 1.1 shows the altitude of the geological formation in study area.

Table 1.1: The proportion of relief levels (in %) of the geological in the study area.

Altitude	< 8 m	8 – 15 m	15 – 20 m	20 – 40 m	> 40 m	Total
F1	4	96	0	0	0	100
F2	51	49	0	0	0	100
F3	45	53	2	0	0	100
F4	0	33	17	47	3	100
F5	6	67	9	14	4	100

Elevation of the outcrop of F2, lower part of Q_{IV}^3 formation - is lower 15 m (Table 1.1). And most of the area below 8 m is distribution in the southern part of the study area. According to geology map 1:50.000 (Toan, 1989), formation F2 comprises alluvial sediments, silty sand, brown color. Total thickness of F1 and F2 formation is 1.2 to 35.5 m (Toan et al., 2000). The topography in F2 is not really flat in whole area. For example, there are some hollows with dimensions from 20 to over 250 m width and up to over 5 km length (Figure 1.4, 1.5).

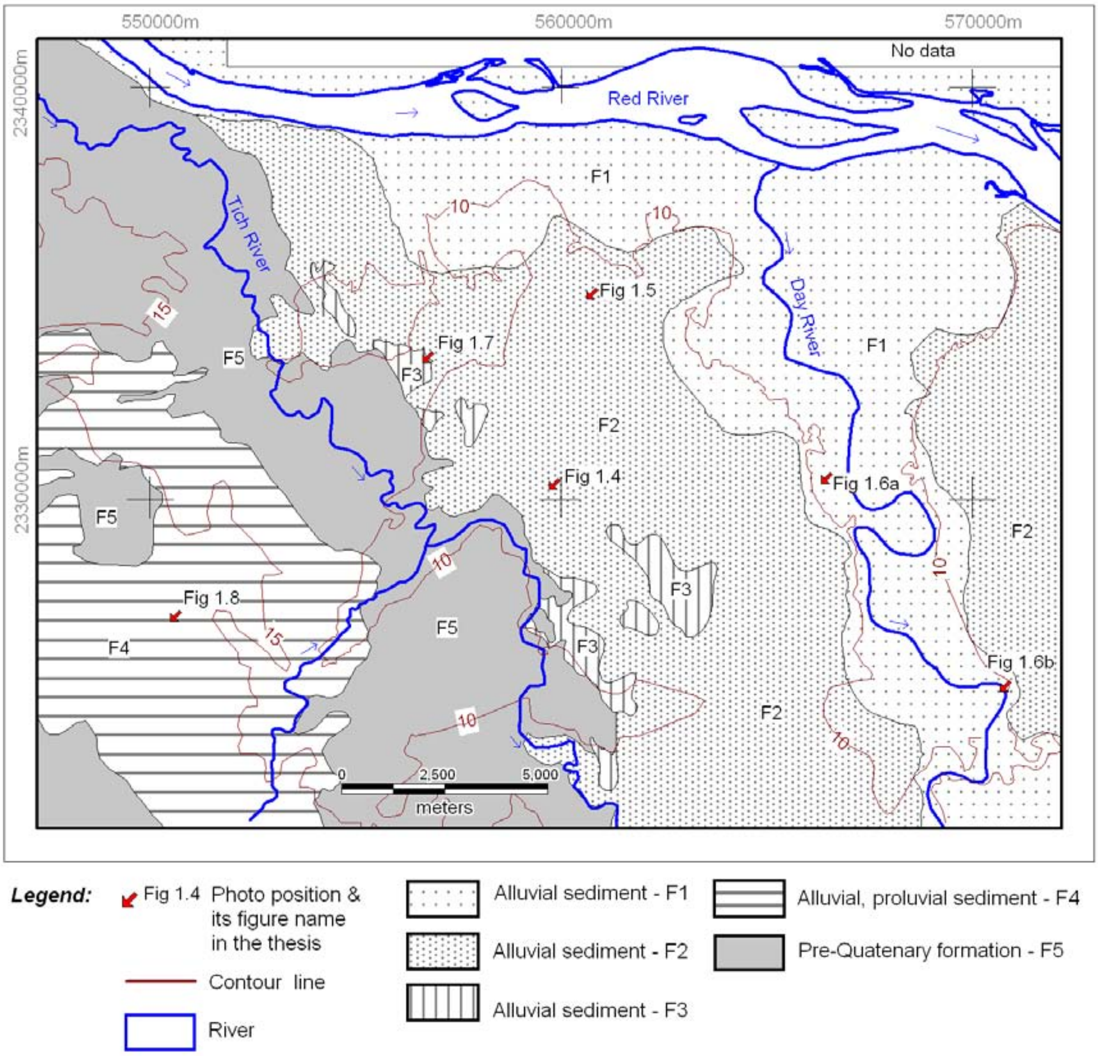

Figure 1.3: Sketch of the geological based on the Geological map 1:50.000 (Toan, 1989). The 10 m and 15 m contour line is created from the DEM. The map focuses on the Quaternary formations. The youngest Quaternary formation (F1) exists in the Day river valley and across the Red River bank. The red arrow in the map highlights the location of the following figures.

Figure 1.4: The flat terrain in F2 formation. The altitude of the area is about 8-9 m. Paddy rice is transplanting. The main soil color is brown.

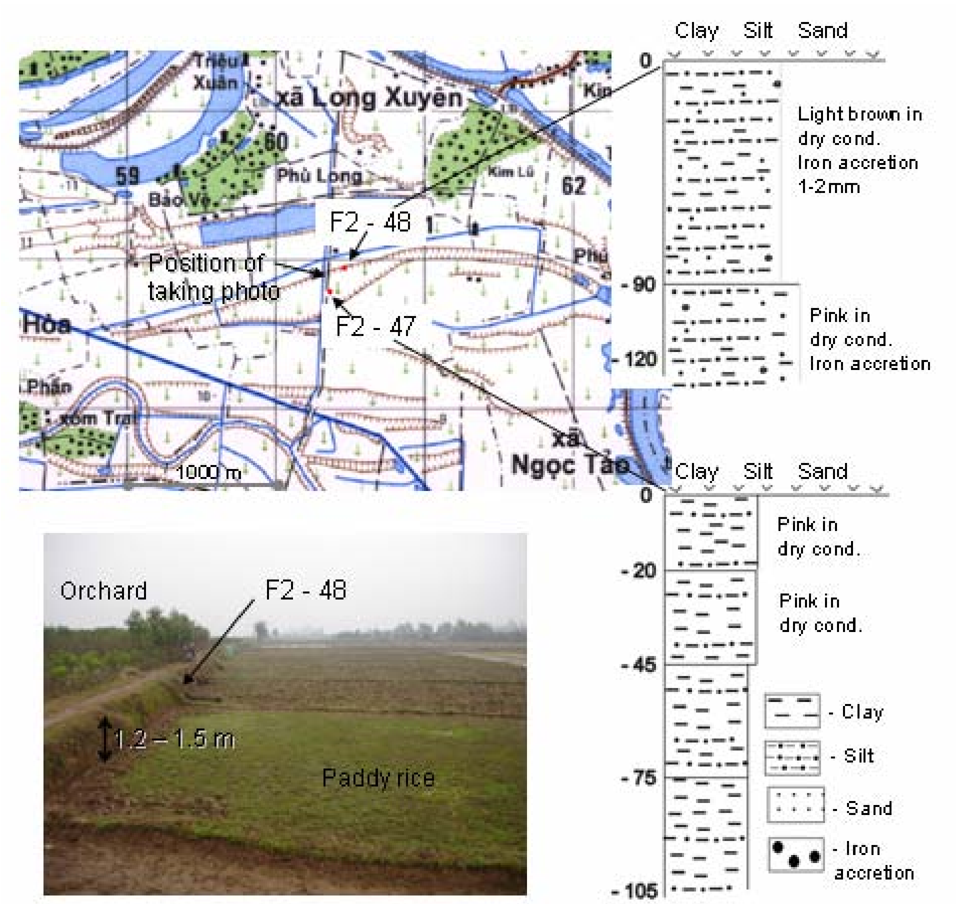

Figure 1.5: One hollow in the F2 formation. The cliff of the hollow is about 1.5m high with orchard at the surface. The lower surface is paddy rice. The soil profile from two different locations shows the difference of soil properties. Soil surface colors in dry of F2-47 and F2-48 are pink (7.5 YR 7/3) and light brown (7.5 YR 6/3) respectively. F2-47 texture (USDA-NRCS) is clay. F2-48 texture is silty clay.

The youngest age formation outcrop is F1 (Q_{IV}^3). In table 1.1, 91% of F1's outcrop is from 8 m to 15 m altitude. The F1 formation locates in the Day River valley an inside the Red River dyke. The terrain of the formation is flat. In areas close to river, the terrain inclines gently towards to the river channel (Figure 1.6). The upper part of the formation component includes silt, clayey silt, a little of sand, light brown color (Toan, 1989).

(a)

(b)

Figure 1.6: The relief in F1 formation. (a) 3 Km far from Red River, flat terrain, silty clay loam, soil color in dry 7.5 YR 7/3. (b) 200 m to Day River, inclined flat relief towards to Day River, silt loam, soil color in dry 5YR 6/3.

Pleistocene formation F3 (Q_{III}^2) outcrop appears mainly from 8 m to 15 m altitude. Its relief is quite rough. Pleistocene formation or F3 in the area is alluvial sediment clayey silt mixed sand, small pebbles with greenish-grey, motled yellowish-grey color (Figure 1.7). Its outcrop is in the form of terrace I. In the plain, the formation has been met within boreholes in the depth of 20 – 40 m. Thickness of formation is from 6 to 38 m (Toan, 1989, 2000).

The outcrop of F4 (Q_{II-III}^1) ranges from 8 m to over 40 m altitude (table 1.1). But, most of F4's outcrop is from 12 to 40 m altitude. The formation comprises alluvial and proluvial sediment. Its main component is silt, sand, clay mixed piece of pebble and grave (grey to yellowish-grey color) (Figure 1.8). Thickness of formation is from 2.5 to 6 m (Toan, 1989; 2000).

Age of formations older than Quaternary age in the level is Proterozoic and Triassic. The Proterozoic formations (PR^1) – metamorphic rocks, outcrops in 10 – 12 m elevation are bitotite-slimanite schist mixed with a bit of quartzite, amphibolite lenses, and biotite gneiss. Thickness of formations is from 300 to 700 m. The Triassic formations components are sand stone, silty sandstone, clay stone, tuffaceous siltstone and effusive rock such as dacite – trachyte tuffs and andezittobazal. Thickness of formations is from 400 to 800 m. (Ky, 1973; Toan, 1989)

Figure 1.7: The landscape of F3 formation. The topography is rough. Soil pH (H_2O) is from 5 to 7, soil color in dry: reddish brown (7.5YR 7/6) or very pale brown (10YR 7/4)

(a)

(b)

Figure 1.8: The landscape (a) and soil profile (b) of formation F4. The photo was taken in hill foot looking towards hill region. In profile, soil pH (H2O): 4.9, soil color in dry: strong brown (7.5YR 5/6), texture (USDA-NRCS): clay but the particle size > 2mm is 55% total weight. The land cover in the formation mainly is artificial forest.

1.3.2 Soil and Landuse

According to the soil map in scale 1:1.000.000 (Vietnam Soil Science Society, 1996), which is built based on the FAO-UNESCO soil criteria, the main soil types are: Eutric Fluvisols, Gleyic Fluvisols, Umbric Gleysols, Plinthic Acrisols, Ferralic Acrisols and Rhodic Ferrasols. However, it exits some difference between the soil type in map of 1:1.000.000 and bigger scale. For example, the type of Acrisols in the study area from the map of 1:1.000.000 is classified into Ferrasols type in the soil map 1:100.000.

Landuse categories in the study area from map “Landuse of Vietnam, 1980 scale 1:1.000.000” include artificial forest land and agricultural land (Tuyen et. al, 1982). Artificial forest land is mainly located in the hill areas in the southwestern part of the study area. Agricultural land is found in the flat areas and hill foots. Based on field information from the present study, the main short-term crops are paddy rice, maize and vegetables. The vegetables are mainly cultivated inside the dyke of the Red and the Day Rivers which belongs to F1 formation (see section 1.3.1). Outside the dyke, paddy rice prevails. Somewhere in outside the dyke, paddy rice and vegetation can be cultivated on two separate paddy fields right next to each other. There are two crop systems in the area. One consists of one paddy rice plus one vegetable per year. The second is two consecutive year of paddy rice cultivation. Perennial crops in the area are mainly fruit trees. Most of them are located in the hill foots and hill relief. Artificial forest is predominant in hill relief. The old villages locate in the outcrop of the F3 formation. The reason is that the terrain of F3 formation is higher than the surrounding area. Therefore the location on this elevated position protected the villages of the frequently occurring flood. The artificial dykes, nowadays, also enable settlement of the formations F1 and F2.

1.3.3 Climate

The climate in study area is tropical humid with a dry season and a monsoon. The rainy season is from May to October and other months fall into the dry season. The mean annual temperature is 23.8 ^{o}C. (People’s Committee of Hatay province; Tu, 2000).

The mean annual precipitation in this area is 1500-1800 mm and 85 – 90 % of annual precipitation is in the rainy season. From January to April, drizzly weather occurs frequently.

The average humidity is 83 – 85 %. The maximum humidity is in March and April. It reaches to 87 – 89 %. In November and December, the humidity is in minimum with 80 – 81 %.

1.3.4 General description of artificial dyke

The first artificial dyke recognized in the history is “Co xa” dyke which protected Hanoi citadel in 1108 AD. Before this time, the dykes only were built to protect small areas such as villages. In 1248 AD, people built "Dinh nhi" dyke which along the Red River from the hill area to the shore line. This time is assumed as starting the time of interruption sedimentation in the Red River delta by human. Most of the dyke was built based on natural levee and since that time, the dykes have been upgraded and had new construction. We do not have detail information about the Day River dyke in the study area. In several hundred years ago, the dyke only protected the outside dyke area until the paddy rice was harvested. Later, the river water in monsoon was allowed to run into the field. At the present, the outside dykes area are protected in whole the year. The current artificial dyke in the study area can be seen in Figure 1.2

In the Day valley, one of the important irrigation constructions is Day Damp (location of the damp in Figure 1.2). The main aim of the Damp which was completed in 1937 is the prevention of the Red River flood flowing into Day valley. In the case of the Red River flood can be threatened Hanoi city (capital), the gates of the damp will be opened. In 1960s, the "Van coc" culvert and its dyke were built in front of the Day Damp and closest to Red River bank. The operation of the system can be described that if flood water level in Hanoi is higher than a threshold which can be dangerous for the capital, firstly, the flood water will be run into the area front of the Day Damp (Van coc area - the area of F1-01, 33, -36, -49, -50). If the flood water level in Hanoi continues increasing, the Day Damp gates will be opened. The flood water from the Red River will run into the Day River valley via the Day Damp gates. It helps the flood water level in Hanoi is decreased.

1.4 Literature review

In 1956, the sketch soil map in the northern part of Vietnam was done in 1:1.000.000 (Fridland et al., 1959). From this time, a lot of soil maps in medium and large scales were implemented such as soil map of Northern part of Vietnam 1:500.000 in 1975, soil map of the Red River delta 1:250.000 in

1993 (Vietnam Soil Science Society, 1996). The soil map 1:50.000 in the study area was carried out in 1960s and 2004 (National Institute of Agricultural Planning and Projection, 2004). Soil classification in these times is based on pedogenesis criteria. In 1996, the FAO-UNESCO soil classification system was applied to Soil map of Vietnam in 1:1.000.000 (Vietnam Soil Science Society, 1996). At the present, the soil map in Vietnam is implemented in either pedogenesis or FAO-UNESCO system.

In recent years, a lot of research on Quaternary geology researches has been carried out in the Red River delta. Map “Weathering crust and Quaternary sediment in Vietnam”, scale 1:1.000.000, (Toan et al., 2000), classified weathering crust and Quaternary sediment. The research also deals with Quaternary sedimentation phases. Toan in his study agreed with Nghi et al. (1991), Dy et al. (1995) in five Quaternary sedimentation phases with each of these phases relating to one of the Quaternary formations in the Red River delta. The Tich River, a small river across the study area, was an object of Tu’s research (2000). The stratigraphy, structural geology and tectonic, neo-tectonic, neo-geokinematic and geomorphology were the main subjects in his project. The investigation gave new insights into the formation of the Tich River. The changing of Geology environment is also deal with in Tu’s research. The research provides a base for the assessment of geological hazard and for exploiting natural resource in the Tich River watershed. The geomorphology, geokinematic, geochemistry and geological environment in the Day River valley were studied by Khanh and his co-workers (2004). Its purpose was to protect the environment of the Day river watershed. In the research, former rivers, type of land forms, local uplifting and subsidence areas were mentioned.

In contrast with the number of Quaternary geology researches in the Red River delta, the quantity of studies dealing with topography and Quaternary sediment in relation to soil properties is very small. In the Red River delta, an important investigation with respect to the in relation of pedology, weathering and parent rock has been presented by Fridland in 1973 in his book *Soil and weathering crust in tropical humid area*. Fridland gave explanations about soil forming related to topography and weathering crust in the Northern part of Vietnam. Mien (1991) studied the relationship between Quaternary sediment and cultivated land in the Red River delta. The research described the main points of soil development with the features of Quaternary sediment. Bac (1997) investigated the relation between geomorphology and pedology and applied it to the landuse planning orientation in the Bavi area situated 50 km to the north-west of Hanoi. The geomorphology factor to pedology is emphasized in the research. He differentiated between four main landform types (with 2-3 subtypes) and related these to the dominant etching processes and the corresponding soil types. Based on the map of geomorphology – pedology of Bavi – Sontay area scale 1:100.000, Bac and his co-worker gave advice on landuse planning in this area. In a nearby study area, in Viettri and Hadong city, the authors of two urban geology projects (Minh et al., 1997; Tam et al., 1999), tried to explain the relationships between different topographic forms, weathering crust types and soil types. In these studies, the soil is classified into the weathering soil, fluvial soil and artificial soil types. In weathering soil and fluvial soil, the subsoil type is strongly related to parent rock/sediment. The orientation of landuse planning is also mentioned in the research. Quang (2001) mapped soil types and established a morpho-pedological classification of the landscape and applying it for sustainable landuse in Vietnam. One of main methods of the study is on geomorphology and pedology by catena. Finally, the soil assemblage (or soil combine) is established in each catena. Most of the studies mentioned above do not have enough analytical data in analysis soil properties with landform and parent material. Thus, quite a lot of subjects are still remaining unanswered.

The evolution of paleochannels is an interest subject in the Red River delta. In the book “Atlas of Hanoi”, the map “Trace of the changed stream of the Red River” was composed in scale 1:250.000 (Dy et al., 1984). In the map, the Quaternary history of channel systems of the Red River and the Day River are outlined. Paleochannels of the Day River valley are also mentioned in research by Khanh (2004). Further studies dealing with Quaternary channel formation of the Day River were presented by Lam et al. (2000) and Duong et al. (2003). In general, these above mentioned studies lack of the absolute age data.

Although the Red River delta is well investigated in term of geomorphology and Quaternary geology, the interrelationship between pedology, geomorphology and Quaternary geology is not investigated to its full understand. Furthermore, there is an unanswered question concerning the timing of paleochannel. Further studies are needed to research soil properties, paleochannel and Quaternary sediment in the Red River delta.

2 Material and Methods

In the first chapter, the general information of study area was mentioned. The purpose of this chapter is to introduce the factor of soil formation, catena concept and the methods for studying. This section also provides some issue in catena and pedological, geological in the study area. The final part of the chapter describes the material and explains the soil physic-chemical analysis, age determination and the processing the remote sensing data for soil mapping and river paleochannel.

2.1 Factor of soil formation

The most common view of the soil from pedological perspective is that it is an independence natural evolutionary body that can be subdivided into subcompartments. (Bockheim et al., 2005) It formed under the influence of the five soil-forming factors. These factors were first mentioned by Dokuchaev at the end of 19^{th} century and supported by Glinka in the beginning of 20^{th} century (Bockheim et al., 2005). In Dokuchaev model, the factors are climate, organisms, parent material. The relief or topography is not one of the factors in this model (Gerrard, 1995). Later worker, such as Shaw (1930; 1932), Jenny (1941) modified this synthesis and added relief to the soil forming factors. Shaw (1932) prepared the first soil-forming factor equation: $S = M(C+V)T+D$ where M – parent material, C – climatic factors, V – organic life, T – time and D – modification of the soil by erosion and deposition. The Shaw's equation was commented as more precisely function for the interacting influences of the factor upon an individual soil (Bockheim et al., 2005).

Jenny's opinion in 1941 showed that the introduction of causality aspects to soil formation is not fruitful. His point of view is every property may be considered a cause as well as an effect (Jenny, 1941). Soil forming should be not forces or causes but is independent variables. The fundamental equatation of Jenny (1941) is

$$S \text{ or } s = f(cl, o, r, p, t, \ldots)$$

Where S denotes the soil, s any soil property, *cl* the climatic factor, *o* the biotic factor, *r* the topographic factor, *p* the parent material and *t* the time factor. Here, it is necessary to distinguish factor and process. These processes form the soil but the factors define the state of the soil system (Brikeland, 1999).

In this thesis, only topography and parent material factors are mentioned. The climate factor is mentioned only in general because the lack of climate data in Quaternary. Parent material is studied in Quaternary sediment and mineralogy. Topography is studied in paleochannel system and surficial process. Studying soil along a slope is one of the simplest yet most elegant ways to discern spatial relationships between soil and topography (Schaetzl, 2005, p.469). It refers to catena which will be discussed in the next item.

2.2 Catena concept

Nowadays, the fundamental of soil survey work is to "seek out middle ground by examining small segment of the landscape, and then extrapolate what we learn onto larger area" (Schaetzl, 2005). On these small segments, the relief is important factor to much of the variation in soil cover.

Milne (1935) originally defined a catena as the sequences of soils between the top of a hill and the floor of the adjacent swamp. The term catena describes the lateral variability on a hillslope. Milne also emphasized that each soil along a slope bears a distinct relationship to the soils above and below it (Birkeland, 1999).

Milne's concept includes catenas where the soils developed on inhomogeneous lithology. In 1942, Bushnell studied catenas with all the various possible topographic, denudation and hydrologic situations but with the same parent material. In 1960, Ruhe investigated the evolution of a catena, disagreeing with the idea that a catena should be restricted to one parent material. However, Ruhe's research suffered from disregard of the geomorphic history of the landscape. Restricting catenas to one parent material is an unreasonable limitation.

Soils along a catena differ in morphology because of variations in drainage conditions and in fluxes of sediment along the catena. Divergent and convergent flow can occur in various locations within the catena. It can influence on depths of various soil properties. For example, both divergent and convergent soil water flowlines influence the local soil moisture. In a hollow relief, soils waters can be easily concentrated adding more water than the mean annual rainfall. In contrast, the soils are on topographic "nose" (contour of a convex downslope), the flow is divergent off the nose. Therefore, the soils downslope of the nose do not get as much moisture as the positions above on the "nose" (Birkeland, 1999). Therefore, each catena is the result of the complex interrelationships between soil and slope processes. It also is governed by the differing ratios of erosion to deposition occurring on different parts of the slope (Gerrard, 1995). Figure 2.1 gives the example in the relationship between soil and topography.

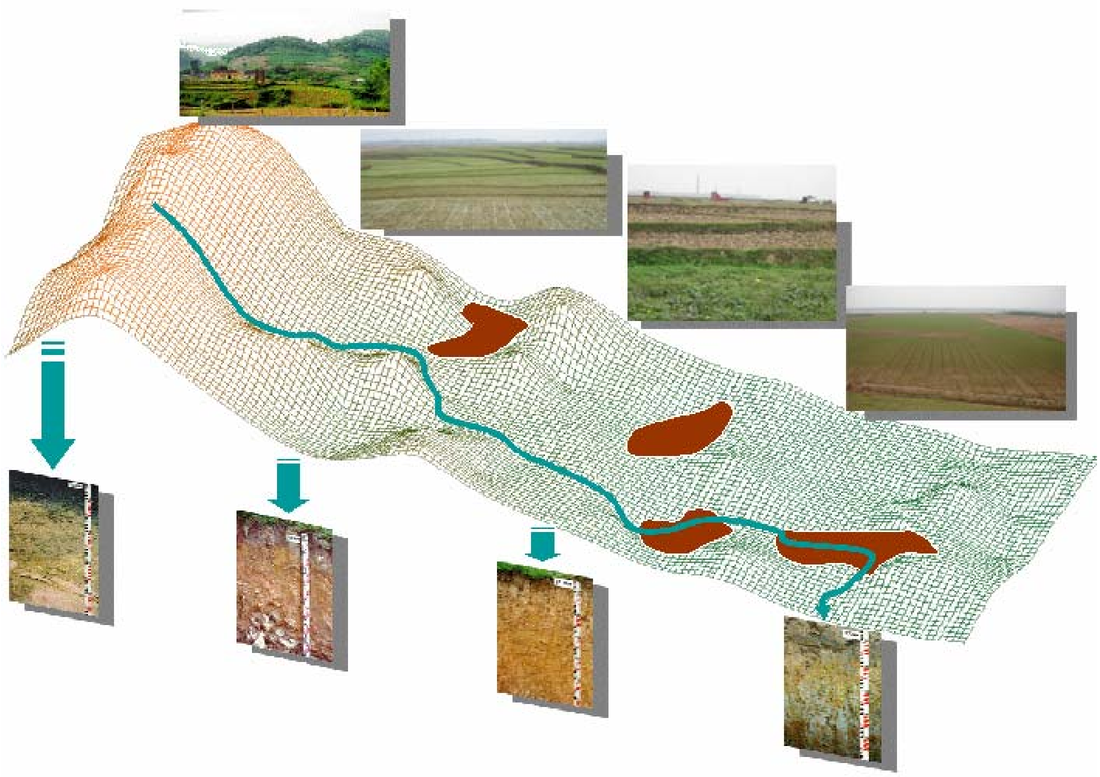

Figure 2.1: The role of topography in soil forming. The figure is one of example in relationships between soil and topography. The characteristic relief made the divergent and convergent flow in the surface. The brown color areas are examples for the hollow areas where have more moisture. This area can create gley soil.

In conclusion, a catena is a transect of soil from the top to the base of a hill perpendicular (or nearly so) to the contour line. A catena includes information on soils, surficial stratigraphy, hill slope, hydrology and shape. In this thesis, I agree with the idea that a catena should not be restricted in a single parent material. In my thesis, two-dimension catena will be carved in two types. One is in uniform geology. Another type is crossed in area of geological complexity.

2.3 Catenas and geological, pedological research in study area.

The study area is the transitive area between fluvial terrain and hill area. Thus, the types of relief in the study area include both the type developed in fluvial and hill area. In fluvial terrain, the changing of river channel created channel with the long length in relief. The phenomenon is easily seen in the Red River delta especially in the boundary of the delta. The soils in the floor of these channels often have more moisture than surrounding area. The difference of moisture makes the difference of soil properties in the floor channel and surrounding area. The particle size of soil in the paleochannel floor will be different from the one in the surrounding area. Using catena which crosses the paleochannel is good way to research the relationship between soil property and the relief. The Red River delta also is known as the “immature” delta (Dy et al., 1995; Toan et al., 2000). Because the artificial dyke was built over several hundred years ago therefore it is the reason to interrupt the sedimentation in the area outside the dyke. In the outside dyke area, the surface is still concavo-convex. This status will affect to the drainage and further the soil moisture. The catena cross to the concavo-convex relief is helpful to elucidate the soil forming in the fluvial terrain.

As shown by Gerrard (1995), soil formation on river terraces is a function of the distinctive landform-material assemblage and the age of the terrace. Bull (1990) has argued that research of soil-landscape interrelations in river terrace should be investigated as to whether terrace-tread incision is the result of up-lift, climatic change or internal adjustments within the fluvial system. Therefore, the investigation of soil in river terrace in this thesis not only mention to soil property and landscape but also to the forming and modifying the river terrace.

The hill in study area is the transitive relief between fluvial relief and mountainous area. The hill type in investigation is small (knob), below 60 m altitude. Not the entire hill slope in area is covered by vegetation. Thus, the erosion surface, re-distribution material will be intensive. In this thesis, the catena will be crossed from the hill foot to the top for comprehensive visualization of soil forming in the hill relief.

The weathering processing is one of important process in influence in the soil forming, especially in hill area or even in the river terrace. The weathering level can be illustrated by soil mineralogy especially clay mineral. As Figure 2.2, the clay mineral with higher number is more stable. Based on clay mineral analysis, we can compare the weathering level between soil profiles.

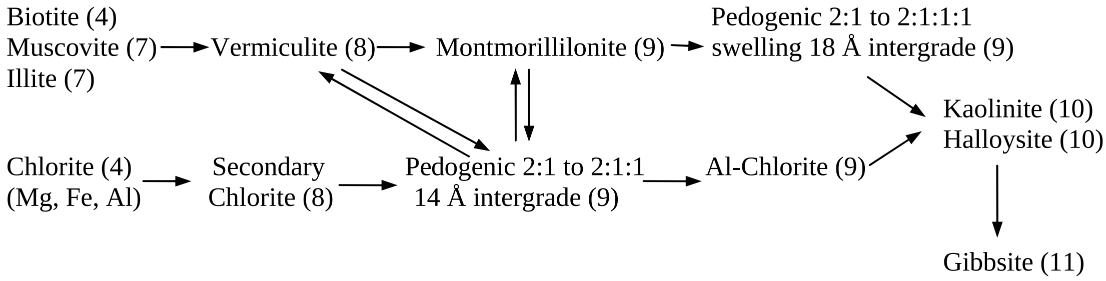

Figure 2.2: Various clay – mineral reactions in soil. Parenthetical number are weathering stability numbers for the clay minerals; mineral stability increase with number. The arrow in the figure indicate some possible path for alteration form one mineral to another by weathering (redrawn from Birkeland, 1999, p. 222)

To understand soil material in this area, necessary to understand the sedimentation phases. Soil in floodplain is exhibited characteristic of both sediment transport and deposition and soil formation. Both fluvial and hill relief in study area are component of Quaternary sediment which are fluvial or proluvi-fluvial sediment. Thus, soil profiles should be examined with the relation to sedimentary environment.

Landuse, including plant belongs to the biotic factor in soil forming equitation. The plant type also influences to the soil development (Fridland, 1973) therefore, landuse should be investigated. Furthermore, not only soil development and landscape but also the landuse changing through time are necessary information for improving planning landuse.

2.4 Material

Based on the methodology, the material was collected to serve the research. The item describes the data using in thesis.

2.4.1 Sampling strategy

Total 34 soil profiles and single soil samples were colleted. In Figure 2.3, the sample position is described by red circle. Id sample include two parts. The first part is the symbol of geology formation. Abbreviation of geological formation can be seen in item 1.2.1. The second part is the ordinal number. For instance, samples with id F1-10 that mean it locates in F1 formation and is the tenth sample.

The criteria for choosing the sample position are the geomorphology, geology and soil type. Quaternary formation is mainly concerned in the study. Thus, there are 29 / 31 samples in Quaternary formations. Two samples in the F5 formation belong to Proterozoic formation (see section 1.3.1). The increase altitude from the flat terrain to hill is another reason to locate several samples. In flat relief, especially in F1 and F2, the paleochannel created special relief such as channel with long length. F2-37 -38, - 47, - 48 are examples of sample positioning in the paleochannel relief.

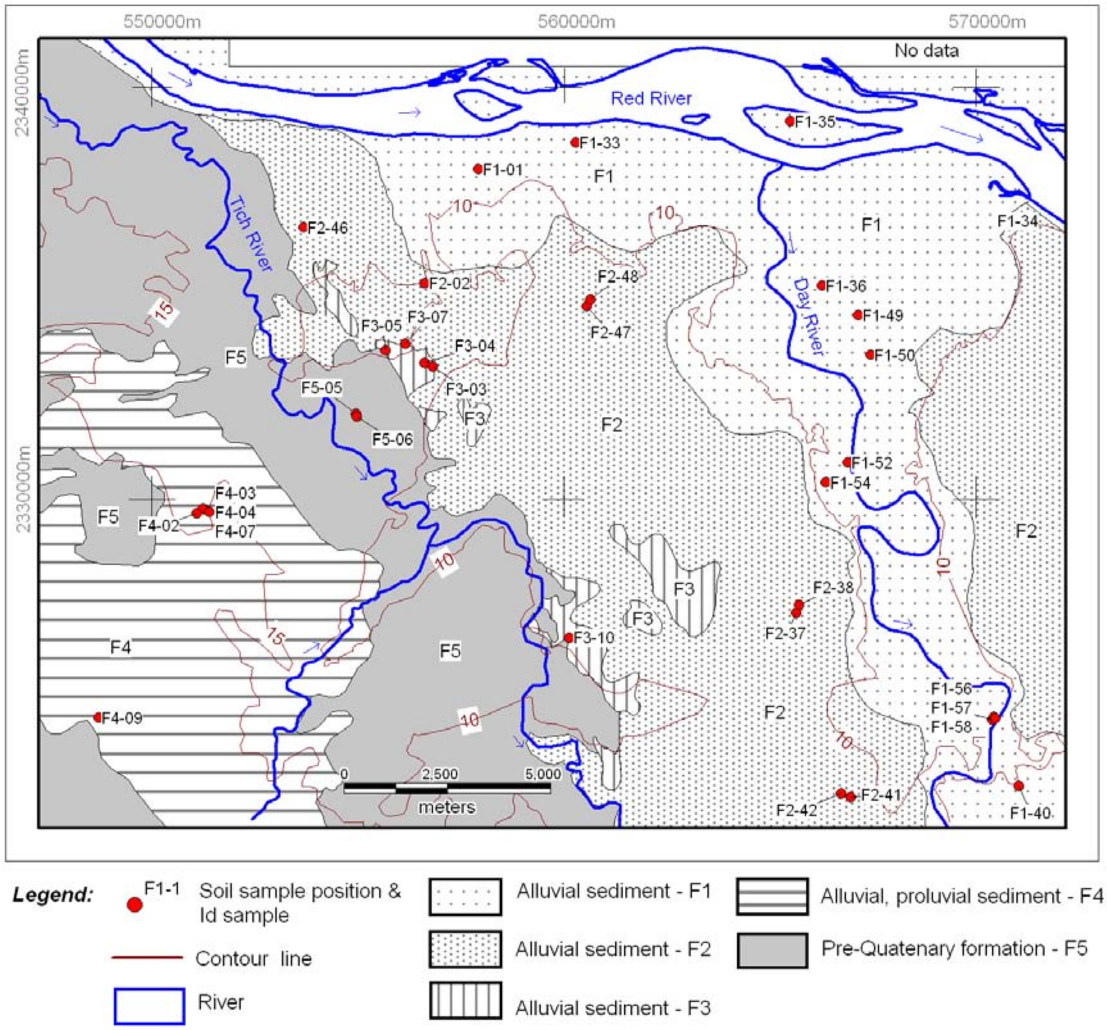

Figure 2.3: Location of soil samples and geology formations. The study focuses on Quaternary formations. Thus, most of soil samples were taken in Quaternary sediment. The terrain is one of criteria to choose the sample position. For example, sample locate in the channel surface and its cliff which created by paleochannel. Only two formations are in pre-Quaternary formation. They locate in Proterozoic formation.

Besides the soil samples, four dating samples are collected (Figure 2.4). Two of them are used for Optically Stimulated Luminescence (OSL) and other are for ^{14}C measurement.

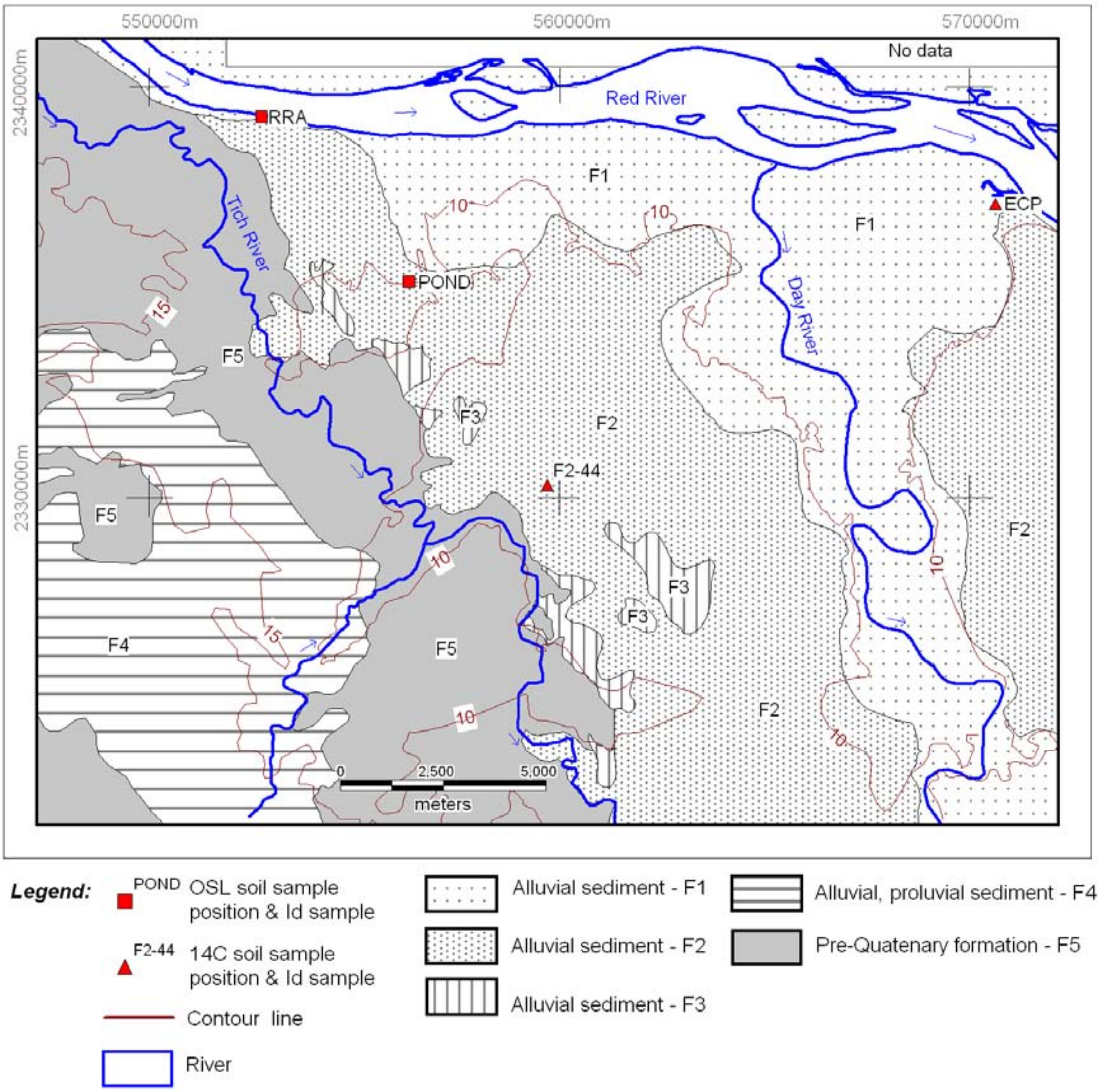

Figure 2.4: Optically Stimulated Luminescence (OSL) and ^{14}C samples in geology map.

The drilling logs were collected from Department of Geology and Minerals of Vietnam and stratigraphic column of the PD core was from the research by Funabiki et al., 2007. The position of these core were presented in Figure 2.5

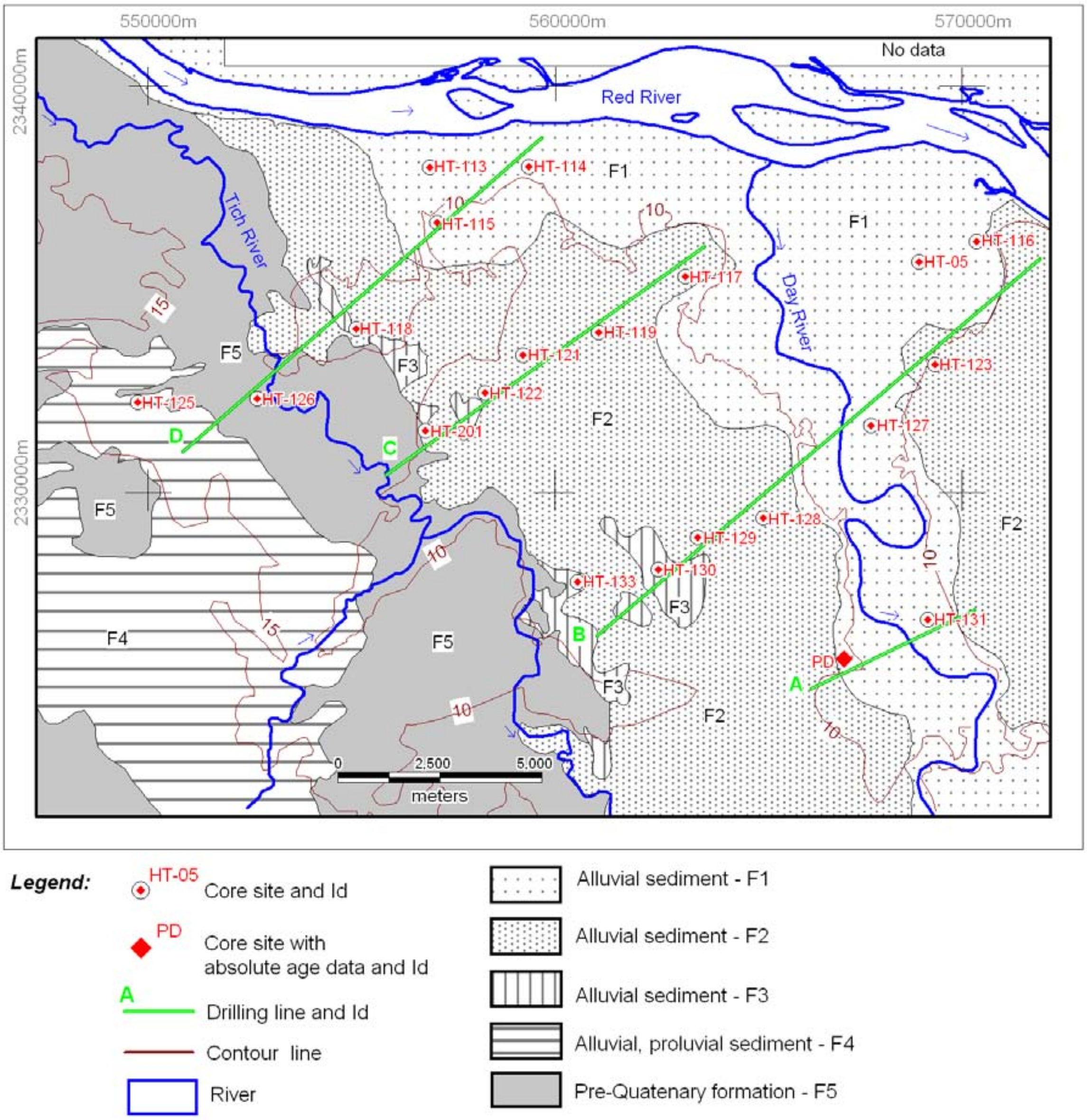

Figure 2.5: The position of drilling core and geological map.

2.4.2 Remote sensing and Geography Information System (GIS) data

Remote sensing data includes:

- SPOT 4 image acquired in 1987, pixel size 15m; SPOT 5 acquired on June 24, 2003 pixel size 10m with multi-spectral bands.

- ASTER image acquired on November 10, 2002; January 13, 2003 15 m pixel size for band 1 – 3N, 30 m pixel size for band 4 – 9.

- Aerial photo scale 1:20.000 acquired in April 2004.

GIS data is:

- Geological map 1:50.000, compose in 1989.
- Contour line and elevation point is digitized based on topography map scale 1:50.000, UTM-WGS 84 zone 48.
- Soil map of Hatay province is digitized based on soil map 1:50.000, compose in 2003.

2.4.3 Hardcopy map

- Topography map 1:50.000 in 1989 UTM-Zone 48, reprinted in 1999 by Department of Cartography – General Staff of Vietnamese People's Army.
- Topography map 1:50.000 in 2000, coordinate VN-2000, printed in 2001 by Map Publishing House.

2.5 Methods

In the following, the methods used in this thesis with respect to physical, chemical and mineralogical methods are described. The method of processing remote sensing data for soil mapping and paleochannel is also mentioned. Optically Stimulated Luminescence (OSL) and ^{14}C dating are the dating methods in the item.

2.5.1 Methods of physical analysis

Particle size distribution

The particle size analysis was carried out by using a combination of wet sieving and sedimentation analysis. The coarse fractions of the samples were extracted using sieves with mesh-sizes of 2000, 630, 200, 63 and 40 µm. The particle size distribution in the < 40 µm-fraction was analyzed by means of a sedimentation analysis with a sedigraph 5000ET (Micromeritics, Georgia, USA). Textural classes of the soils were determined following the textural triangle of USDA system.

2.5.2 Methods of chemical analyses

Soil samples for soil chemical analysis were air-dried and sieved to pass through a 2 mm sieve. These soils are stored in plastic box for subsequent analysis.

pH value in H_2O

The pH (H_2O) value was measured according to OeNORM L-1083-89 (cited by Blum et al., 1996). 10 g of soil were placed into a plastic bottle with 25 ml deionized water. Shake it by hand and make sure all soil is in water. The suspension is kept in 24 hours. After that, pH (H_2O) is measured from the suspension by pH measurement equipment.

Cation exchange capacity (CEC)

2.5 ± 0.01 g soil mixed with 33 ml Ammonium acetate 1M, pH value of solution is 7.0. The suspension solution is shaken in one hour. Clear solution is taken by using filter paper. The clear solution was measured for cation Ca, Mg, K, Na by ICP-AAS (after Anderson and Ingram, 1993)

Dithionite and oxalate extractable Fe / Al / Mn

The extraction of the pedogenic oxides of Fe, Al and Mn (Fe_d, Al_d and Mn_d) was carried out by dithionite-citrate-bicarbonate at pH 7.4 according to the method of Holmgren (1967). 2.0 ± 0.01 g soil and 2.0 g Natriumdithiodit ($Na_2S_2O_4$) were mixed with 100 ml extraction solution. The extraction solution include 0,3 M Na-citrate ($Na_3C_6H_5O_7.2H_2O$) and 1 M Natrihydrogen carbonate ($NaHCO_3$) with mixing proportion of 4:1 (70.58 g Na-citrate and 16.80 g $NaHCO_3$ are mixed in 1000 ml deionized water). The soil and extraction solution were shaken for 16 hours. The clean solution was extracted by using filter paper and subsequently measured by ICP-AAS for Fe_d, Al_d and Mn_d.

The determination of the free oxides of Fe, Al and Mn (Fe_o, Al_o and Mn_o) was carried out by extraction with ammonium oxalate [$NH_4C_2HO_4$] at pH 3.25 according to the method of Schwertmann (1964). The extraction solution included 25.56 g Oxalic acid dehydrate $(COOH)_2.2H_2O$ and 28.40 g di-Ammonium Oxalate monohydrate $(COONH_4).H_2O$ per litter. The pH value of the solution to 3.2 was corrected by using ammoniac NH_4OH. 2.0 ± 0.01 g soil was mixed with 100 ml oxalate solution in a dark bottle which was shaken for 1 hours. The clean solution was extracted by using filter paper and was subsequently measured for Fe_o, Al_o and Mn_o by ICP-AAS.

2.5.3 Methods of mineralogical analyses

Bulk mineral analysis

The samples were oven dried over night at 105 °C and then ground in an agate mortar. The powder samples were prepared according to the “backloading procedure”. These were measured by X-ray diffraction (XRD) in a Philips X-ray-diffractometer PW 1710 with a long fine focus tube and Cu-Kα-radiation (45kV, 40mA) from 2° to 70° 2θ. The measuring time was 1 second in step-scan mode and the step size was 0.02°. Semi quantitative mineral composition of the bulk samples were estimated using the method described by Schultz (1964).

Clay mineral analysis

Only the samples with clay fraction (<2 µm) were analyzed. The X-ray diffraction equipment was described in the bulk mineral analysis. The measure time was 1 second in a step-scan mode and a stepsize of 0.02^o. Sample preparation generally followed the methods described by Whittig (1965) and Tributh (1989). Dispersion of clay particles and destruction of organic matter was achieved by treatment with dilute hydrogen peroxide (10 %). Separation of the clay fraction (<2 µm) was carried out by using the centrifugation. The exchange complex of each sample (<2 µm) was saturated with Mg and K using chloride solutions by shaking. The preferential orientation of the clay minerals was achieved by suction of 20 mg clay in suspension through a porous ceramic plate (Kinter & Diamond, 1956). To avoid disturbance of the orientation during drying, the samples were dried and equilibrated some days with saturated NH_4NO_3 solution in a desiccator. Afterwards, expansion tests were made using ethylene glycol (K- and Mg-saturated samples), and dimethylsulfoxide (DMSO) (K-saturated samples) as well as contraction tests after heating the samples to 300 and 550 C for at least 2 hours. After each step the samples were X-rayed from 2 - 40 ° or 2 – 14 ° 2Ө (heated samples).

The clay minerals were identified according to Thorez (1975), Brindley and Brown (1980), Moore and Reynolds (1997) and Wilson (1987). Semi-quantitative estimations were carried out by using the corrected intensities of characteristic X-ray peaks (Riedmüller, 1978).

2.5.4 Age determination

OSL dating of sediment

Optically Stimulated Luminescence (OSL) dating determines the last exposure to sunlight of a sediment. Sedimentation ages are calculated by dividing the equivalent dose (De) by the dose rate (Do). The equivalent dose, expressed in Gy (= 1 J/kg), is a measure of the radiation dose accumulated in minerals such as quartz and feldspars during burial. The dose rate describes the natural ionizing radiation in sediments and is expressed in Gy/a. Sources of natural radioactivity in sediments are 232Th, 238U, 235U and 40K found in a lot of minerals, and cosmic radiation.

Two samples (PON1 and PON2) were prepared for coarse grain measurements of the quartz fraction. For this, the grain size fraction between 100 and 200 µm was extracted by dry sieving and subsequently subjected to diluted HCl and H_2O_2 in order to remove carbonates and organic matter.

Heavy density liquid separation was used to extract the quartz rich fraction, which was subsequently etched in HF (40%) for 40 min to destroy remaining feldspars and to remove the outer alpha-irradiated rind of the quartz grains. For determination of the equivalent dose, the Single-Aliquot Regenerative-Dose Protocol (SAR) (Murray and Wintle, 2000, 2003) was applied using small (1mm diameter) aliquots, consisting of around 50±25 quartz grains. For each sample, 18 aliquots were measured, and the central age model (Galbraith et al., 1999) was used for the mean De calculation.

Two further samples (RRA1 and RRA2) were prepared for luminescence measurements of the polymineral fine grain fraction. The samples were subjected to diluted HCl and H_2O_2 to remove carbonates and organic matter, and subsequently, the grain size fraction from 4-11 µm was extracted by sedimentation procedures. For each sample, five aliquots were prepared by covering the entire steel disc with the fine grain fraction (9 mm diameter). The De was determined using a SAR protocol. Stimulation was carried out by using infra-red light emitting diodes, which only produces luminescence of the feldspar fraction. The mean De was calculated by using the central age model.

For calculation of the dose rate, radionuclide concentrations were determined by means of laboratory gamma spectrometry. 800 g of sample material were dried and stored for three weeks in air-tight marinelli beakers. The gamma emission of U, Th, and K was collected within a measurement period of 20 h. The radionuclide concentrations were converted into dose rates using the conversion factors of Adamiec and Aitken, and a water content of 30 ± 10% (samples PON1 and RRA1), 20 ± 10 % (RRA2) or 15 ± 10 % (PON2) was considered in the calculation of the dose rate.

^{14}C analysis

The AMS ^{14}C measurement was done in Poznan Radiocarbon Laboratory, Poland. Two samples were processed. The description of these samples was presented in Appendix 8. Before measuring, the samples were processed to produce graphite cathode from carbon contained in the sample. The procedure must remove any contamination which was deposited in the sample after of dated organism. This procedure is described by Czernik and Goslar, 2001. The procedure cathode can then be inserted into AMS spectrometer for measurements of carbon isotopic ratios.

The ^{14}C concentration of the samples is measured in the spectrometer "Compact Carbon AMS" - produced by National Electrostatics Corporation, USA, and described by Goslar et al., 2004.

Conventional ^{14}C ages are calculated based on the $^{13}C/^{12}C$ ratio measured by our AMS-system simultaneously with the $^{14}C/^{12}C$ ratio.

2.5.5 Soil spectral from spectroradiometer in the laboratory

In the laboratory, soil samples were dried at room temperature for one week, ground and sieved at 2 mm. The spectroradiometer equipment is ASD FieldSpec Pro, with the spectrum ranging from 350 to 2500 nanometers with 1nm increments. The so called "Contact Probe", which includes a halogen bulb for illumination and measures in biconical geometry, was used to contact to the soil samples. In order to obtain reflectance spectra, the measurement values of reflected radiation were related to a white reference standard (Spectralon). Each sample is measured at least nine times by spectroradiometer. The last soil spectral in the lab of a field sample is calculated by the average of these data measurements.

2.5.6 Processing remote sensing data

2.5.6.1 Processing ASTER data for soil mapping

pre-Processing

ASTER data which acquired on 13 January 2003 was used for soil mapping. The ASTER bands used for the task are the visible and near-infrared bands 1 – 3N and the short-wave infrared (SWIR) bands 4 – 9. Before meaningful information can be extracted by using an end-member analysis method, ASTER data has to be resampled (to have the same pixel size in all bands) and converted to reflectance values. Furthermore, the geolocation of data should be correct for further overlaying. This pre-processing involves a series of steps that is shown in the flowchart (Figure 2.6)

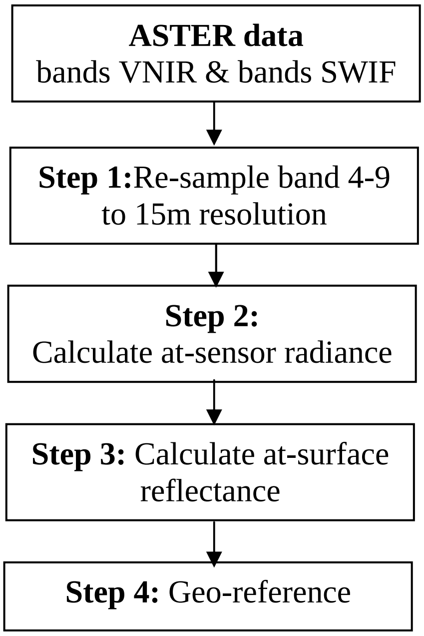

Figure 2.6: Flowchart of pre-processing ASTER data. Before end-member analysis, the data run through to 4 steps. The aim of the task is the fulfillment the requirement of end-member method.

The raw ASTER data from band 1 to 9 has two resolutions of 15 m and 30 m. In the first step, it is required to convert the data to one resolution. The resolution of choice in this case study is 15 m. Therefore, in step 1, bands 4 –

9 (SWIR band) are resampled to 15 m resolution by the PCI software version 8.1 based on a nearest neighbor algorithm.

In step 2, a standard method is used to convert the ASTER raw digital number to at-sensor radiance (Smith, 2007; Yuskel et al., 2008).

The equation to convert ASTER raw "digital number" to value of at-sensor radiance is

$L_{sat} = (DN-1) * UCC$

Where:

L_{sat} = at-sensor spectral radiance

DN = digital number (the pixel values in the original ASTER data)

UCC = Unit Conversion Coefficient. This is different for each ASTER band, and also depends on the gain setting that was used to acquire the image. Based on these gain settings, the appropriate UCC is selected for each band. The parameter is described in the table 2.1

In fact, in the ENVI 4.2 software, the step 2 is processed automatically.

Table 2.1: Parameters of ASTER Gain that is used to convert digital number values (the pixel values in the original ASTER data). Source Abrams et al., 1999, p.26

Band	**Coefficient** ($W/m^2*sr*um)/DN$)			
	High Gain	**Normal**	**Low Gain 1**	**Low Gain 2**
1	0.676	1.688	2.25	
2	0.708	1.415	1.89	
3N	0.423	0.862	1.15	
4	0.1087	0.2174	0.2900	0.2900
5	0.0348	0.0696	0.0925	0.4090
6	0.0313	0.0625	0.0830	0.3900
7	0.0299	0.0597	0.0795	0.3320
8	0.0209	0.0417	0.0556	0.2450
9	0.0159	0.0318	0.0424	0.2650

Surface reflectance corrects for two sets of factors. The first is variations in solar illumination influenced by properties such as the solar elevation angle and earth-sun distance. The second factor involves the influence of atmospheric haze and aerosols on the signal detected by the sensor. By correcting for these factors, the surface reflectance should characterize the land features themselves. In step 3, calculation of the surface reflectance is implemented by the following equation from the method of Warner (2008). This method is based on earlier methods published by Chavez (1996) and Lu et al. (2002)

$$\rho = (\pi * (L_{sat}-L_{haze}) * d^2)) / (Esun_\lambda * [(\cos\theta_s)^2])$$

Where:

ρ = surface reflectance

$\mathbf{L_{sat}}$ = at-sensor radiance (calculated in step 2)

d = factor accounting for variation of earth-sun distance, calculated using this equation:

d = (1 - 0.01672 * COS(RADIANS(0.9856 * (Julian Day - 4))))

$\mathbf{Esun_\lambda}$ **=** a constant that is different for each ASTER band. The constants are listed in table 2.2.

Table 2.2: $ESUN_i$ parameters are used in the equation to convert ASTER at-sensor radiance value to surface reflectance value. Source: Smith (2007)

Band	$ESUN_i$
1	1845.99
2	1555.74
3N	1119.47
4	231.25
5	79.81
6	74.99
7	68.66
8	59.74
9	56.92

$\boldsymbol{\theta_s}$ **(solar zenith angle):** The solar zenith angle = 90 - Solar Elevation Angle. The Solar Elevation Angle can be obtained from the ASTER metadata file in the “Solar_Elevation_Angle” section. In the equation, the denominator contains the term $(\cos(\theta_s))^2$. Some versions of this equation use only the term $\cos(\theta_s)$, but here the second $\cos(\theta_s)$ is used to approximate tau, the atmospheric transmittance. This method is appropriate for humid climates, such as the tropical landscapes in this study (Warner, 2008).

L_{haze} = estimate of upwelling scattered path radiance due to atmospheric haze, aerosols, etc. The subtraction of L_{haze} from L_{sat} is a “dark object subtraction” approach to determine the portion of the at-sensor radiance that is attributable to ground properties, while subtracting out the portion that is attributable to atmospheric effects. This method has been found to be reasonably accurate, and is the most feasible approach to atmospheric correction when actual atmospheric data are not available (Chavez 1996, Lu et al. 2002). To determine L_{haze} for each ASTER band, the histogram of data values for the at-sensor spectral radiance raster is viewed. The value at the toe of the histogram (right at the point where the histogram began to register a significant number of pixels) is manually selected. This value should be around the 0.05th to 0.1th percentile of all pixel values. We avoided selecting the lowest value on the histogram, which could be outlying “noise” not representative of a typical dark object on the landscape.

In order to overlay data in GIS software, the ASTER data needs to be geo-referenced. This procedure is visualized as step 4 in the flowchart of Figure 2.6. The geo-referencing method transfers ASTER data from pixel-line coordinates to map coordinate system. By using the re-sampling algorithm and ground control points (GCP) between geo-referenced database and the uncorrected image, the uncorrected image will be transformed to the map coordinate system. The geographic coordinate chosen in the study is UTM WGS-84, zone 48, the Northern hemisphere. The re-sampling algorithm is nearest neighbour and 2nd order polynomial model. The root mean square (RMS) error for X, Y coordinates of all accepted ground control points in this model is smaller than 1.0. This criterion is required to gain a high accuracy in the overlaying process.

WRB soil mapping based on end-member analysis of ASTER data

To account for the improved information content of the new generation sensors like the ASTER sensor, hyperspectral analysis techniques were chosen for soil mapping in the study area. The method is based on the fact that every material is characterized as a unique spectral signature in the electromagnetic spectrum. This signature can be reconstructed if sufficient bands in the remote sensing data exist. Therefore, for mapping the surface composition, image-derived reflectance spectra of the pictured earth surface are compared to (known) reference spectra of material. There are also referred to as end-members (Adams et al., 2006). End-members can be obtained from different sources such as field measurements, spectral libraries or from the image data. The method of end-member analysis in the study is described in Figure 2.7. The "Spectral Hourglass tool" in ENVI 4.2 was used for the analysis.

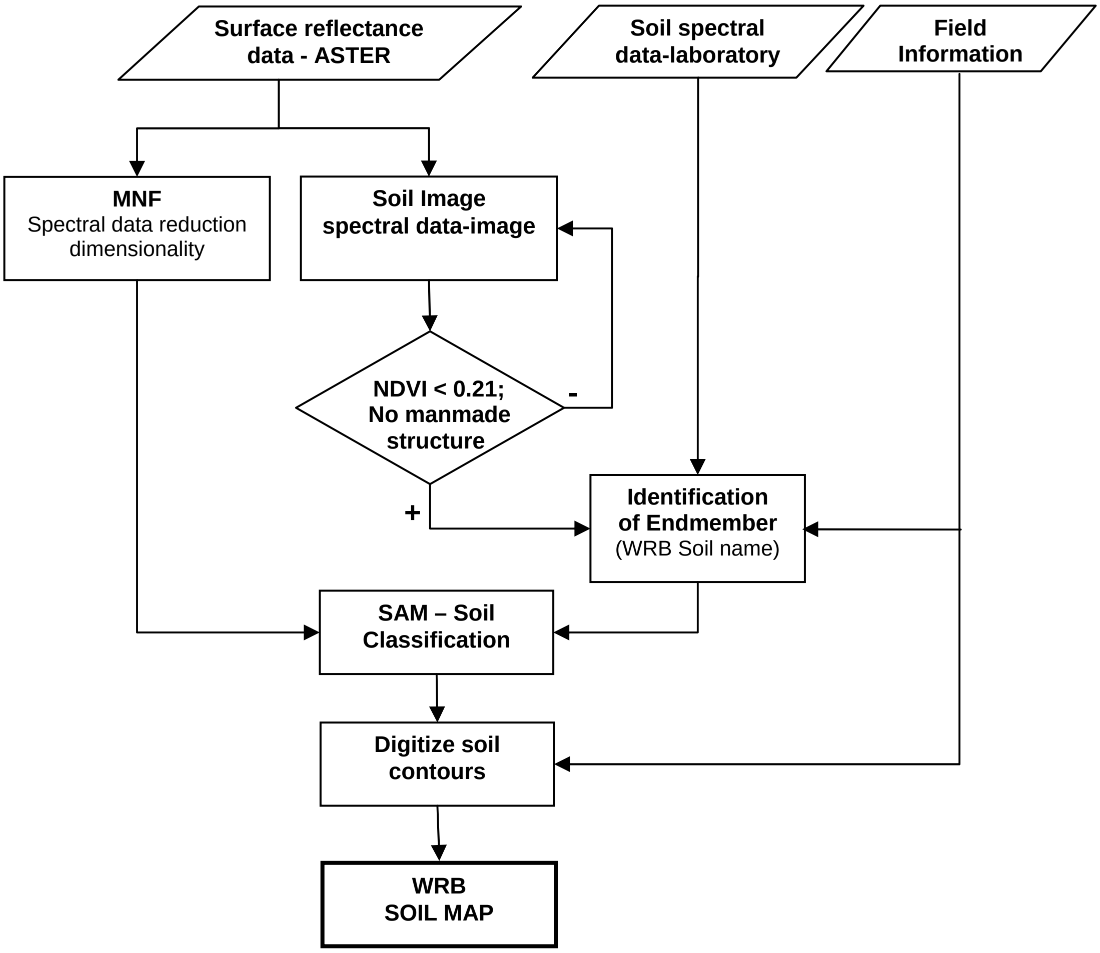

Figure 2.7: Flowchart of soil mapping based on end-member analysis. The quality of end-member is very important in the processing scheme.

From this study, the method to use directly soil spectral in the lab as end-members in the "Spectral Hourglass tool" of ENVI 4.2 is not useful. The reason is that the ASTER data could not be processed with Atmospheric correction tool due to lack of atmospheric information. The soil humid conditions and vegetation cover from the field at image acquisition time were too complicated. Furthermore, the soil spectral in the present study is not "in-situ" spectra therefore it is not suitable to use soil spectra in the lab as end-members. The alternative end-member selection was performed by comparing the soil image spectra with soil spectroradiometer measurements in the laboratory. The method to perform soil spectroradiometer measurements is mentioned in section 2.5.5. The image spectra of each soil type are collected from pixels selected by visual interpretation in the ASTER pseudocolor image (Red: band 3N, Green: band 2, Blue: band 3). The pseudocolor image is used to easily choose pixels without vegetation cover. The resolution of the ASTER image (pixel size) in the study is 15 m which equals 225 m^2 in the field. The soil pixels can show a mix with undesirable objects, such as vegetation or man-made structures, while pixels of bare soil are needed for soil end-members. Thus, the Normalized Difference Vegetation Index (NDVI) was used to select pure soil pixels. All NDVI values of the collected soil pixels in the image are smaller than 0.21 (see Appendix 6). Aerial photos which were acquired in 2004 were also used to ensure that pixels without man-made structures are collected.

Not all the image spectra will become end-members. End-members were chosen from the image spectra data based on the regression between the image spectra with laboratory spectra obtained from spectroradiometer measurements of top soil samples from the field. The square of the Pearson product moment correlation coefficient (r) was used as a criterion. The minimum of r value is 0.11 for image spectra becoming an end-member (see Appendix 6). Field soil samples were named according to World Reference

Base (WRB) criteria (see FAO, 1998) (see soil field name in Appendix 1). The WRB name of an end-member was given according to soil sample which has the highest r value between the image spectrum and the spectrum measured in the laboratory at the soil samples (see Appendix 6). The number of end-members to be used later for Spectral Angle Mapper (SAM) is presented in Table 2.3. In the study area, the Ferralic Cambisols type occurs with very small areas in formation F3 (river terrace I). Therefore, this type cannot be presented in WRB soil map. But this type is shown in catena with bigger scale (see Figure 3.16). Besides the WRB end-members, there is a "sand" end-member for the sand in island river area. This end-member is not listed in Table 2.3 but it is used in the soil mapping.

Table 2.3: Number of end-members relates to each WRB soil type.

Number of end-members	WRB Soil type	Number of end-member	WRB Soil type
5	Ochric Fluvisols	1	Areno Ochric Fluvisols
7	Umbric Fluvisols	3	Ferralic Fluvisols
3	Gleyic Ochric Fluvisols	4	Plinthic Ferrasols
3	Gleyic Umbric Fluvisols	2	Gleyic Plinthic Ferrasols
1	Gleysols	*Total: 29 WRB end-members*	

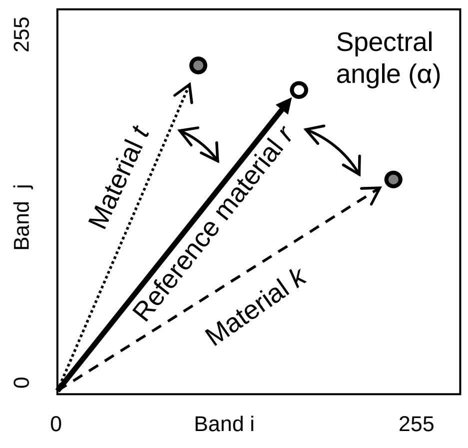

Figure 2.8: The logic associated with the Spectral Angle Mapper (SAM) algorithm (redrawn from Jensen, 2005, p.453)

For the soil mapping, the Spectral Angle Mapper (SAM) was chosen. SAM is a physically-based classification algorithm that determines the spectral similarity between reflectance image spectra and reference spectra. Figure 2.7 shows the example for two materials *r* and *t* in the simple two-dimensional case. In this case, the unknown material *t* has a spectrum that is more similar to the reference spectrum *r* than the spectrum for material *k*. The angle (α) in radians between *r* and *t* is smaller than the one between *r* and *k*.

Due to the vegetation cover in study area, not the whole area was classified by SAM methods. To overcome the issue, soil contour was digitized based on the SAM map result. The digitization process was also supported by the field information. The final WRB soil map is shown in Figure 3.8.

2.5.6.2 Visual interpretation of paleochannels

River activities, especially the change of the river bed in the past, may affect the soil properties. Satellite images from three data and aerial photo from one data are used. The data set includes ASTER images acquired on November 10, 2002 and January 13, 2003 and SPOT 5 image acquired on June 24, 2003, aerial photos acquired in April 2004. Thus two images were taken during harvest time (the one in January and the one in June). All images and aerial photos were geo-referenced to UTM WGS 84, Zone 48 using control point from topographic maps 1:50.000. The geo-reference process used here is explained in section 2.5.6.1

The key geomorphological features for the recognition of paleochannel are channels or oxbow lakes. The channels can be continuous or interrupted. The altitude difference between the surface of channel and elevated surrounding is responsible for the difference in soil moisture. In many case, the different soil moisture causes the development of different plant types. The difference is easy to recognize in both the pseudo-color satellite image and in the aerial photo. In some cases, the “embossing” of channel edge is recognizable in the aerial photo (Figure 2.9). The paleochannel map is presented in Figure 3.9

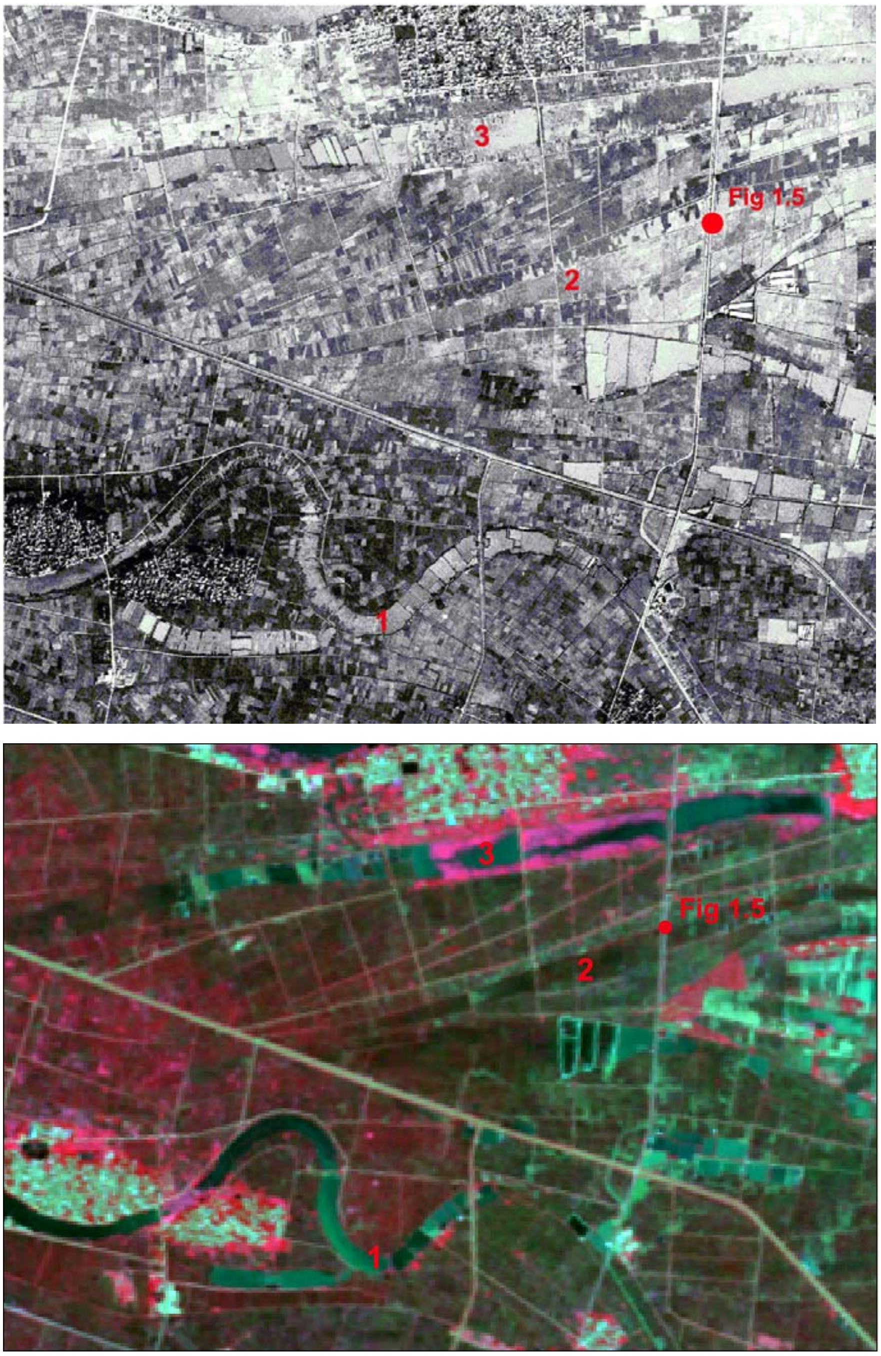

Figure 2.9: The paleochannel in the aerial photo and in the SPOT satellite image. In the field, paleochannels is channels which its cliff is 0.8 – 1.5 m high. In aerial photo, the floor of the channel is bright in tone. In many cases, we can recognize the “embossing” of the channel edge (channel 2 in this fig.) The pseudo color rendering of the SPOT image is Red: band 3, Green: band 2 and Blue: band 1. In pseudo color of SPOT image, the channel often has a dark tone. The landscape of paleochannel #2 can be seen in Figure 1.5 (red circle).

2.5.6.3 Landcover/Landuse map from remote sensing data

The landcover/landuse is important information for this thesis. Two dates of landcover/landuse were chosen in 1987 and 2003. For visual interpretation of landcover/landuse in 1987, the data includes: SPOT image acquired in 1987 and topography map 1:50.000 from 1989. For landuse in 2003, data includes: ASTER image acquired on Nov. 10, 2002 and Jan. 13, 2003; SPOT image acquired on June 24, 2003; aerial photos (scale 1:20.000) acquired in April 2004.

The legend of landcover/landuse types in 1987 and 2003 interpreted from remote sensing data is:

Paddy rice (2 crops / years)
Vegetable
Perennial plant
Shrub
Artificial forest
Thin forest (natural forest)

Permanent bare soil
Bare soil in island river
Specialized area (such as industry area, army base)
Residential area
Residential area mixed orchard
Construction site
Water

The landcover/landuse maps of 1987 and 2003 are drawn in Figure 3.10 and 3.11

2.5.7 Analysis spatial data

GIS functions are used to determine the elevation distribution of each geological formation (see Table 1.1) and to compile landcover/landuse chance matrices (Table 3.14, 3.15, 3.16 and 3.17)

3 Results

This chapter describes the results from the methods and samples which were presented in the second chapter. Soil sample properties will be described in groups according to the location of the samples within the geological formation. The WRB soil map which was composed based on remote sensing data is the next issue described. The last and one of the most important results of the thesis is the catenas with the soil profile properties, geomorphological and geological information.

3.1 Physical soil properties

3.1.1 Particle size distribution

The particle sizes found in the samples investigated range from gravel, sand, silt and clay. The results of the particle size analysis are presented in Appendix 2. For the interpretation of soil properties, the gravel fraction (>2 mm) usually is not included. Therefore, in the thesis the sand to clay fraction is converted to 100% and the gravel fraction is quoted in a separate column in Table 3.1 and Appendix 2.

Table 3.1 : Particle size distribution within samples of Quaternary formations

Geological formation	Group	Gravel fraction (%)	Sand / Silt ratio			Silt / Clay ratio		
			min	max	*Mean*	min	max	*mean*
F1	1	0	0	0.03	***0.01***	0.69	2.54	***1.36***
	2	0	0	0.2	***0.04***	1.53	4.38	***2.67***
	3	0	0.12	2.24	***0.78***	2.83	5.44	***3.93***
F2	1	0 - 9	0	0.23	***0.08***	0.32	2.44	***1.04***
	2	0	0.28	1.87	***1.12***	0.88	1.18	***0.91***
F3	-	0 - 32	0.17	1.29	***0.44***	0.40	0.85	***0.64***
F4	-	0 - 53	0.16	7.50	***1.41***	0.12	2.21	***1.20***
F5	-	0 - 39	0.65	1.39	-	0.77	0.85	-

As mentioned in section 1.3.1, the F1 formation outcrop in the study area is in the Day River valley. Soil samples of this formation can be divided into three groups based on the ratio sand / silt and silt / clay (Table 3.1). Samples belonging to the first group are F1-36, - 49, - 50 and located between the Red River and the Day Dam (sample's location see Figure 2.3). They are characterized by very small proportions of the sand fraction (maximum is 2 % of the total weight) and relatively high contents of silt and clay. The silt fraction ranges from 41 to 71 % and the clay fraction from is 28 to 59 % of the total weight. (see Appendix 2)

The second group is dominated by the silt fraction with a proportion range from 58 to 73% of the total weight. The clay fraction is below 38 %. Samples F1-01, -33, -35 located between the Red River to Day River dam and samples F1-40 behind the Day River dam belong to this group.

The third group is located behind the Day River dam and includes the samples F1-53, -54, -56, -57 and -58. The sand proportion in this group ranges from 6 – 65% whereas the clay fraction only makes up 6 – 24 %. The silt content in this group is from 29 to 70 %.

Sample within the F2 formation can be divided into two groups (Table 3.1). The clay and silt fraction of the first group ranges from 25 to 76 %, and from 24 to 62 % respectively. The sand proportion is below 14 %. The gravel proportion is only found from 1 to 9 % in samples F2-37 and -41.

Samples within the second group are F2-02 and -38. The sand fraction reaches up to 43 %. The silt and clay proportions of this group range from 30 to 47 % and from 34 to 40 % respectively.

The samples in the F3 formation contain proportions of gravel ranging from 0 to 3 % and reaching 32 % of the total weight in sample F3-10 (70-140 cm). The dominant fraction in the group is clay ranging from 41 to 64 %. The silt is below 41% and the sand is below 27%. Except for sample F3-10 (15-40 cm), the ratios of sand / silt and silt / clay range from 0.17 to 0.56 and from 0.47 to 0.79 respectively. These ratios in the sample F3-10 (15-40 cm) are significantly different with 1.29 (sand / silt) and 0.4 (silt /clay).

In formation F4, the gravel fraction ranges from 0 to 53 % of the total weight. The sand fraction is 14 – 48 % and the clay fraction is 23 – 56 %. The range of the silt fraction is very large from 6 to 62%. The sand / silt ratios of the two samples (located in the hill top and on erosion terrace II) are very high (up to 7.5), whereas the silt / clay ratios are low (0.12)

From the F5 formation, two topsoil samples in close vicinity were analyzed (see Figure 2.3). However, their grain size distributions vary considerably. The gravel fraction in sample F5-06 is 39 % but is not present in sample in F5-05. The sand / silt ratio in samples F5-05 and F5-06 are 0.65 and 1.39 respectively. The silt / clay ratio is 0.77 in sample F5-05 and 0.85 in sample F5-06.

3.1.2 Textural class

The textural classes of the selected soil samples of four Quaternary formations are presented in Figure 3.1. Because only two topsoil samples in the F5 formation were analyzed, this section only discusses the data of formations F1 to F4. Most of the samples from F1 and F2 formation can be classified as loam subclasses or silty clay. An exception is sample F2-42 and -47, which consist of clay. Silty clay and clay textural are appearance in samples from F3 and F4 samples. With samples in foothill of F4 formation, the texture is mainly silt loam and silty clay loam.

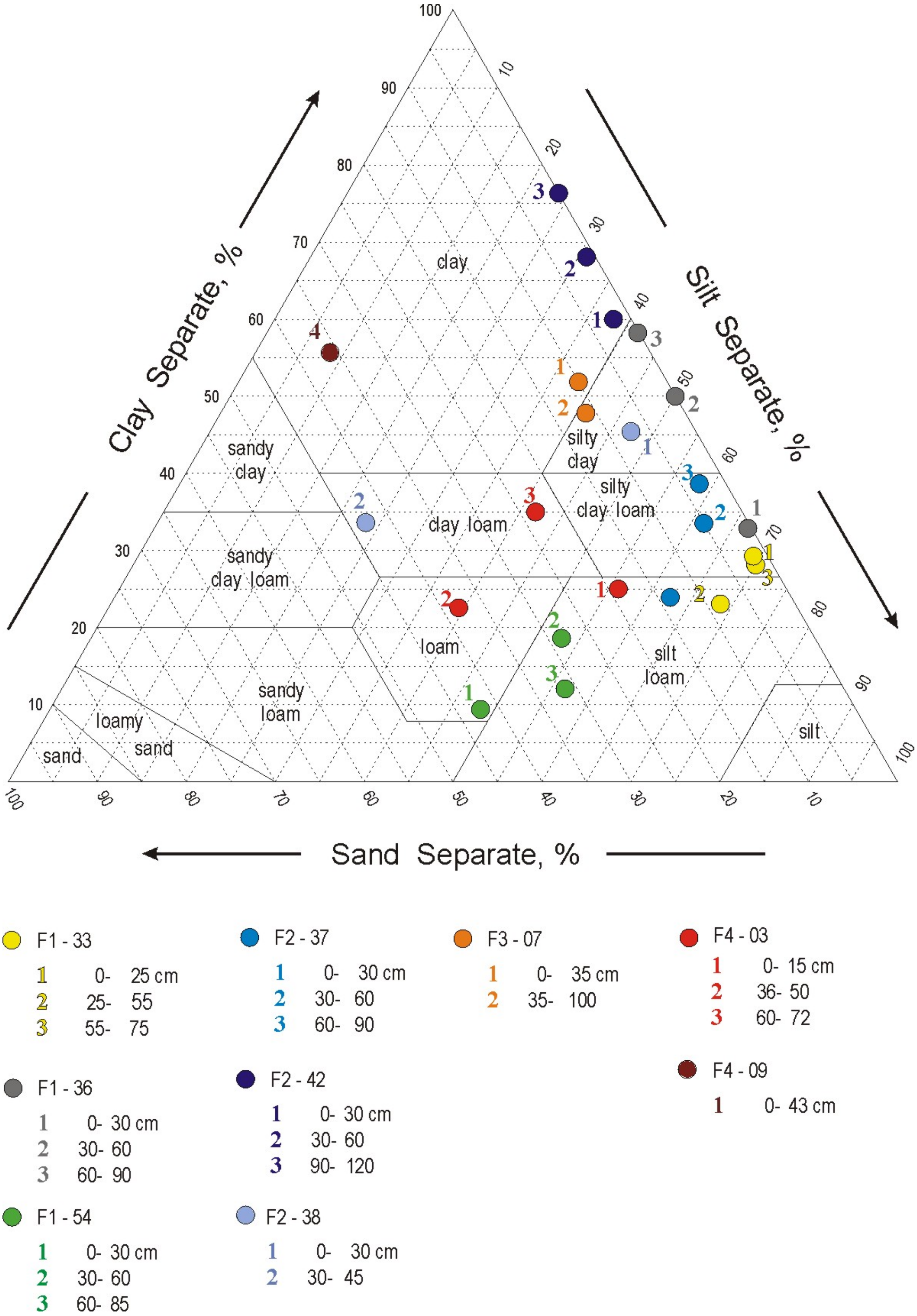

Figure 3.1: The textural class of the selected soil.

3.1.3 Munsell soil color

Munsell color of soil samples were defined in dry and moist conditions. The color data given in Table 3.2 was determined in moist condition.

Table 3.2: Munsell colors of samples determined in moist condition for five geological formations present in the study

Geological formation	Group	Hue	Value	Chroma	Description
F1	1	5YR - 7.5 YR	5 - 6	3 - 5	Brown / Reddish brown
	2	5YR - 7.5 YR	4 - 5	3 - 4	Brown / Reddish brown
	3	5YR	4 - 5	3	Reddish brown
F2	1	7.5YR - 10YR	5 - 6	3 - 6	Brown / Brownish yellow
	2	7.5YR	4 - 5	3 - 4	Brown
F3	-	7.5YR - 10YR	5 - 6	4 - 8	Strong brown / Yellowish brown / Reddish brown / Red
F4	-	5YR - 10YR	5 - 6	3 - 8	Brownish yellow / Yellowish brown / Reddish yellow
F5	-	10 YR	5	4	Yellowish brown

There are some remarkable differences in the soil color (Table 3.3). The color of samples F2-42 (-20 cm and deeper) is light yellowish brown or brownish yellow, whereas the remaining samples from this profile (0-20 cm) and other samples from F2 formation is brown. In profile F3-10, there are two differences. First, the color in this profile is different from all other samples from formation F3. Second, there is a variation in color within the profile, ranging from brownish yellow in a depth of 15-40 cm to red in a depth of 40cm and deeper. Profile F4-02 also shows color differences from top to bottom. Yellow colored samples were only found in the top layer of profile F3-10, F4-02 and F5-05.

Table 3.3: Munsell color of selected samples.

Sample Id	Depth (cm)	Dry condition	Description	Moist condition	Description
F2 - 42	0 - 20	10YR 7/3	Very pale brown	10 YR 5/3	Brown
	20 - 40	10YR 8/1; 10YR 8/3	White / Very pale brown	10YR 6/4	Light yellowish brown
	40 - 60	10YR 8/3	Very pale brown	10YR 6/6	Brownish yellow
F3 - 10	15 - 40	10YR 7/6	Yellow	10YR 6/6	Brownish yellow
	70 - 140	10YR 7/6; 10R 5/8	Yellow / Red	10R 5/8	Red
F4 - 02	40 - 110	10YR 7/6	Yellow	10YR 6/6	Brownish yellow
	110 - 130	5YR 6/6	Reddish yellow	5YR 6/8	Reddish yellow
F5 - 05	40 – 55	10YR 7/6	Yellow	10YR 6/6	Brownish yellow

3.2 Chemical properties of soils

3.2.1 pH (H_2O) value and Cation Exchange Capacity (CEC)

The pH (H_2O) values are given in Appendix 3. The range of pH-values is presented in Table 3.4. In samples from the formations F1 and F2, the pH-value is alkaline. The pH-values are weakly acid in samples of F3 and acid in F4.

Table 3.4: Range of pH-values and Cation Exchange Capacity (CEC) in each geological formation.

Geological formation	Group	pH		CEC (mMol/100g)		Quantity CEC samples
		min-max	*mean*	min-max	*mean*	
F1	1	6.6 - 7.9	***7.6***	12.35 - 25.31	***17.65***	14/15
	2	5.1 - 7.9	***7.4***	5.64 - 21.87	***14.53***	8/16
	3	6.1 - 7.7	***6.8***	8.05 - 14.83	***10.53***	3/3
F2	1	4.9 - 7.0	***6.1***	5.02 - 12.35	***9.80***	16/16
	2	6.1 - 6.8	***6.5***	6.33 - 8.33	***7.30***	2/3
F3	-	4.3 - 7.1	***5.3***	0.92 - 8.15	***4.96***	7/7
F4	-	4.1 - 5.2	***4.4***	0.53 - 2.34	***0.97***	6/11
F5	-	4.5 - 5.3	***4.9***	3.08		1/2

Cation exchange capacity (CEC) is highest in the first group of the F1 formation with 17.65 mMol/100g mean value. It decreases to 0.97 mMol/100g mean value in F4 formation.

3.2.2 Pedogenic oxide

The data of the pedogenic oxides is presented in Table 3.5, 3.6 and Appendix 3. Because only two topsoil samples in the F5 formation were analyzed, the following section only discusses the data of formations F1 to F4.

3.2.2.1 Dithionite extractable iron, aluminum and manganese

Table 3.5 shows the range of the dithionid extractable of iron, aluminum and manganese.

Table 3.5: Range of dithionite extractable iron, aluminum and manganese of each geological formation in the study area.

Geological Formation	Group	Fe_d (g kg^{-1})		Al_d (g kg^{-1})		Mn_d (g kg^{-1})	
		min-max	*mean*	min-max	*mean*	min-max	*mean*
F1	1	22.64 - 31.63	***29.13***	0.96 - 1.47	***1.27***	0.54 - 1.03	***0.80***
	2	17.82 - 32.88	***24.5***	0.79 - 1.9	***1.29***	0.58 - 1.0	***0.80***
	3	11.83 - 22.91	***15.87***	0.43 - 1.01	***0.64***	0.27 - 0.84	***0.46***
F2	1	21.13 - 48.89	***24.94***	1.28 - 3.56	***2.08***	0.12– 1.31	***0.73***
	2	14.89 - 24.14	***19.87***	0.61 - 1.56	***1.02***	0.46 - 0.95	***0.57***
F3	-	19.88 - 153.83	***53.69***	1.85 - 12.86	***5.14***	0.03 - 0.29	***0.13***
F4	-	16.25– 140.8	***62.58***	1.41- 16.01	***6.75***	0.01 - 0.5	***0.09***

Free iron oxides (Fe_d): There are some remarkable differences in some samples. In samples F3-10 (70-140cm depth), the Fe_d reaches to 153.83g kg^{-1}, but in 0-35 cm the value is only 31.85 g kg^{-1}. In sample F3-07, the Fe_d values vary from 50.24 to 60.7 g kg^{-1}. In hill foot of F4 formation, the samples from 60 cm to deeper, the values reach from 111.44 to 140.8 g kg^{-1}.

Free aluminum oxides (Al_d): In samples F3-10 (70-140cm depth), the Al_d reaches to 12.86 g kg^{-1}, but in 0-35 cm the value is only 4.2 g kg^{-1}. The Al_d values in sample F3-07, vary from 5.15 to 6.51 g kg^{-1}. In hill foot of F4 formation, the samples from 60 cm to deeper, the values reach from 6.04 to 16.01 g kg^{-1}.

Free manganese oxides (Mn_d): The Mn_d values are distributed relatively uniform over the profiles investigated.

3.2.2.2 Acid oxalate extractable iron, aluminum and manganese

Table 3.6 describes the data range of acid oxalate extractable iron, aluminum and manganese.

Table 3.6: Range of acid oxalate extractable iron, aluminum and manganese of each geological formation in the study area.

Geological formation	Group	Fe_o (g kg^{-1})		Al_o (g kg^{-1})		Mn_o (g kg^{-1})	
		min-max	*mean*	min-max	*mean*	min-max	*mean*
F1	1	2.04 - 4.18	***2.68***	0.48 - 0.7	***0.58***	0.4 - 0.96	***0.69***
	2	2.1 - 5.01	***3.36***	0.44 - 1.1	***0.65***	0.43 - 0.95	***0.63***
	3	1.37 - 2.79	***1.96***	0.25 - 0.48	***0.35***	0.24 - 0.66	***0.39***
F2	1	0.6 - 7.29	***2.35***	0.58 - 0.85	***0.71***	0.08 - 1.01	***0.53***
	2	1.52 - 5.54	***3.17***	0.37 - 0.54	***0.48***	0.14 - 0.78	***0.43***
F3	-	0.71 - 3.77	***1.86***	0.33 - 1.06	***0.75***	0.01 - 0.24	***0.09***
F4	-	0.83 - 4.58	***2.19***	0.51 -1.49	***0.96***	0.01 - 0.21	***0.03***

There are no noticeable from the result of Acid Oxalate extractable iron, aluminum and manganese.

3.2.2.3 Data of correlation between dithionite and acid oxalate extractable of iron, aluminum and manganese

Figure 3.2 to 3.4 display the correlation between dithionite and acid oxalate extractable of iron, aluminum and manganese with the samples from each geological formation.

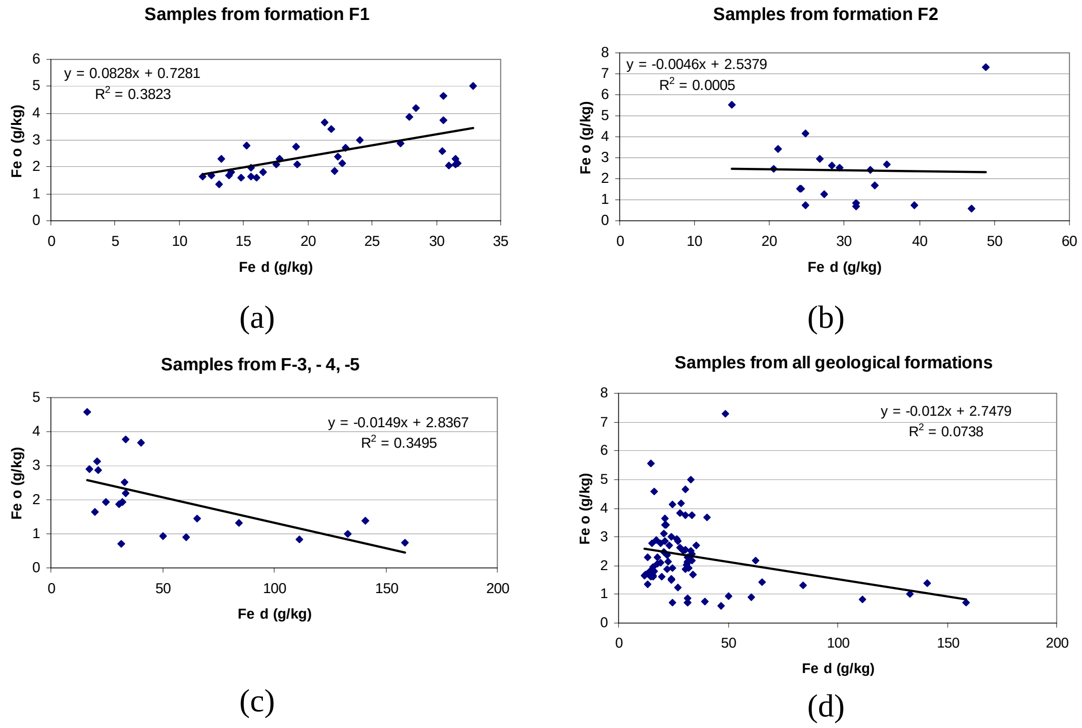

Figure 3.2: Correlation between dithionite and acid oxalate extractable of iron in geological formations

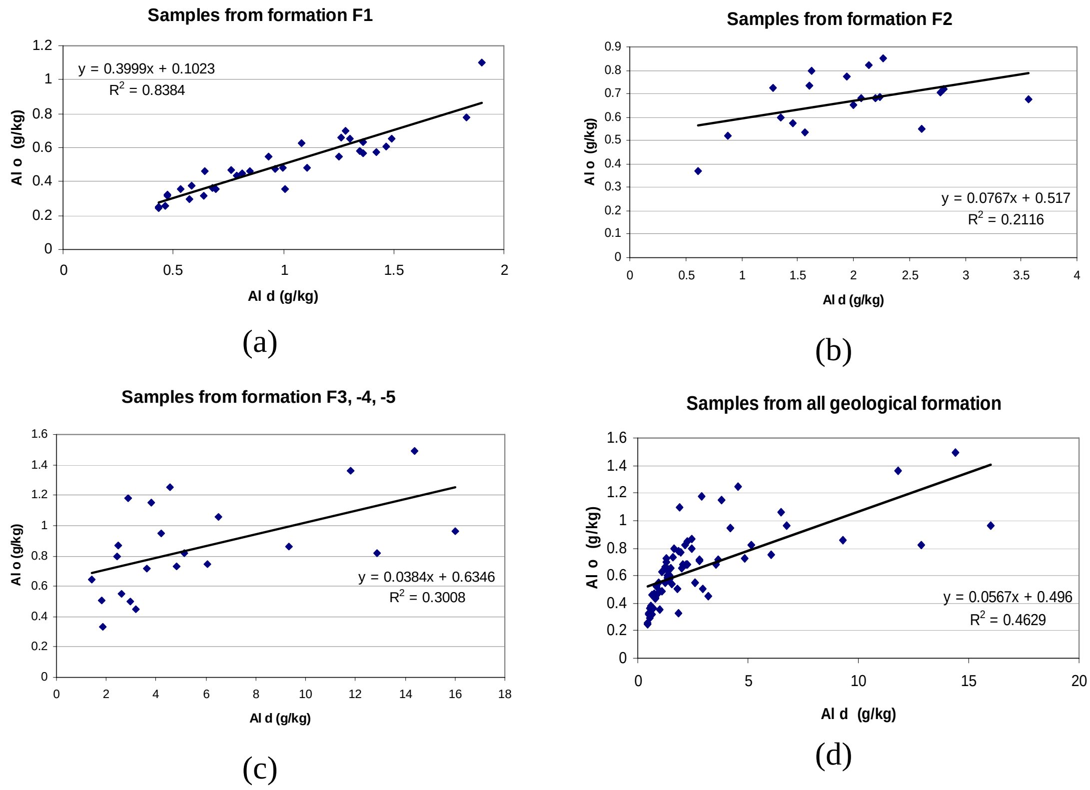

Figure 3.3: Correlation between dithionite and acid oxalate extractable of aluminum in geological formations

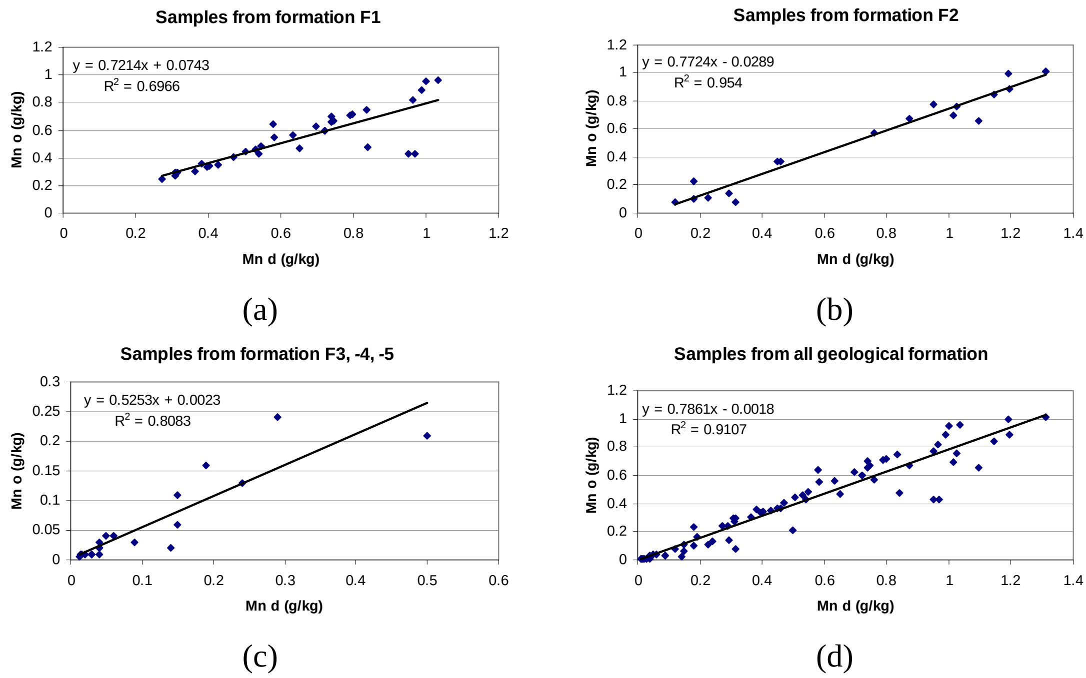

Figure 3.4: Correlation between dithionite and acid oxalate extractable of manganese in geological formations

As the data is displayed in these figures, the correlation between Fe_o and Fe_d is very low, especially the lowest in the correlation of samples from the F2 formation. The correlation is higher in the samples from F1, 3, 4 and 5. The correlation between the pair Al_o and Al_d, Mn_o and Mn_d are better than Fe_o and Fe_d.

3.3 Mineralogical analytical result

The analysis process of the samples was described in section 2.5.3. The amount of each mineral was defined as high, moderate, small amounts, traces, unsure and none (Appendix 4 and 5). The results are summarized in Table 3.7 and 3.8

3.3.1 Bulk mineral result

The semi-quantitative estimation of the bulk minerals is shown in the Appendix 4. The samples within in formation F1 comprise mica and hematite in traces and plagioclase in small amounts. The sheet silicate minerals are of moderate amounts in the samples from the first group and of small amount in the samples from the second group. Quartz ranges from moderate to small amounts. Goethite occurs in traces or is absent. Calcite and dolomite only occur in some sample with a very small amount. There is no obvious difference among three groups with respect to all other mineral groups.

Samples from two groups of formation F2 exhibited very similar mineral concentration. Mica and hematite in the samples of formation F2 occur in traces amounts. The plagioclase content ranges from moderate amounts to traces and is of small amounts in most of the samples. The sheet silicate minerals range from a small to high amounts (mainly in moderate amount). Small amount to absence of potassium feldspar is observed in the samples. Quartz ranges from a small to moderate amounts (mainly in moderate amount). Goethite occurs in traces or is absent.

Table 3.7: Bulk minerals of the samples correspondence with geological formation.

Geological formation	Group	Mica (1)	Mica (2)	Amph (1)	Amph (2)	Silicate layer (1)	Silicate layer (2)	Quarz (1)	Quarz (2)	Goeth (1)	Goeth (2)	KFSP (1)	KFSP (2)	Plag (1)	Plag (2)	Calcite (1)	Calcite (2)	Dolomite (1)	Dolomite (2)	Hematite (1)	Hematite (2)
F1	1	Traces	Traces		Traces	Medium	Medium	Small	Medium		Traces	Traces	Traces	Traces	Traces		Traces			Traces	Traces
	2	Traces	Traces		Traces	Traces	Medium	Small	Medium		Traces		Traces	Traces	Traces		Traces		Traces	Traces	Traces
	3	Traces	Traces		Traces	Traces	Medium	Small	Medium		Traces	Traces	Small	Traces	Traces		Traces			Traces	Traces
F2	1	Traces	Traces			Traces	High	Small	Medium		Small	Traces	Traces	Traces	Small					Traces	Traces
	2	Traces	Traces			Traces	Small	Medium	Medium		Traces	Traces	Small	Small	Medium					Traces	Small
F3			Traces			Traces	Small	Traces	Medium	Traces	Medium		Traces		Traces					Traces	Small
F4						Traces	Small	Traces	Medium	Traces	Medium		Traces							Traces	Medium
F5						Traces	Traces	Medium	Medium	Traces	Medium	Traces	Traces							Traces	Small

Table 3.8: Clay minerals of the samples correspondence with geological formation.

Geological formation	Group	Verm. 14Å (1)	Verm. 14Å (2)	Verm. 18Å (1)	Verm. 18Å (2)	Illite (1)	Illite (2)	Kao. Well (1)	Kao. Well (2)	Kao. Poorly (1)	Kao. Poorly (2)	Chlorites Primary (1)	Chlorites Primary (2)	Chlorites Secondary (1)	Chlorites Secondary (2)	Mixed layer (1)	Mixed layer (2)
F1	1	Traces	Traces		Traces	Medium	Medium	Small	Small	Small	Small	Small	Small			Traces	Traces
	2	Traces	Small	Traces	Small	Medium	Medium	Small	Small	Small	Small	Small	Small				Traces
	3	Traces	Small	Traces	Traces	Medium	Medium	Small	Small	Small	Small	Traces	Small			Traces	Traces
F2	1	Traces	Small		Small	Medium	Medium	Small	Medium	Traces	Small	Small	Small				Traces
	2	Traces	Small		Small	Medium	Medium	Small	Small	Small	Small	Small	Small				Traces
F3		Traces	Small		Small		Small	Small	Medium	Small	High		Small		Traces		Small
F4			Small					Traces	Medium	Medium	High				Medium		Traces
F5		Small	Small					Traces	Small	Medium	High	Traces	Small	Small	Medium	Traces	Small

Note for table 3.7 & 3.8: column (1) – min quantity; column (2) – max quantity

None ☐ Traces (cyan) Medium amounts (orange) Vermi. - Vermiculite

Small amounts (yellow) High amounts (red) Kao. - Kaolinite

Sample F2-42 differs from the other samples of formation F2 with a high amount of silicate layer minerals and a small amount of goethite.

Concerning the mineral composition of sample within in the F3 formation, mica and plagioclase are absent in most of the samples or they occur in traces. The sheet silicate minerals range from moderate to small amounts.

Potassium feldspar occurs either in traces or absent. Quartz occurs in moderate amounts to traces but the dominant quantity is moderate or small amount. Goethite is from traces to small amounts and hematite occurs in traces.

In samples of the F4 formation, mica and plagioclase are absent. The sheet silicate minerals occur from moderate to small amounts. Potassium feldspar is present in traces. Quartz occurs from high to small amounts. Goethite ranges from moderate amounts to traces. Hematite is from small amounts to traces.

Two samples located in F5 are dominated by quartz with moderate amounts. Silicate layer is also abundant and occur in small amounts in sample F5-06 and in moderate amounts in sample F5-05. Hematite is in present in moderate quantities in sample F5-06 and in traces in sample F5-05.

3.3.2 Clay mineral result

The clay minerals in three groups from the F1 formation are very similar. Illite is the dominant mineral with a moderate amount and kaolinite is present in small amounts in these samples. Primary chlorite is mainly in small amounts. Vermiculite (14Å) and (18Å) ranges from small amounts to traces.

Except for sample F2-46, Illite is the dominant mineral in samples from F2 with a moderate amounts. Primary chlorite is in small amounts in all samples.

In the first group, kaolinite well crystalline ranges from small to moderate amounts. Vermiculite (14Å) is present in small amount to traces. Vermiculite (18Å) only occurs in some samples and only in traces. In the second group, vermiculite (18Å) reaches to small amounts in F2-02 and is absent in F2-38. Other clay minerals in the second group are similar to the first group.

With respect to the clay mineral content in formation F3, sample F3-10 shows different features compared to the other samples from this formation. Secondary chlorites only occur in traces in F3-10 and illite is absent. Within profile F3-10, the layer at 15-40 cm depth differs from deeper layers with respect to the quantity of poorly crystallized kaolinite, vermiculite and primary chlorite.

The dominant clay mineral of samples located at the hill foot (formation F4) such as F4 -02, -03, -04, -07 is poorly crystallized kaolinite and secondary chlorite. Vermiculite (14Å) is present mainly in small amounts. Vermiculite (18Å), illite and primary chlorites are not present in these samples.

The clay minerals in samples located in the erosion terrace II and hill area such as F4-08, -09 are mainly well and poorly crystallized kaolinite. Secondary chlorites occur in traces.

Poorly crystallized kaolinite is also the dominant clay mineral in samples of F5 with moderate to high amounts. Secondary chlorite is the second most abundant mineral occurring in small to medium amounts. Vermiculite (14Å) and primary chlorite occur in small amounts or traces. Other clay minerals are absent.

3.4 WRB soil classification map

3.4.1 Classification of field soil samples

WRB criteria (FAO, 1998) were applied to classify the analyzed soil samples. The Appendix 1 presents the result. There are four main soil types with some sub soil types in the study area (table 3.9).

Table 3.9: WRB soil types in the study area.

<table>
<tr><th>Main soil type</th><th>Sub soil type</th><th>Main soil type</th><th>Sub soil type</th></tr>
<tr><td rowspan="6">Fluvisols</td><td>Ochric</td><td>Gleysols</td><td></td></tr>
<tr><td>Umbric</td><td>Cambisols</td><td>Ferralic</td></tr>
<tr><td>Ferralic</td><td rowspan="2">Ferrasols</td><td>Plinthic</td></tr>
<tr><td>Gleyic Ochric</td><td>Gleyic Plinthic</td></tr>
<tr><td>Gleyic Umbric</td><td rowspan="2" colspan="2"></td></tr>
<tr><td>Areno Ochric</td></tr>
</table>

3.4.2 Soil spectra measured by spectroradiometer

The soil spectral measured by spectroradiometer of selected top soil samples from four geological formations with difference soil types are presented in Figure 3.5. The curves in Figure 3.5 illustrate that the different soil types exhibit differences.

In the spectral reflectance side, some bands are important and they form the base for evaluating the reflectance. Bands from 450 to 600 nm and 800 to 1100 nm are affected by iron oxide. The major spectral regions are active for clay mineral are from 1300 to 1400 nm, 1800-1900 nm and 2200-2500 nm (Hunt and Salisbury, 1970). In the absorption band from 1300-1400 nm, the range is affected by water molecule and lattice OH. The peak at 2200 nm indicates the presence of kaolinite (Ben-Dor et al., 1999; Dematte et al., 2004). The intensity of band absorption was calculated by using “Continuum Removed” tool in the ENVI 4.2 software. The spectra of profiles F3-10, F4-02, F5-05 are displayed in Figure 3.6. The evaluation of soil spectral curves from F3-10 (15-40 cm depth), F4-02 (40-110 cm) and F5-05 (40-55 cm) are shown in Table 3.10. The evaluation of soil spectra in the lab from F2-46, F3-04 and F3-07 was carried out according to the description given in Figure 3.7 and Table 3.11

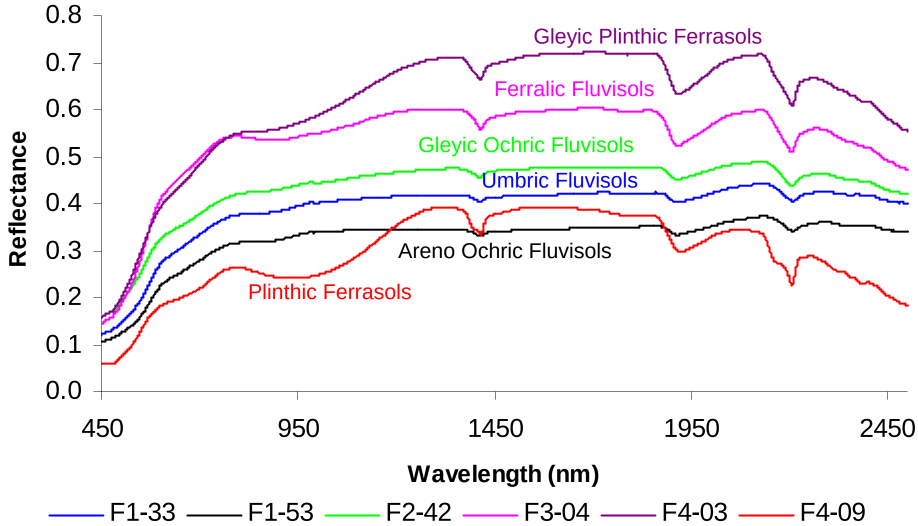

Figure 3.5: Soil spectra measured by spectroradiometer of the selected top soil samples. The different soil types have different spectral. *Note:* F2-37: Areno Ochric Fluvisols; F1-33: Umbric Fluvisols; F2-37: Ochric Fluvisols; F2-42: Gleyic Ochric Fluvisols; F3-04: Ferralic Fluvisols; F4-03: Gleyic Plinthic Ferrasols; F4-09: Plinthic Ferrasols.

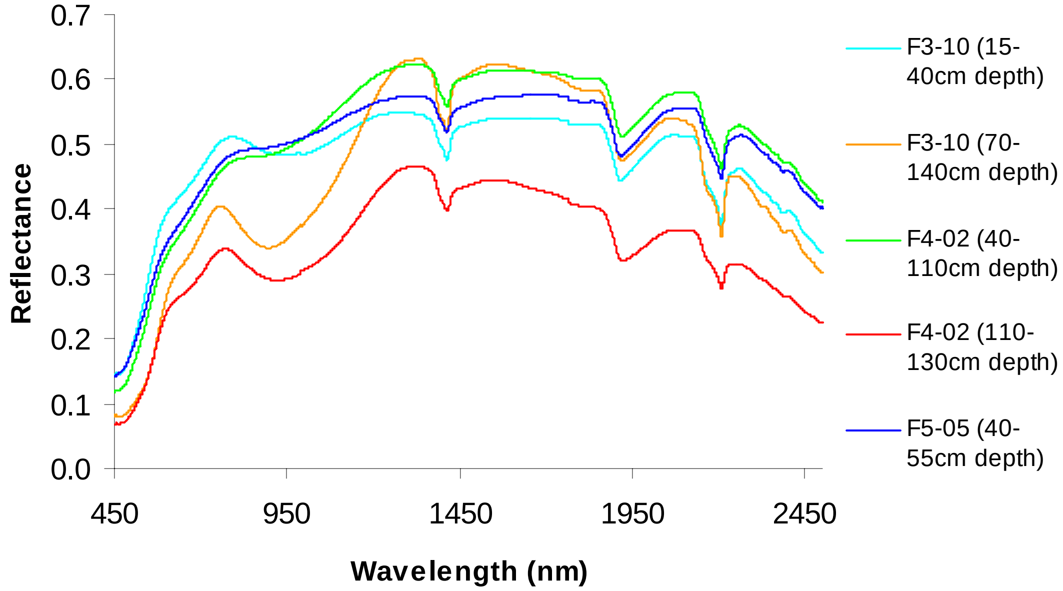

Figure 3.6: Soil spectra measured by spectroradiometer of some selected soil profiles: F3-10, F4-02, F5-05. The difference of the spectra between the top of profile and deeper layers is evident from the figure.

Table 3.10: Evaluation of soil spectra measured by spectroradiometer from F3-10, F4-02 and F5-05 profile.

Id sample	Depth (cm)	Intensity of band absorption (%)				
		450 - 600 nm	800 - 1100 nm	1400 nm	1900 nm	2200 nm
F3-10	15 - 40	21.9	7.8	13.1	15.6	22.5
	70 - 140	34.1	27.9	17.6	16.6	25.8
F4-02	40 -110	20.5	5.8	10.1	13.9	16.0
	110 -130	31.7	23.9	13.6	18.8	17.3
F5-05	40 - 55	16.1	2.8	9.7	15.0	15.8

The spectral curves from F3-10 (15 - 40 cm), F4-02 (40 - 110 cm) and F5-05 (40 – 55 cm) is quite similar. (see Table 3.10 and Figure 3.6)

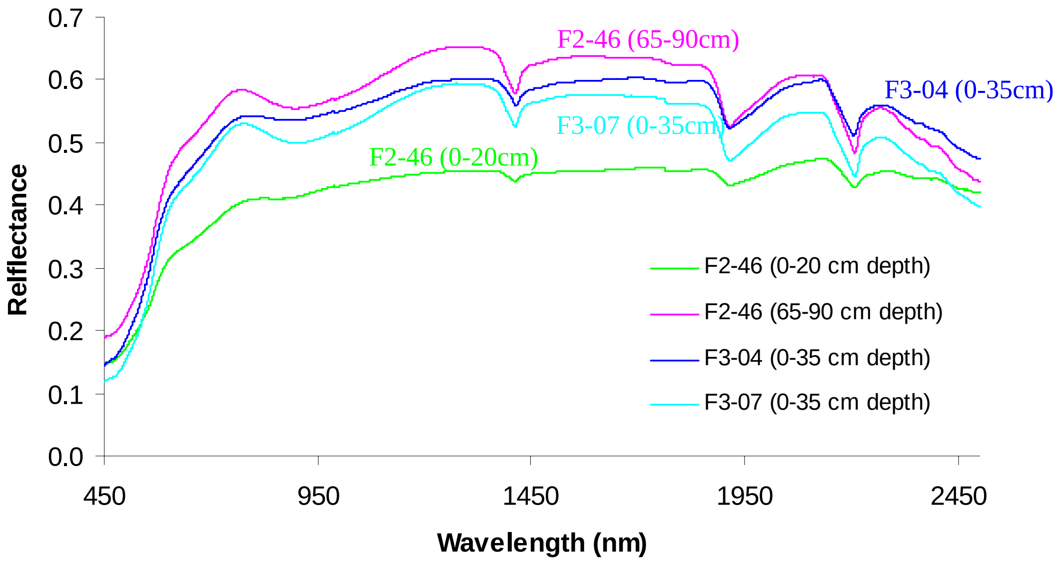

Figure 3.7: Soil spectra measured by spectroradiometer of F2-46 profile and the two top soil samples in F3 formation.

Table 3.11: Evaluation of soil spectra from F2-46, F3-04 and F3-07 samples

Id sample	Depth (cm)	Intensity of band absorption (%)				
		450-600 nm	800-1100 nm	1400 nm	1900 nm	2200 nm
F2-46	0 - 20	14.2	1.9	4.2	8.2	8.2
	65 - 90	20.1	8.2	10.9	15.5	16.5
F3-04	0 - 35	20.6	4.0	7.1	13.1	12.0
F3-07	0 - 35	27.1	9.0	10.5	16.2	15.5

The soil spectra from F2-46 profile show that the spectra from layer 65 – 90 cm depth are similar with layer 0 – 35 cm of F3-04 and F3-07 (see Table 3.11 and Figure 3.7)

3.4.3 WRB soil map from remote sensing data

Figure 3.8 presented the WRB soil map which was composed by remote sensing data and soil spectra data measured by spectroradiometer in the lab (more detail in section 2.5.6). The Ferralic Cambisols type occurs with very small areas in formation F3 (river terrace I). Therefore, this type cannot be presented in WRB soil map. The Ferralic Cambisols type is only shown in catena with bigger scale (see Figure 3.16).

3.5 Age absolute result

The dating samples were measured by Optically Stimulated Luminescence (OSL) and ^{14}C methods. The dating data are presented in Table 3.12 and 3.13. The position of these samples is shown in Figure 2.4 (in page 24).

Table 3.12: The dating data of OSL samples

Id samples	Geological formation	Depth from surface (m)	Altitude (m) – above the sea level	Age (years)
POND 2	F2	- 0.4	6.4	1240 ± 160
POND 1	F2	- 0.8	6.0	1320 ± 170
RRA 2	F2	- 1.0	7.0	5600 ± 900
RRA 1	F2	- 1.5	6.5	6100 ± 900

Table 3.13: The dating data of ^{14}C samples

Id samples	Geological formation	Depth from surface (m)	Altitude (m) above the sea level	Conventional age (years B.P.)	Calibrated age (years B.P.)
F2 – 44	F2	- 4.0	4.0	4490 ± 35	5166 ± 92
ECP	F1	- 3.0	8.0	3115 ± 30	3332 ± 42

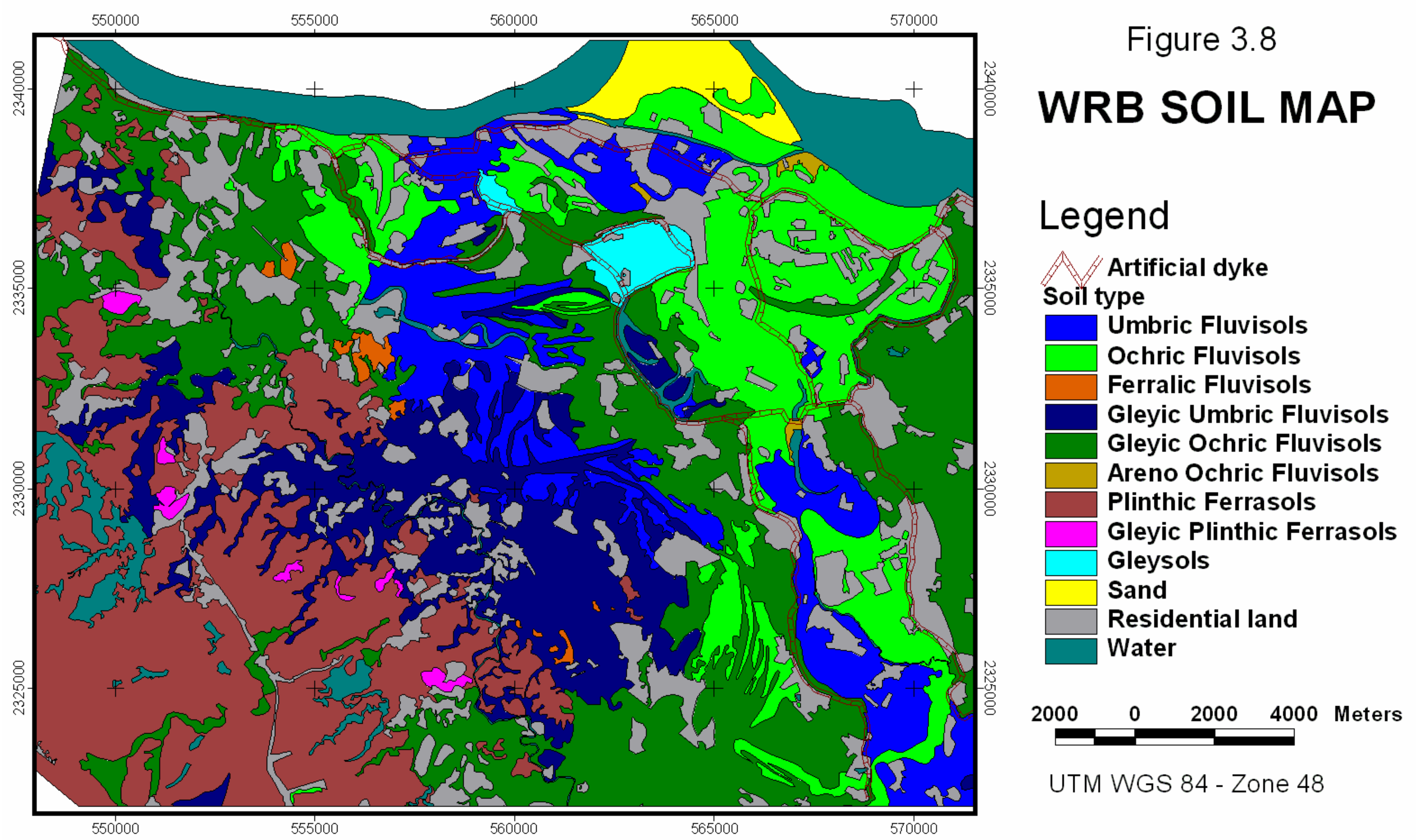
Figure 3.8
WRB SOIL MAP
Legend
Artificial dyke
Soil type
Umbric Fluvisols
Ochric Fluvisols
Ferralic Fluvisols
Gleyic Umbric Fluvisols
Gleyic Ochric Fluvisols
Areno Ochric Fluvisols
Plinthic Ferrasols
Gleyic Plinthic Ferrasols
Gleysols
Sand
Residential land
Water
2000 0 2000 4000 Meters
UTM WGS 84 - Zone 48
550000
555000
560000
565000
570000
2340000
2335000
2330000
2325000

3.6 Paleochannel interpreted by using remote sensing data

Based on satellite images, aerial photos and topographic maps (1:50.000), the paleochannels were interpreted. The paleochannels are classified into four systems numbered from one to four (see Figure 3.9). The criteria for classifying the systems are the flow direction of the paleochannels. It is classified into Day River, Tich River and three Red River paleochannels system.

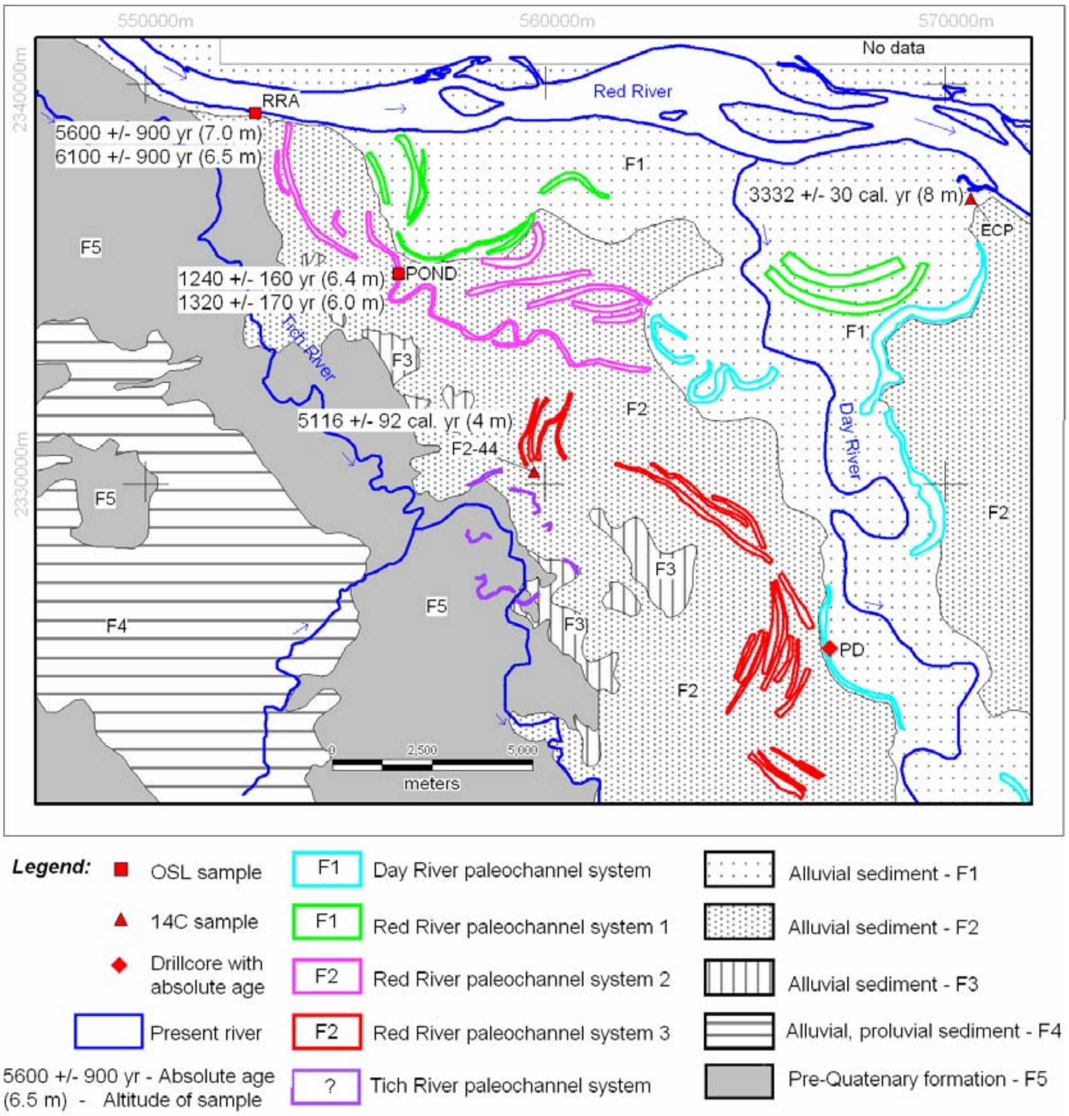

Figure 3.9: The traces of paleochannels were interpreted from remote sensing data and topographic maps. The paleochannels were classified into four systems relating to four difference times of their formation. Samples for OSL and ^{14}C dating (see Table 3.12 & 3.13) were taken to establish a chronology of the paleochannel formation. PD core is studied by Funabiki et al., 2007

3.7 Landcover/Landuse in 1988 and 2003

3.7.1 Landcover/Landuse map in 1988 and 2003

Maps of the landcover/landuse in the study area 1988 and in 2003 are shown in Figure 3.10 and in the Figure 3.11 respectively. Note that the legend of the 2003 landcover/landuse map does not contain the type “permanent bare soil”. As opposed to the 1987 landcover/landuse map, whereas the 1987 map does not contain the type “Construction site” as opposed to the map of 2003.

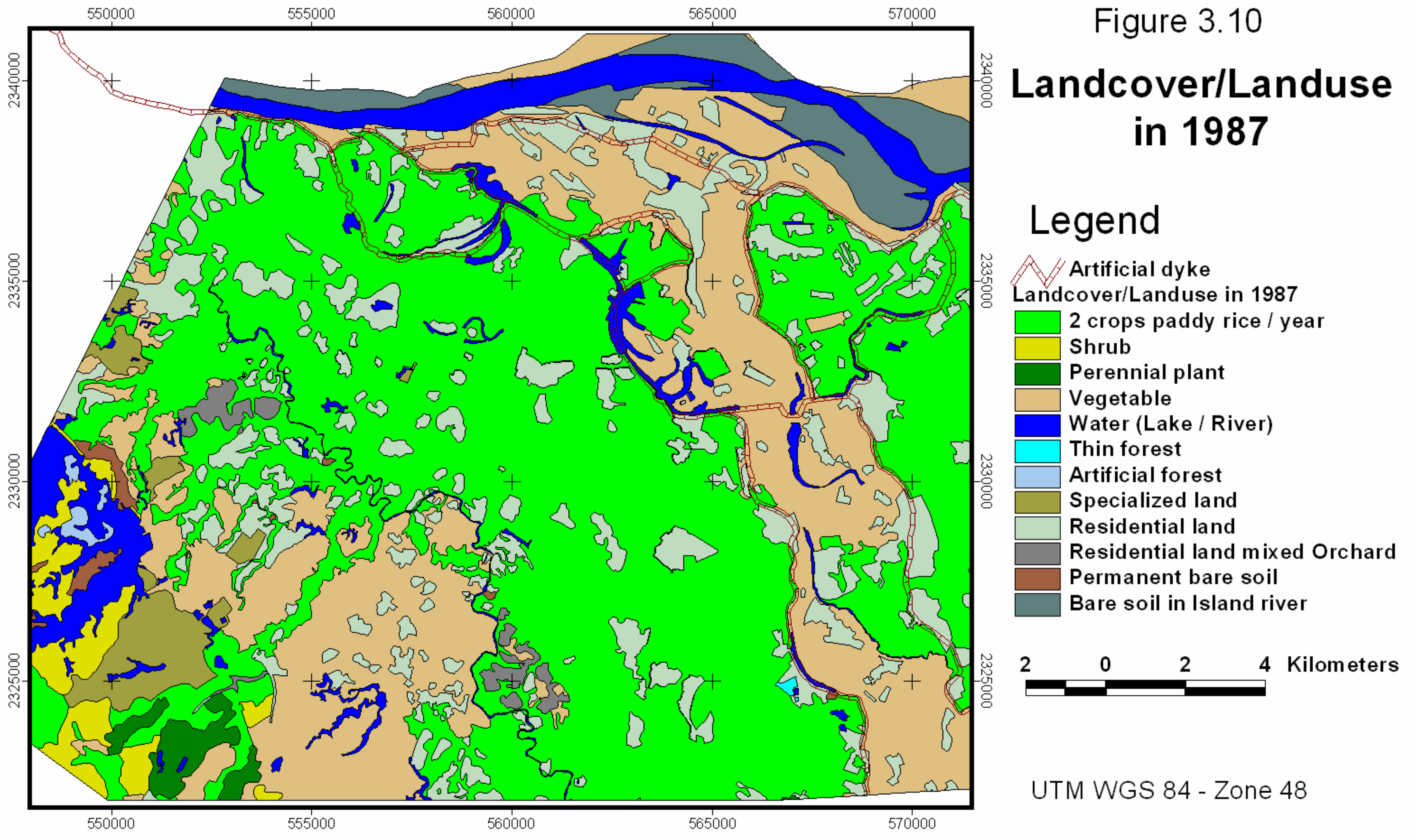
Figure 3.10
Landcover/Landuse in 1987
Legend
Artificial dyke
Landcover/Landuse in 1987
2 crops paddy rice / year
Shrub
Perennial plant
Vegetable
Water (Lake / River)
Thin forest
Artificial forest
Specialized land
Residential land
Residential land mixed Orchard
Permanent bare soil
Bare soil in Island river
2 0 2 4 Kilometers
UTM WGS 84 - Zone 48
550000
555000
560000
565000
570000
2340000
2335000
2330000
2325000

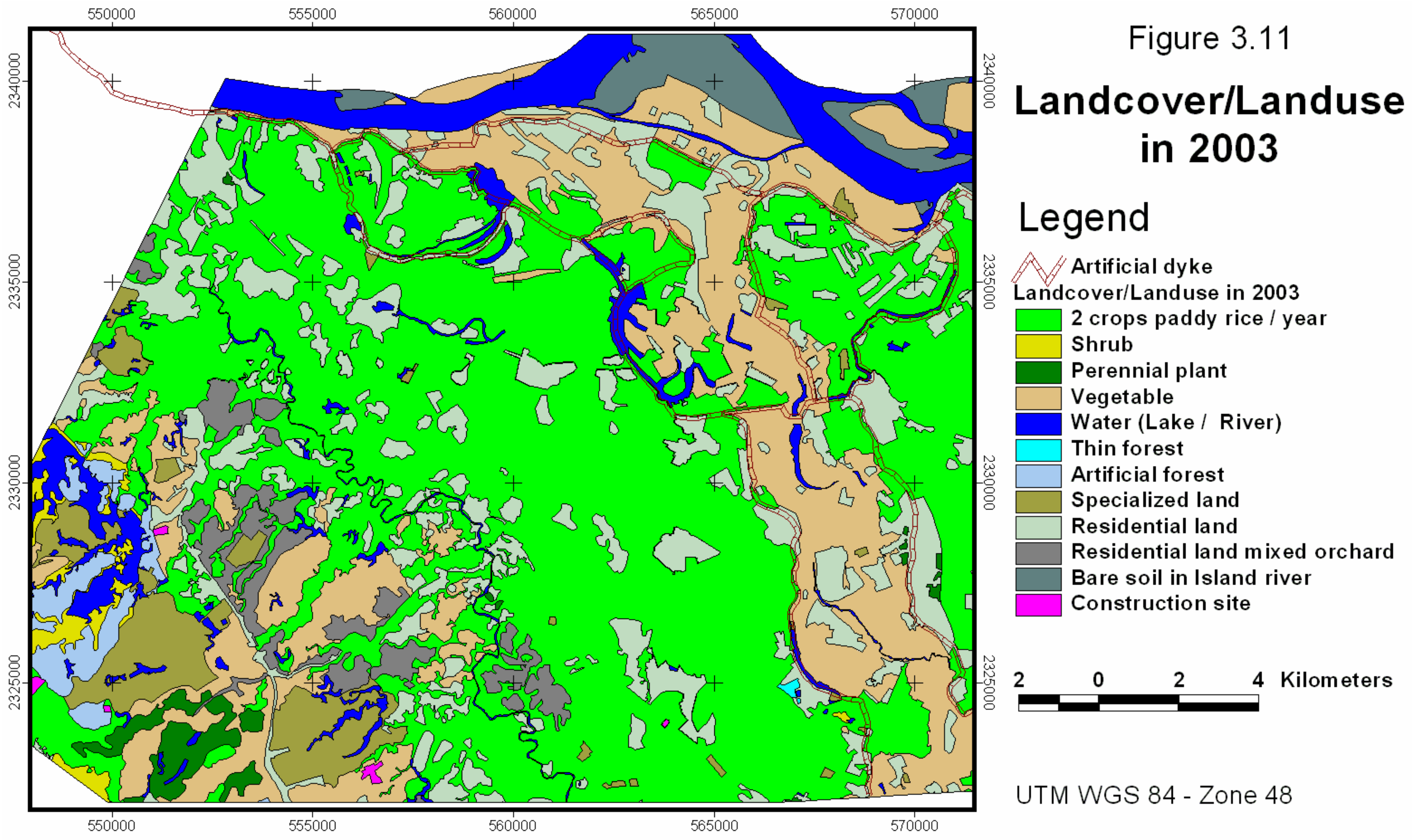
550000
555000
560000
565000
570000
2340000
2335000
2330000
2325000
Figure 3.11
Landcover/Landuse in 2003
Legend
Artificial dyke
Landcover/Landuse in 2003
2 crops paddy rice / year
Shrub
Perennial plant
Vegetable
Water (Lake / River)
Thin forest
Artificial forest
Specialized land
Residential land
Residential land mixed orchard
Bare soil in Island river
Construction site
2 0 2 4 Kilometers
UTM WGS 84 - Zone 48

Table 3.14: Pivot table of landcover/landuse change from 1987 to 2003. The area is in hectare and calculated based on the data from the Mapinfor software.

Area (Ha)	**Land cover/landuse in 1987**												
Landcover/ landuse in 2003	2 paddy rices / year	Vegetable	Perennial plant	Shrub	Thin forest	Artificial forest	Residential land	Residential mixed Orchard	Specialized land	Bare soil in Island river	Permanent Bare soil	Water	**Grand Total**
2 paddy rices / year	17367	1814	9	112							9	78	**19389**
Vegetable	1026	5803	24	197					18	292	17	132	**7509**
Perennial plant	77	33	360	19			4				3	1	**497**
Shrub	8	5		122		3					34	270	**442**
Thin forest					14								**14**
Artificial forest		50		486		26					120	38	**720**
Residential land	758	506		3			5189	30	3		6	11	**6506**
Residential mixed Orchard	57	396					427	300	6		3		**1189**
Specialized land	71	566		97		62	6		854		9	58	**1723**
Bare soil in Island river		178								440		380	**998**
Construction site	34	22	1	4								1	**62**
Water	53	232	11	5						764		2001	**3066**
Grand Total	**19451**	**9605**	**405**	**1045**	**14**	**90**	**5626**	**330**	**881**	**1496**	**201**	**2970**	**42115**

Table 3.14 is created by overlaying the landcover/landuse in 1987 and 2003. The data in the table 3.14 show the change from landcover/landuse type in 1987 to one or more types in 2003.

3.7.2 Landcover/Landuse change from 1988 to 2003

Table 3.14 describes the change of all landcover/landuse types in the study area between 1987 and 2003. Based on the table, the agricultural land is significantly decreased by increasing urbanization. To show the change of agricultural land in more detail, Table 3.15 is created.

Table 3.15: Landcover/landuse change in some selected types from 1987 to 2003.

1987	2003	Change in percent	Loss agricultural land by urbanization	
			percent	ha
2 paddy rice	Vegetable	5.3%		
2 paddy rice	Perennial plant	0.4%		
2 paddy rice	Residential land	3.9%		
2 paddy rice	Residential mixed Orchard	0.3%	4.8%	920
2 paddy rice	Specialized land	0.4%		
2 paddy rice	Construction site	0.2%		
Vegetable	2 paddy rice	18.9%		
Vegetable	Perennial land	0.3%		
Vegetable	Residential mixed Orchard	4.1%		
Vegetable	Residential land	5.3%	15.5%	1490
Vegetable	Specialized land	5.9%		
Vegetable	Construction site	0.2%		
		Total	20.3%	2410

Based on Table 3.15, from 1987 to 2003, 5.7 % area of two paddy rice land in 1987 was converted to other kind of agricultural land in 2003. In the same time, 19.2 % of vegetable land area was converted to other kind of agricultural land. The loss of agricultural land by urbanization equals 20.3% or 2410 ha.

3.7.3 Landcover/Landuse change and soil types

For researching the landcover/landuse change in each soil types, the WRB soil map and the data of landcover/landuse changing from the year 1987 and 2003 were overlaid. The date is displayed in Table 3.16

Table 3.16 Landcover/landuse change from 1987 to 2003 in relation to soil type. Column (2) is soil type area in the study area.

WRB soil type	(1) Landcover/Landuse changing area in soil type (ha)	(2) Soil type area (ha)	(3) Percent of (1) and (2)
Umbric Fluvisols	403	3970	10.2%
Ochric Fluvisols	1004	5037	19.9%
Ferralic Fluvisols	0.6	165	0.4%
Gleyic Umbric Fluvisols	482	4911	9.8%
Gleyic Ochric Fluvisols	869	10475	8.3%
Areno Ochric Fluvisols	1.8	67	2.7%
Gleysols	37	441	8.4%
Plinthic Ferrasols	3938	8723	45.1%
Gleyic Plinthic Ferrasols	6	179	3.3%

According to Table 3.16, the landcover/landuse from 1987 to 2003 changed most significantly in areas of Plinthic Ferrasols. Table 3.17 is created to analyse in detail the landcover/landuse change in Plinthic Ferrasols. The significant change is noted in areas with shrubs and permanent bare soil in 1987 to artificial forest in 2003 (total 606 ha). The second significant changes are from shrub and permanent bare soil to vegetable land (total 207 ha)

3.8 Selected catena in different geological formation

Catenas were established in alluvial accumulation, paleochannels, river terrace I, erosion terrace II and hill (Figure 3.13 to 3.17). These catenas are established in unique and complex geological formations. The position of the catenas is given in Figure 3.12.

Table 3.17: Detail kind of landcover/landuse change from 1987 to 2003 in Plinthic Ferrasols.

AREA (ha)	**Landcover/landuse in 1987**										
Landcover/Land-use in 2003	2 paddy rices /yr	Shrub	Perennial plant	Specialized land	Residential land	Residential land mixed orchard	Permanent bare soil	Water	Vegetable	Artificial forest	**Grand Total**
2 paddy rices /yr		103	9				6	1	498		**617**
Vegetable	341	191	24	14			16	2			**588**
Perennial plant	45	24							33		**102**
Shrub							32	272	3	2	**309**
Artificial forest		486					120	34	34		**674**
Construction site	31	4	1					1	22		**59**
Residential land	3								37		**40**
Residential land mixed orchard	53			4	365		3		335		**760**
Specialized land		97					9	54	540	62	**762**
Water	5	3	1	2					16		**27**
Grand Total	**477**	**908**	**35**	**20**	**365**	**0**	**186**	**364**	**1518**	**64**	**3938**

Note: The yellow background highlights the significant chance

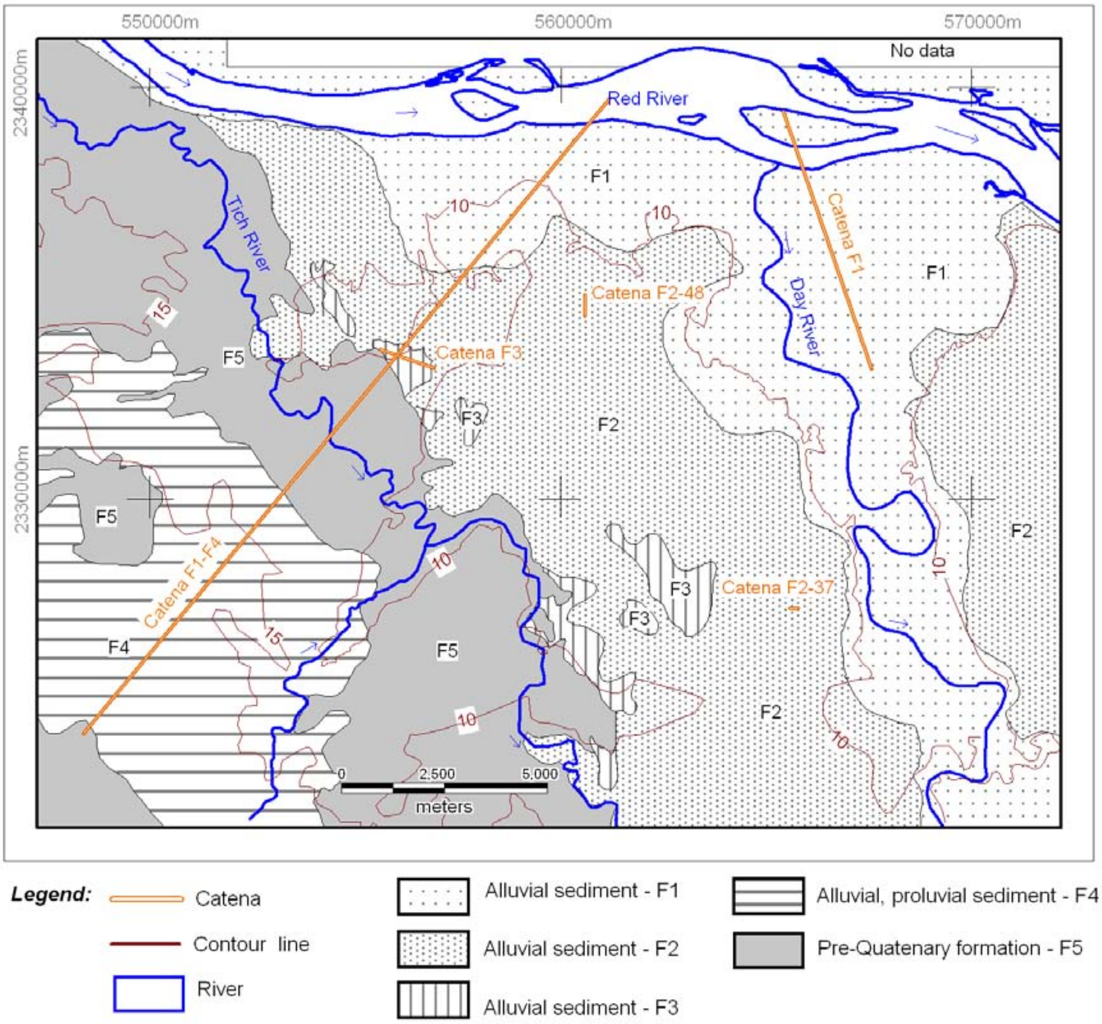

Figure 3.12: Catena locations in different geological formations.

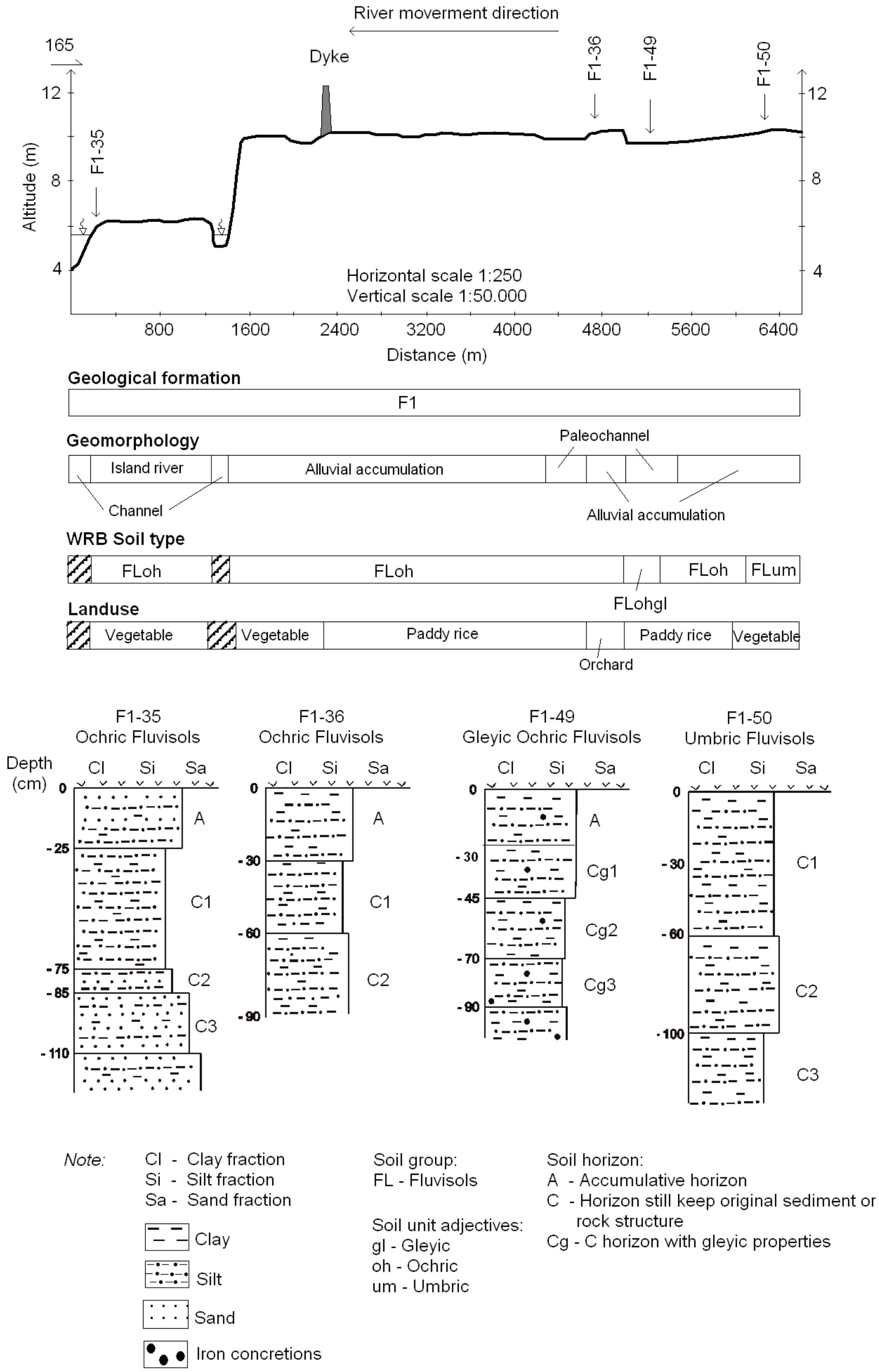

Figure 3.13: Catena F1 from the channel to alluvial accumulation. The samples are in F1 formation.

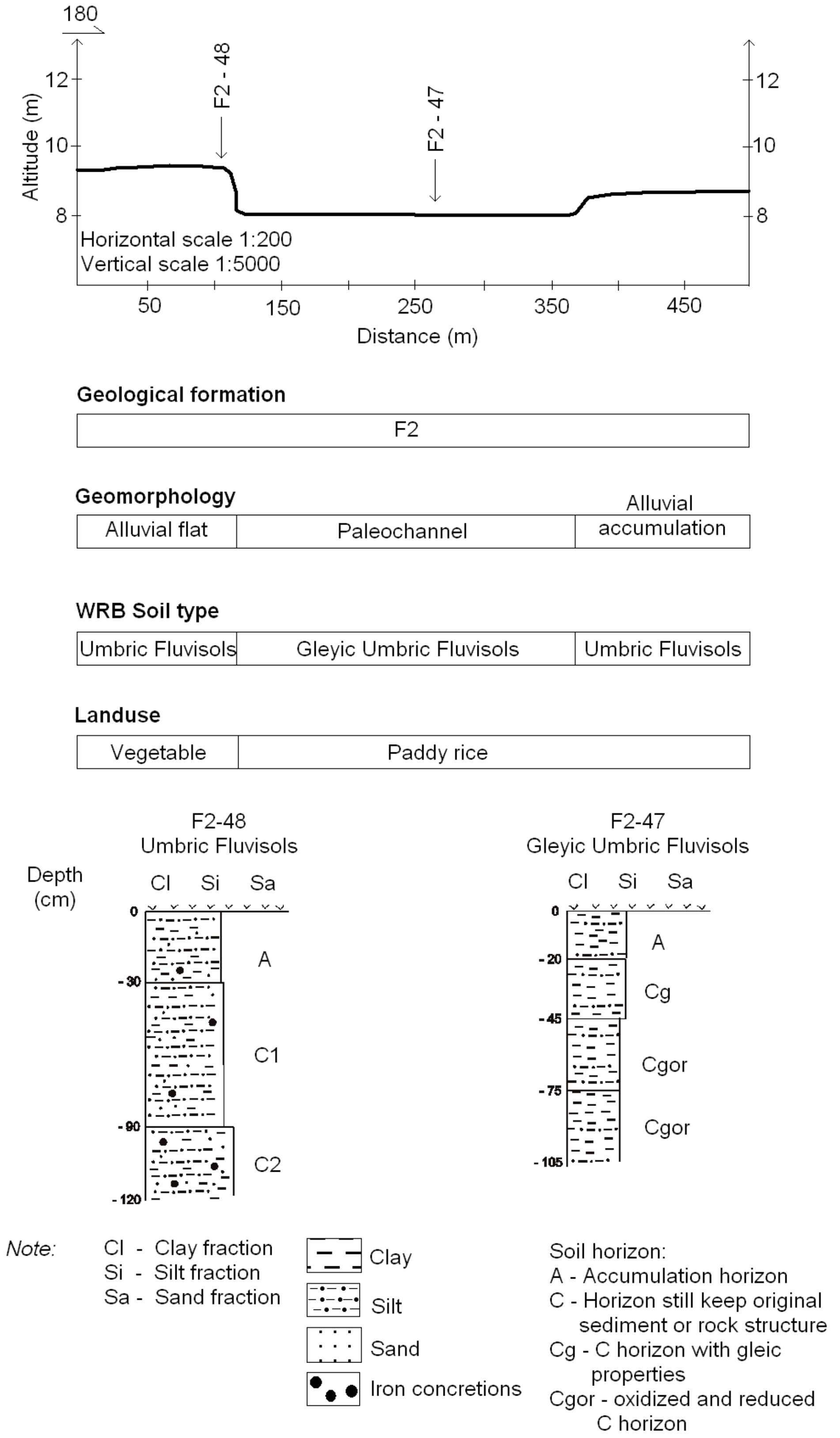

Figure 3.14: Catena F2-48 crosses the paleochannel. The soil samples are F2-47, -48.

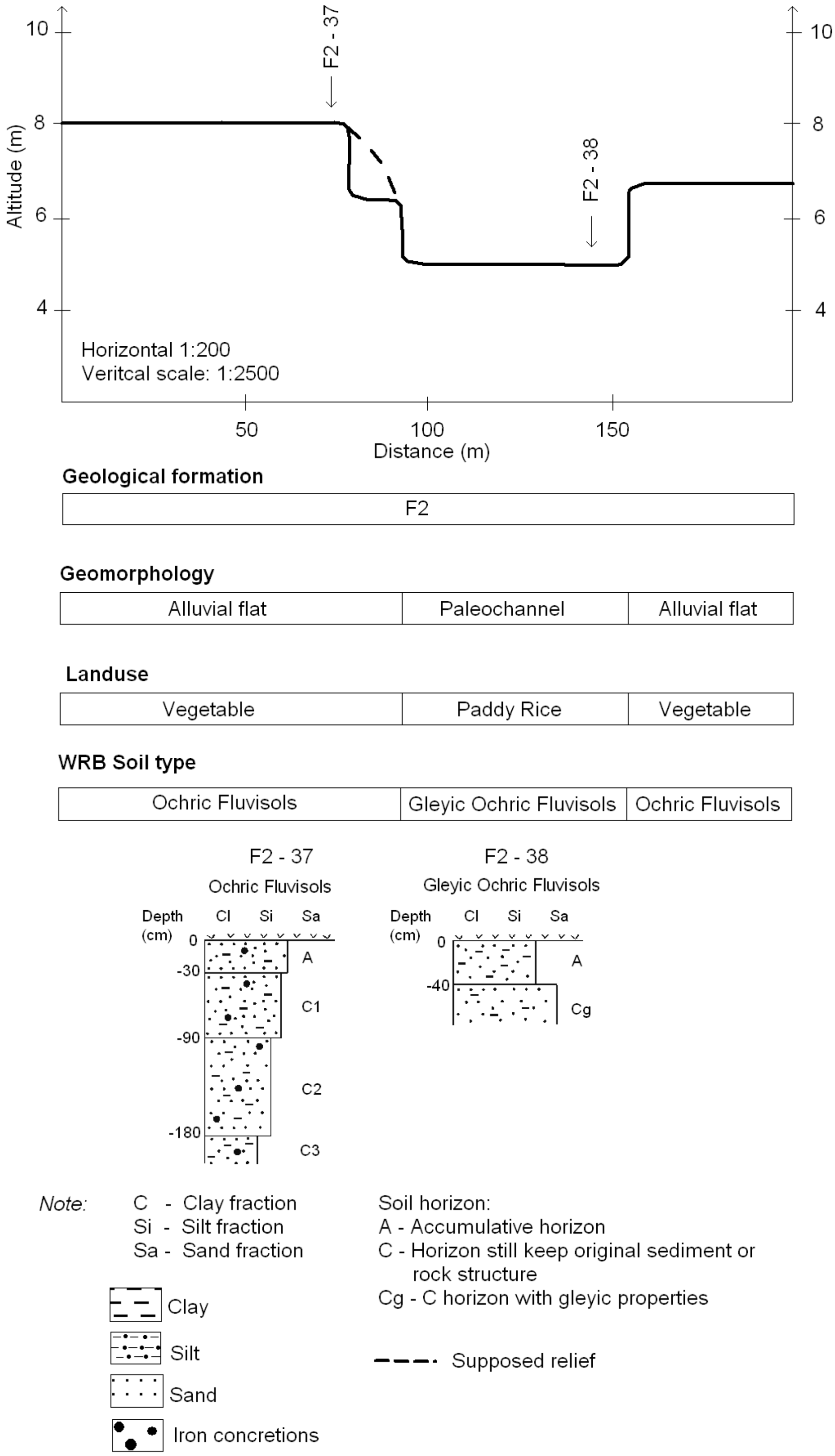

Figure 3.15: Catena F2-37 crosses the paleochannel. The soil samples are F2 -37, -38.

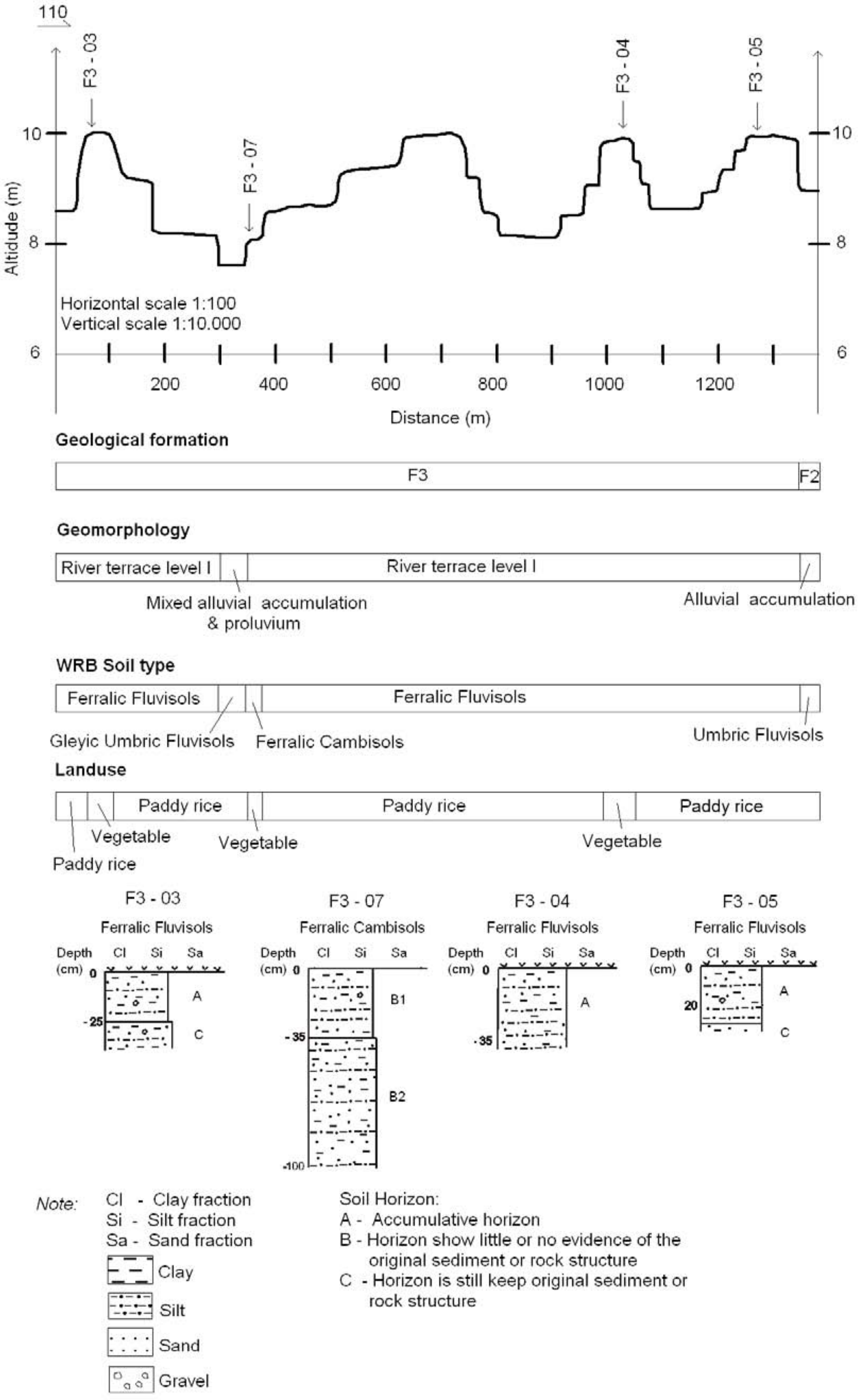

Figure 3.16: Catena F3 crosses the river terrace I. The geological formation is F3.

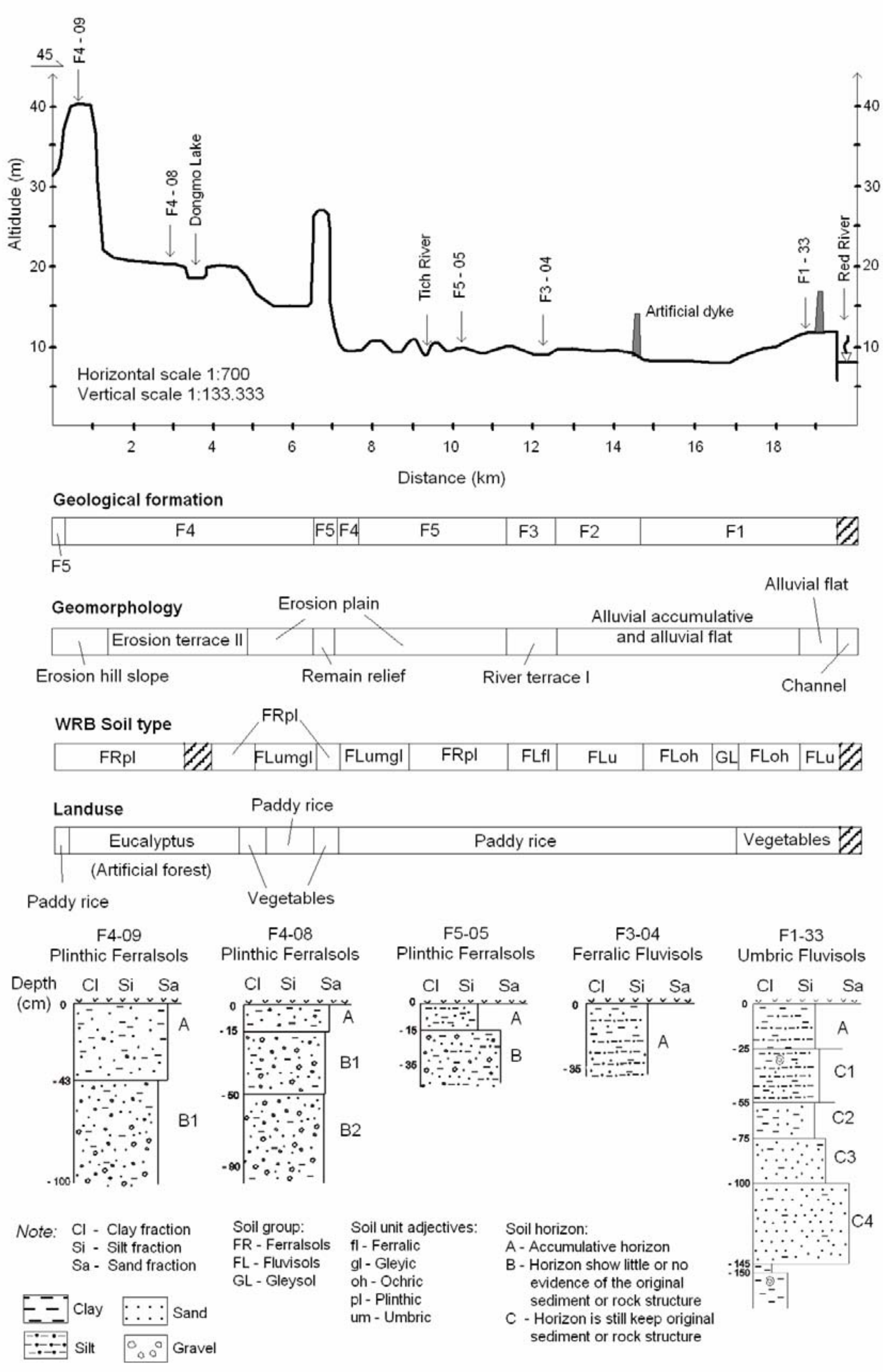

Figure 3.17: Catena F1-F4 from hill area to the Red River bank.

4 Discussion

In the chapter 3, the results were presented. This chapter discusses the paleochannel system and Holocene evolution in study area. Soil properties will be analyzed in the relationship with geological formation. The role of topography and the paleochannel will be discussed with respect to the soil development by analysis of catenas. Landuse change is another concern in this chapter and the change of vegetation will be discussed. The impact of landcover/landuse change from 1987 to 2003 will be assessed to give a recommendation for landuse planning orientation.

4.1 Paleochannel and Holocene evolution

There are two paleochannel systems that belong to formation F1. The Day River paleochannel system with a north-south direction is located in the Day River valley. The other is the Red River paleochannel system 1 (Figure 3.9). A series of drillholes analyzed by Huyen et al. (1997) in the F2-46 area found river channel sedimentary facies in the F2 formation. Huyen also concluded that the paleochannel in the area of F2-46, -02, -47 is a part of the Red River. This finding is consistent with previous studies by Dy et al., 1984; Huyen et al., 1997; Khanh et al., 2004, who also assigned the paleochannel system in the area of F2-46, -02, -47 to the Red River. In Figure 3.9, the system is termed the Red River paleochannel system 2. The age of the paleochannel system 2 is around 1200 years according to luminescence ages (Figure 3.9, Table 3.12). The conclusion is proven by the Red River paleochannel system 2 crossing the paleochannel system 3. The Red River paleochannel system 3 was dated to 5166 ± 92 cal. years B.P. (sample F2-44, Table 3.13). The age of the Tich River paleochannel system remains undefined.

The common boundary between the Holocene and the Pleistocene for the Red River delta is 10,000 years B.P. (Dy, 1998; Toan et al., 2000, Haruyama S. et al., 2001) and it is applied for the study area. Based on the information from the PD core (Figure 2.5, Funabiki et al., 2007), the dating results (Table 3.12 and 3.13), the location of the paleochannel systems (Figure 3.9) and the character of the samples analyzed in the present study, the Holocene evolution in the study area can be classified into three stages. The stage I is from 10,000 to 7500 years B.P. and the stage II from 7500-5000 years B.P. and the stage III from 5000 years B.P to present. The stage I is characterized by the transitional from terrestrial environment in the early of the stage to a supratidal flat (Funabiki et al., 2007). This stage is correlative with the Flandrian sea transgression which reached a maximum at around 6000 years B.P. (Yang and Chen, 1987; Zhenguo et al., 1991; An, 1996). The transgression explains an upward increase of marine diatoms and bioturbation and a decrease of fresh diatom in PD core unit (16.5 – 11.35 m in depth). The stage II is defined as a transitional period between the oldest and youngest stage. The stage II is characterized by the mangrove swamp environment and it is an evidence for the maximum sea levels in the Red River delta.

The cores HT-128 (6-23 m), - 131 (18.7 – 23.9 m) comprise the grey and black grey clay mixed with organic matter and plant fragments (see position of drilling core in Figure 2.5 page 25). The layers underlie formation F2 (Q_{IV}^3) and not occur in the cores from drilling line C. From the drilling line C, the cores from HT-121 clearly show the sediments of the F4, F3 and F2 formation. The core HT-119 (0-35 m depth) shows the fluvial sediment which directly overlies formation F4. Only in the core HT-117 (8 – 24 m depth), there is a black grey, violet-brown layer of sand mixed with clay which is located between the F3 and F2 formation. Information found in the PD core and the luminescence age of sample RRA (6100 ± 900 yr) describe at the time of stage I and II, the peak of maximum tide might not pass through the area of drilling line C. In the late of stage II, the fluvial environment was become dominant.

The stage III is characterized by fluvial environment which created the floodplain in the study area. The floodplain surface was incised by the channel systems and two of them are dated at maximum 5166 ± 92 cal. years B.P. (Red River paleochannel system 3) and around 1240 ± 160 years. (Red River paleochannel system 2).

4.2 Soil properties and Quaternary formation

The different soil properties are relationship to different types of geological formation.

In term of particle size distribution, there are differences between the samples from each geological formation. Grain sizes in soil samples from the F1 formation are dominated by the silt fraction (Table 3.1 and Appendix 2). In the study area, formation F1 is the youngest formation and it is highly affected by the Red River sediment. The result is consistent with the data from Lai, 2005 who found the grain size distribution of bed load sediments of the Red River situated 10 km upstream from the study area is dominated by the silt fraction (48,8 – 70,2%). The difference grain size within the three groups of the F1 formation focuses in sand fraction and clay. The third group of formation F1 has the highest sand fraction and the first group of F1 has the highest clay fraction in the three groups. The sand fraction in soil samples from the F2 formation is decreased except for the samples locates within or close to the paleochannel. Silty grain sizes still dominated but the clay fraction is quite higher than sample from formation F1. The gravel fraction only occurs in samples from the F3 and F4 formations. Samples from formation F3 have predominance in the clay fraction. Soil samples from the F4 formation have higher sand contents. The sample location at the foothill has relatively high silt content. In contrast, the silt fraction is smaller than 10% and the clay content increases in soil samples from terrace II and the hilltop. The grain size distribution in soil varies with different geological formation. The differences in soil grain sizes occur also in a geological formation such as soil from formation F1 and F2. It is the result of different sedimentation conditions and the soil location in the topography. The role of relief is mentioned in section 4.4. In short, the grain size distribution of soil samples depends on the geological formation of the soil location.

The pH (H_2O) values change from alkaline level (samples from F1, F2) to weak acid (samples from the F3 formation) and acidic level (samples of the F4 formation) (see table 3.4 and Appendix 3). In correlation, the Cation Exchange Capacity (CEC) from these samples also decreases. In other words, the older formations have the lower pH values.

In theory, the ratio of amorphous to crystalline iron oxides (Fe_o / Fe_d) of soils developed in Quaternary sediments has been shown to decrease systematically as a function of soil age or relative development, i.e. low ratios are present in old soils and high ratios in younger soils (Torent, 1980; McFadden and Hendricks, 1985). The ratio (Fe_o/Fe_d) x 100 is given in Appendix 3. However, there are no significant correlation between Fe_o and Fe_d, especially in the samples from formation F2 (Figure 3.2b). The correlation in samples from formation F1 is more significant but Fe_o values are directly proportional to Fe_d values (Figure 3.2a). The reason for the phenomenon is that the sediment transported by the Red River was most likely highly weathered material. Furthermore, the F1 and F2 formations are young age (Holocene), therefore local weathering may do not have enough time to create more difference. It is the reason why the ratio of Fe_o / Fe_d is not working properly as an indicator of soil development in the F1 and F2 formation. The correlation between Fe_o and Fe_d in the F3, F4 and F5 formations are better than in the F1 and F2 formation (Figure 3.2c). But the correlation is very low for the samples from all geological formations in the study area (Figure 3.2d). Therefore, in the present study, the ratio of Fe_o / Fe_d is not used to determine relative ages of the soils. The evaluation of soil development is based on Fe_d values, mineral character and other features in the profile.

The bulk mineral content is very similar in samples from the F1 and F2 formation (Table 3.7 and Appendix 4). Quartz, potassium feldspar and sheet silicate amounts in samples from formation F2 are slight higher than in formation F1. Belonging to sheet silicate minerals, mica content are similar in both the F1 and the F2 formation. Amphibolite is only in formation F1. The bulk minerals from samples of the F3 formation are different from the samples of F1 and F2 and more different in the F4 formation. For example, mica and other amount of other sheet silicates decreased in the F3 and F4 formation. Mica is absent in formation F4. The same situation is evident with plagioclase. In contrast, hematite and goethite increase in amount. The increase of hematite and goethite is one reason for the increase in the concentration of Fe_d in samples from the F3 and F4 formations.

The differences in clay minerals are also evident between the formation of the fluvial plain (F1, F2) and formations of the terrace and hill (F3, F4). The change of the kaolinite content in the four Quaternary formations is interesting. Kaolinite concentration increases from F1 to F3 and reach highest quantities in samples from the F4 formation. In formation F4, poorly crystallized kaolinite is abundant. Illite and vemiculite (18Å) concentration on the contrary decrease in F1 and F2 to formation F3 and are absent in formation F4. Contrary to kaolinite, primary chlorite occurs only in F1, F2 and F3 formation. Secondary chlorite appear in some samples from the F3 formation and is abundant in samples from the foothill of formation F4. The amounts decrease again in samples from the F4 formation which are located at the hilltop and erosion terrace II.

In conclusion, it can be deduced from the clay mineral analysis that from F1 to F4 formation, type 2:1 clay minerals such as illite, vermiculite (18Å) and primary chlorite were destroyed. However, there is no clear change or trend in the amount of vermiculite (14Å). On the other hand, 1:1 clay mineral such as kaolinite increased with increasing age of the formation. With respect to the bulk mineral contents, hematite and goethite increased with the age of the formation whereas plagioclase and mica were destroyed. Therefore, bulk and clay mineral contents are good indicator of relative soil ages.

4.3 Laterites in Quaternary formations and soil

Laterite is understood as highly weathered red subsoil or material rich in secondary oxides of iron and/or aluminum nearly devoid of bases and primary silicates and commonly with quartz and kaolinite (Bates and Jackson, 1984) Lateritization is the process by which soils and rocks are depleted of silica and bases and enriched with hydrated aluminum and iron oxides.

The lateritization happen dependently on parent rock, climate (include paleoclimate) and the topography (Fridland, 1973; Tardy, 1997)

With respect to paleoclimate, the time between 135,000 and 81,000 years in the Bandung area (Indonesia) was characterized by warm and humid climate (Van der Kaars and Dam, 1995). Research in Lang Trang – approximately 100 km to the south of the study area confirmed that 80,000 – 60,000 years northern Vietnam was characterized by tropical condition similar to present climate conditions (Long et al., 1996). Other studies from Ma U'Oi and Duoi U'Oi cave – 60 km to the southeast of the study area – indicate that the climate in northern Vietnam was warm and humid tropical 66,000 years and humid tropical 193,000 years (Bacon et al., 2006 and 2008). Based on palynological studies from the Mekong delta, the Early to Mid Pleistocene climate was characterized by tropical conditions (Thuan, 2005). In late Pleistocene, there was a transition to hot - dry tropical climate

(Bieu et al., 1998; Thuan, 2005). In the Holocene, the climate in the Red River delta was humid tropical climate with cool and warm (Li et al., 2006a and 2006b). Therefore, paleoclimate in the northern part of Vietnam made facilitation to lateritization.

As mentioned in section 1.3.1, there are five sedimentation phases in the Red River delta corresponding with five geological formations (Nghi and Toan 1991; Nghi et al., 1991; Dy et al., 1995; Nghinh et al., 1991; Toan et al., 2000). At the end of second sedimentation of formation F4 (Q_{II-III}^{1}), the accumulation process mostly was interrupted. Relief was moved up that made good conditions for underground water operating in cycle (Dy et al., 1995). The underground water conditions and the climate in Middle - Late Pleistocene were good conditions for lateritization in upper part of F4 sediment. The high value of Fe_d and Al_d (Appendix 3) and the increase of hematite and goethite in samples from the F4 formation support to the laterite genesis. The laterite in the F4 formation more develops in the foothill. It can be explained by the ground water speed from hill slope is decreased and risen close to surface in the foothill. It makes oxidation conditions increasing in the area and ion Fe is precipitated. The Fe_d concentration from samples in the foothill of F4 formation (F4-02, 03, 04) is highest from investigated samples (Appendix 3). The soil properties in the area are acidity, CEC low. It makes the cause that the soil in these areas is not good for agricultural plant such as paddy rice.

The tropical climate in Late Pleistocene is advantage for lateritization of the F3 formation. The laterite was found in F3-07 and -10. These profiles show clear evidence of the fluctuation of the ground water table which is one of the main reason for the creation of the strong laterite layer from -50 cm to deeper in F3-10. In comparison with F3-10, the lateritization from F3-07 is lighter by some 1:1 clay mineral as illite still exit F3-07 profile and Fe_d concentration from the F3-07 are lower than F3-10. Top soil from F3-07 is classified into Ferralic Cambisols whereas the remaining samples from the F3 formation are Ferralic Fluvisols. The phenomenon will be discussed in relationship with topography in section 4.4.3. There are unusual layers in 0 - 50 cm depth from the profile F3-10 which will be discussed in section 4.5.

The Fe_d and Al_d concentration from the samples of F3-07, -10 and formation F4 prove that the lateritization in the study area accumulated dominantly iron oxides in laterite profiles. The Al_d concentration increases insignificant in these samples.

The Fe-Mn accretions are assumed as the initial structure of laterite (Fridland, 1973). The Fe-Mn accretions exit in some profiles from the F2 formation. It can be the profiles at the edge of paleochannel such as F2-37, -41, -48 or in paleochannel floor such as F2-42. The occurrence of Fe-Mn accretions in F2-42 relates to gleyic properties in the profile. It can be explained by the relationship between the forming processes of iron oxide accretions with transform processes of Fe^{3+} to Fe^{2+} and inversely in low altitude of flood plain (Fridland, 1973).

4.4 Alteration of soil properties and landcover/landuse with the change of topography and geological formations.

In this section, the soil properties will be discussed in detail in relationship with the topography and geological formation by some catenas.

4.4.1 Catena of formation F1

The changing course of a river influences the soil genesis. Figure 3.13 shows the catena F1 from the channel to the alluvial accumulation. There are two paleochannels of the Red River paleochannel system 1 located in the area of this catena (see Figure 3.9). The course of the river in the area of catena F1 is from the south to the north – the arrow direction in the catena (Figure 3.13).

The conclusion was defined by comparing the positions of the paleochannels in the alluvial accumulation and the present Red River bank. The soils in the catena are Ochric Fluvisols (F1-35, -36) and Umbric Fluvisols (F1-50). The soil color from profile F1-50 is “darker” than the one from F1-36. The pH (H_2O) of samples from F1-50 are lower than F1-36. The mineral assemblages are very similar except for goethite which occurs in the whole profile F1-50 but not in the top soil of F1-37. The similarity can be explained by the fact that sediment from both of the profiles was transported and deposited by same river. The difference between two profiles possibly indicates that the soil from profile F1-50 was formed shortly before F1-37. The changing course of a river explains this situation. The top soil from profile F1-35 (located in island river) is youngest soil in comparison with the investigated soil from the catena. The soil classification in the catena F1 shows the relationship between the soil development with the change of ricer course or the sedimentation time. The paleochannel and profile F1-49 demonstrate the relation between paleochannel and gleyic properties in soils. According to the catena F1, vegetable is cultivated in island river and alluvial accumulation inside the Red River dyke. Vegetable and orchard are planted in the high altitude or alluvial accumulation. The high altitude of the relief makes it to reduce the abundant moisture ability especially in monsoon. Paddy rice is transplanted in the lower altitude such as paleochannel floor because the terrain is advantage for moisture.

4.4.2 Catenas in formation F2

The influences on the soil development by paleochannel are described in Figure 3.14 and 3.15 with the catena F2-48 and F2-37. The paleochannels in two catenas belong to the Red River but they are in difference periods. The paleochannel from catena F2-48 belongs to the Red River paleochannel system 2 and the one from catena F2-37 is the Red River paleochannel system 3 (see Figure 3.9). The different paleochannel periods made the different soil properties in paleochannel floor. In grain size fraction, F2-38 has more sand fraction and less clay fraction than F2-47. Soil in profile F2-47 is classified into Gleyic Umbric Fluvisols and F2-38 is Gleyic Ochric Fluvisols.

Fe-Mn concretions were found in some profiles at the edge of the paleochannels (F2-37, -48). The diameters of these concretion reach to 3 mm as in profile F2-37. Fe_d concentration from the top soil of F2-37 is higher than the one in F2-48. It can be explained by F2-37 and -41 are located at the edge of the Red River paleochannel system 3 which is older than the Red River paleochannel system 2 where F2-48 located (see section 4.1, Figure 2.3 and 3.9). Therefore, the top soil from profile F2-37 is older than the top soil from profile F2-48.

Agricultural plant types correspond with topography. In the floor of the paleochannel, paddy rice is transplanted and vegetable or orchard is grown in the “embossing” of the channel edge. As mentioned in section 4.4.1, paddy rice requires more moisture and easy for irrigation. The relief in the paleochannel floor is suitable for paddy rice. In contrast, the higher area as the “embossing” is drier and more difficult to irrigate. Therefore, this area is not suitable for paddy rice.

4.4.3 Catena of formation F3

The catena F3 (Figure 3.16) is located in terrace I. In the Red River delta, the average altitude of terrace level I is from 14 to 16 m (Dy et al., 1995; Toan et al., 2000). The altitude of F3-03, -04 and -07 is 8-10 m and their topography is rough. The amplitude of altitude is 2 meters and changed in small area. The status can be explained by a different intensity of denudation and erosion surface processes. F3-07 is located at an altitude that is lower than the samples on the top of terrace I. As mentioned in section 4.3, profile F3-07 is influenced by ground water fluctuation. The goethite content in samples from F3-07 is higher than in other samples in the catena (Appendix 4). Fe_d concentration in samples from F3-07 is high (60.7 g kg^{-1}). F3-07 was classified into Ferrallic Cambisols. But other three samples located in the top of terrace I were classified into Ferrallic Fluvisols. In short, the material in F3-07 is more altered than other samples on the top of terrace I in the catena F3. The different locations in topography made the difference soil properties.

There are no significant in landcover/landuse from the catena. Vegetable is planted only on the top of the terrace. But the paddy rice is cultivated not only in the lower altitude of terrace but also on the top of the terrace I. The area has a good irrigation system that helps local farmers to plant paddy rice on the top of terrace I.

4.4.4 The catena over the formations F1 to F5

The catena F1-F4 crossed all geological formations in the study area (Figure 3.17). Based on the catena, Plinthic Ferrasols formed in the outcrop of the F4 and F5 formation. Ferralic Fluvisols formed in formation F3 and other subtypes of Fluvisols such as Umbric and Ochric types are located in the outcrop of the F1 and F2 formation. In the catena, Gleysols are located in the lowest altitude. The pH of top soil samples from the catena increase from alkaline to acidic value according to the position from the Red River bank to hill area. The issue can be explained that young fluvial sediment as in the F1 and F2 formation still keep most of original sediment material that fluvial soil was developed. The F3 formation with its terrace I was affected by impregnated weathering (Toan et al., 2000) that made the iron concentrate increased and 2:1 clay mineral amounts decreased. F5 formation and formation F4 with proluvium sediment were influenced by the change of hot – dry tropical climate (see section 4.3) and ground water fluctuation (Toan et al, 2000) which made impregnated weathering. It created plinthic horizon with an iron-rich, humus-poor mixture of kaolinitic clay and quartz. In short, the soil types were developed in correlation with the geological formations.

In landcover/landuse, artificial forests as Eucalyptus and Acacia are planted on the erosion hill slope and erosion terrace II (F4 formation). Vegetables mostly are cultivated in high altitude of the F1, F5 formation and foothill of the F4 formation. Paddy rice is grown in the lower altitudes of the F2 and F1 formation. But paddy rice is also transplanted in the high altitude area as F3 formation (terrace I), around 10 m and even 20 m altitude of the F5 formation (erosion plain) where it has good artificial irrigation system.

4.5 Discontinuous soil profile

Discontinuous soil profile term is used for the soil profiles in present study which have at least one horizon independent development with its deeper horizons.

The layers from F3-10 (15-40 cm), F4-02 (40-110 cm) and F5-05 (40-55 cm) have the same yellow soil color (10YR7/6 in dry and10YR6/6 in moist), bulk mineral content (Appendix 4) and nearly similar soil spectral curves (Figure 3.3 and Table 3.10). The three yellow color layers have a large proportion of clay reaching to over 40%. The silt fraction is from 20.9 to 34.3% and the sand fraction from 22.3 to 26.8% weight. These layers cover unconformity to weathered bed rock layers which have very different grain sizes and color. The source of these layers can be explained by below theory.

From the Mid Holocene (Q_{IV}^2) on the area belonged to an alluvial delta (Lam et al., 2001 and 2005; Tanabe et al., 2003; Tu et al., 2004; Funabiki et al., 2007). According to Lam et al. (2001, 2005) during the flood periods water overflowed on the delta and the further away from the river channel, the slower the velocity of the flow. At some point a threshold is reached where silt, silty clay, clayey silt is deposited. The sedimentary facies of the yellow layers are classified to silty clay or clayey silt on high alluvial flat. The grain size in the yellow soil layer can be explained by mentioned sedimentation type. The comparison of minerals with weathering bed rock's and surrounding geological formation indicates that the yellow soil layers were greatly influenced by the geological formations of the study area. That means, in flood times, temporary river flows created sedimentation which had local sources and deposition sites depended on river flows and the feature of the relief.

Another discontinuous profile is F2-46. The top soil sample color in dry condition is 7.5 YR 6/3 (light brown) and layer from 65 – 90 cm in depth is 5YR 7/6 (Reddish yellow) and 5YR 8/1 (White). The quantity of goethite, potassium feldspar and plagioclase in the two layers is most different (Appendix 4). Concerning the clay minerals, the amount of poorly crystallized kaolinite in the top soil is less than in the deeper layer (Appendix 5). The soil spectra measured by spectroradiometer from the two layers are also very different and the curve of layer 65 – 90 cm is similar to samples from F3 formation (Figure 3.3 and Table 3.11). Huyen et al. (1997) by studying boreholes in this area, found the young sediment overlying the F3 formation. F2-46 is located in the area where the Red River paleochannel system 1 exists (see section 4.1). Therefore, the source of the top layer is young sediment from the Red River. The material from layer 65 – 90 cm can be classified into the F3 formation.

4.6 Lancover/landuse change from 1987 to 2003

The period of fifteen years is chosen to analyze the landcover/landuse change in the study area. Several landcover/landuse changes took place between 1987 and 2003 (Table 3.15). With respect to agricultural land, paddy rice and vegetable areas experienced the greatest change. The change from paddy rice or vegetable are to other agricultural land types is significant (see Table 3.17). In the fluvial landscape, most of the landcover/landuse change is noticed in the Day River valley (F1 formation) with most of the change from paddy rice to vegetable land. In the F2 formation (outside the artificial dyke), the paddy rice area remained quite stable. In the foothills, below approximately 15 m altitude (F4 and F5 formation), a lot of vegetable land was converted to orchard (residential mixed orchard type in the landcover/landuse map).

The other main cause of landcover/landuse change in agricultural land is urbanization. 4.8% (920 ha) of the paddy rice areas in 1987 were changed to residential areas, construction site and specialized land (such as industrial zone) (Table 3.15). However, there are huge of vegetable and shrub areas (1926 ha) were changed to paddy rice between 1987 and 2003. Therefore, the land for rice cultivation has decreased only by a total of 62 ha in 15 years. The vegetable areas were also decreased by urbanization with 15.5% or 1490 ha. This figure is bigger than the paddy rice loss through urbanization. Shrub land also was changed to vegetable land (197 ha) and bare soils on the island river have been used for vegetation (292 ha). Nevertheless, the total vegetable land in 2003 is decreased by 1439 ha in comparison with 1987. The data does not take into account the lost vegetable land in river islands due to course changes of the river. Therefore, the agricultural area lost by urbanization affected in particular the paddy rice and vegetable. The phenomenon is not discovered in the perennial plant type. The urbanization is mainly expressed in the extension of the villages and new areas with small factory or enterprises. The extension of the villages occurs both outside of the artificial dyke and in the Day River valley. Other hot-spots of increasing residential land are along the highway. With the aim of conservation agricultural land in the flat terrain, some factories and industrial zones were built in the low altitude hill and foothill areas which were vegetable land in 1987.

Permanent bare soil, shrub and artificial forest land are located in the hill area and the changes of these types are also interesting. Permanent bare soil and shrub areas in 1987 were changed mainly to artificial forest. Artificial forest types are mainly Eucalyptus and Acacia trees. The permanent bare soil land type was not found in 2003 in the study area. Shrub land also was converted to paddy rice mostly along the streams and vegetable areas in the hill area.

Plinthic Ferrasols developed almost in hill area and landcover/landuse changed most in this soil type (Table 3.16). As Table 3.17, the significant changes are vegetable to perennial plant and paddy rice. These areas are also used for specialized land and residential land mixed orchard. There are also a lot of paddy rice areas that were converted to vegetable land within the Plinthic Ferralsols areas. The next important change is the conversion of shrub area to artificial forest and vegetable areas. Permanent bare soils did not exist in 2003 and most of them were changed to artificial forest. The impact of these changes on the Plinthic Ferrasols is one of main subjects in the next section.

4.7 Landuse planning orientation

The criteria for landuse planning orientation are based on soil properties, geomorphology and the landcover/landuse change during 1987-2003. Landuse planning orientation in the study area will be discussed for three sub-areas. The first sub-area is the area inside the Red River dyke and Day River valley. The second and the third areas are located outside the artificial dykes. The second sub-area is the alluvial accumulation (developed in formation F2) and terrace I (developed in formation F3). The third sub-area is the erosion plain (mainly formed in formation F5), erosion terrace II and erosion hill slope (formation F4).

The first sub-area as described above is a flood influenced area. The Ochric and Umbric Fluvisols in the Red River dyke are suitable for vegetable and short-term industrial crops. These soils are quite good (pH 5.1 – 7.9); moderate CEC value; mainly silty clay loam and silt loam). These soils are also suitable for paddy rice. Paddy rice can be cultivated in low altitude such as in the paleochannel and vegetable can be cultivated in the higher altitude.

This information is good for decision making when the local government carry out converted cultivation model in the area. The Day River valley plays an important role in the capital's (Hanoi) flood control system. The Day Damp and its dyke were built in the Day River valley with the aim to diverge the Red River flood for decreasing flood pressure to Hanoi (the operation of the system see section 1.3.4). Every landuse planning in the area should be ensured to avoid obstruction of flood flows in the valley. During the field work in 2007 and 2008, some orchards and fruit gardens were discovered in the Day River valley. For the flood control aim, these fruit garden should be allowed only for cultivating seedlings gardens (arboretum). Because the old and big trees in these areas will be influenced to flood flows in the valley in urgent cases. Another concerning in the Day River valley is the extension of the villages (section 4.6) and the high of the house. These problems decrease the drainage capacity of valley and the speed of the flows when the Day Damp gates are opened to diverge flood.

The main soil type of the second area is Fluvisols with subclasses as Umbric, Ochric, Gleyic and Ferralic. Ferralic Fluvisols formed in the F3 formation – terrace I. At present, the cultivation in the soil is one paddy rice crop and one vegetable or two paddy rice crop per year. However, the high altitude of the relief is difficult and costly for irrigation especially plant is paddy rice. The soils should be continued to study for transition to fruit tree or high economic flower. The soil properties within formation F2 (pH 5-6.8; moderate CEC; texture mainly silty clay, silt loam, silty clay loam; flat relief) are suitable for paddy rice cultivation. In the high areas, vegetable can be grown. The paddy rice in the area should be protected for security of food. The area is also facing problem with the extension of residential areas and new small factories. The new factories should not be placed in the area.

The main soil types of the third area are Gleyic Umbric Fluvisols, Gleyic Ochric Fluvisols, Gleyic Plinthic Ferrasols and mainly Plinthic Ferrasols. With respect to the soils in the erosion plain of formation F5 and in the foothill of formation F4, the suitable plants are vegetable and paddy rice in the low altitude. In some areas in the foothill such as F4-03, -04 and -07 exit the Plinthic Ferrasols with high silt proportion. These areas are only suitable for vegetation. The foothill and the erosion terrace II are suitable for artificial construction such as building and small factories. On the erosion terrace II and the erosion hill slope, the main soil type is Plinthic Ferrasols and the artificial forests consist of Eucalyptus and Acacia trees. Mostly artificial forest land in 2003 was converted from shrub land and permanent bare soil in 1987 (table 3.17). In some case, the circumstance is better because the trees prevent erosion better than the permanent bare soils. However, soils under Eucalyptus tree are not highly protected again erosion. Eucalyptus with thin canopy, deeply penetration and high absorbent root made soil easily dries out and is eroded. With respect to economical aspect, eucalyptus is harvested one time per seven years. Therefore, it is not of high value. Although Eucalyptus has been planted together with Acacia trees -Acacia support fertility to soil which loss by Eucalyptus- but the artificial forest in the study area should be replaced by agro-forestry combination.

The Plinthic Ferrasols should be continued to be studied for evaluating the suitable trees which can protect the soils and increase farmer’s benefit. The research proposes some replaceable trees in the area. Table 4.1 shows the ecosystem requirements for some fruit and industrial trees which can be grown on Plinthic Ferrasols.

Table 4.1: Ecosystem requirements for some fruit and industrial trees which can be grown on Plinthic Ferrasols (Tuc, 2000; Soi, 2002; Cuc, 2002; Dat, 2004)

Criteria	Litchi	Longan	Pineapple	Sugarcane	Tea
1. *Optimal temperature*: Growing Flowering	 24-29^o 18-24^o	 24-29^o 20-27^o	24-27^o	24-30^o	20-30^o
2. *Rainfall* -Average rain fall/yr - Air humid	1250 - 1700mm 75-80%	1200 - 1700mm 70-80%	1000 - 1500mm 70-80%	>1500mm 70-80%	>1500mm 80-85%
3. *Capability* -Against drought - Against waterlogging	Good Bad	Moderate Moderate	Good Bad	Good Bad	Good Bad
4. *Other* - Slope - pH soil -Depth soil - Soil texture USDA - Soil fertility	< 20^0 4.5-6.0 > 60cm Loam Quite good	< 20^0 5.5-6.5 > 70cm Not important Good	< 25^0 Depend on variety > 30cm Silt loam Moderate	< 15^0 5.5-7.5 > 80cm Loam – Silt loam Good	< 25^0 4.5-5.5 > 60cm Silt loam Good

Note: Soil texture in the table is converted from the light and moderate heavy soil in original to USDA system.

The average annual of rainfall in the Plinthic Ferrasols area in the study area is from 1700 to 1800 mm (People's Committee of Hatay province; Tu, 2000). Therefore, pineapple trees may not be suitable. Based on the slope criteria, the suitable area for litchi and longan trees is the foothill area of the F4 formation. The area has some main streams that facilitate irrigation because especially litchi and longan require highly humid soils. In fact, there are some small litchi and longan farms in the hill foot area. Other ecosystem criteria should be studied to make facilitate the decision to expand these farms. The pH in Plinthic Ferrasols is appropriate for tea tree and the slope criterion would be acceptable on erosion plain (formation F5) and erosion hill slope (formation F4). Sugarcane needs a lot of water and good drainage (Soi, 2002). The tree can be planted in the Plinthic Ferrasol in formation F5 which formed from effusive rocks. These areas are located to the south of the study area.

5 Conclusion

The paleochannel systems in the study include the Day River, Red River and Tich River system. There are three systems belonging to the Red River paleochannel system. Age of the Day River and the Red River paleochannel systems 1 is youngest. The age of the Red River paleochannel system 2 is around 1200 years. The maximum age of Red River paleochannel system 3 is 5166 ± 92 cal. years B.P.

The study support more evidences for the fluvial environment in the study from 5000 years B.P to present. In the stage 7.500-5.000 years B.P, the sea water did not cover the whole study area. The boundary of maximum tidal in this stage should be continued to study.

Remote sensing methods with satellite, air photo and spectroradiometer data can be applied to soil mapping in scale 1:50.000 or bigger scale in tropical area such as Vietnam. In future, soil mapping in Vietnam should be continued to implement by automatic digital processing methods and using Hyperspectral data. The soil spectral library should be established soon. It will help to increase the accuracy of soil classification by using remote sensing methods. The multi-time digital soil spectral libraries would be useful for researching and monitoring development and degradation soils in Vietnam - the important issue for a developing agricultural country.

Ratio Fe_o / Fe_d cannot be used to determine relative age of the soil in the study area especially with the soil formed in the young geological formation as formation F1 and F2.

Relationships between soil properties, geomorphology and geology in the study area are:

- The pH and grain size distribution relate to the geological formation and geomorphology. From the F1 to F4 formation (from Red River bank to hill area), pH decrease and grain size is coarser.
- The change of the bulk and clay mineral amount in the top soil layer correspond with relative soil age and weathering level. From F1 to F4 formation, type 2:1 clay minerals were destroyed and type 1:1 clay minerals were created. With respect to the bulk minerals, hematite and goethite increased with soil age whereas plagioclase and mica decreased.
- Plinthic Ferrasols formed in the F4 and F5 formation or erosion hill slope, erosion terrace II and erosion plain. Ferralic Fluvisols developed in the F3 formation or terrace I. Umbric and Ochric Fluvisols formed in the F1 and F2 formation or mainly alluvial accumulation. Soils with gleyic properties formed in depression area and in the floor of the paleochannels.

The present study only mentions to initial relationships between soil properties, geomorphology and geology. In future, it needs more detail studies in the issue in the Red River and Mekong deltas – two main deltas in Vietnam. More importantly, the forecast of the development and degradation of soil in two main deltas should be analyzed in future researches.

During lateritization in the study area accumulated dominantly iron oxides in laterite profiles. In the Quaternary formations, laterite highly developed in the foothills within formation F4 and the terrace I of formation F3.

From 1987 to 2003, the landcover/landuse change occurred with a different degree in different geological formations and soil types. The paddy rice was quite stable in formation F2. There was the transfer from paddy rice to vegetable and in the reverse direction in the F1 formation (inside Red River dyke and Day River valley). Urbanization is the main reason to reduce agricultural land in the fluvial terrain. A significant landcover/landuse change in Plinthic Ferrasols (in F4 and F5 formation) from shrub areas to artificial forest and vegetable was noticed.

Landuse planning in the study area should aim at conserving the agricultural land in fluvial terrain especially with respect to the paddy rice areas outside the artificial dyke (F2 formation). Factories, industrial zones and other entertainment zones should be built in the hill area or foothill. In the Day River valley, the orchard with big and high trees should not allow to grow due to the flood control aim. The landuse in foothills and hill areas should be transferred from artificial forest (Acacia and Eucalyptus tree) to agro-forest combination models.

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Appendix 1 - Soil color and WRB soil name

Id Sample	Depth (cm)	Hor-iozon	Munsell Color				WRB soil type
			Dry	Description	Wet	Description	
F1 formation - 1st group							
F1-36	0 - 30	A	7.5YR 7/3	Pink	7.5YR 6/4	Light reddish brown	Ochric Fluvisols
	30 - 60	C1	7.5YR 7/4	Pink	7.5YR 5/3	Brown	
	60 - 90	C2	7.5YR 6/3	Light brown	7.5YR 5/4	Brown	
F1-49	0 - 30	A	5YR 6/3	Light reddish brown	5YR 5/4	Reddish brown	Gleyic Ochric Fluvisols
	45 - 70	Cg2	5YR 6/3	Light reddish brown	5YR 5/4	Reddish brown	
	70 - 90	Cg3	5YR 6/3	Light reddish brown	5YR 5/4	Reddish brown	
F1-50	0 - 30	C1	5YR 7/3	Pink	5YR 6/4	Light reddish brown	Umbric Fluvisols
	30 - 60	C2	5YR 7/3	Pink	5YR 6/4	Light reddish brown	
	60 - 100	C3	5YR 6/3	Light reddish brown	5YR 5/4	Light reddish brown	
F1 formation - 2nd group							
F1-35	0 - 25	C1	7,5YR 6/4	Light brown	7,5YR 5/4	Brown	Ochric Fluvisols
	50-75	C2	7,5YR 7/3	Pink	7.5YR 4/4	Brown	
F1-33	0 – 25	A	7,5YR 7/3	Pink	7,5YR 4/3	Brown	Umbric Fluvisos
	25-55	C1	7,5 YR 6/3	Light brown	7,5YR 5/4	Brown	
	55-75	C2	7.5YR 6/3	Light brown	7,5YR 5/5	Brown	
F1-01	0-25	A	7.5 R6/4	Light brown	7.5 R4/4	Brown	Ochric Fluvisols
F1-40	0 – 30	A	5YR 7/3	Pink	5YR 5/3	Reddish Brown	Umbric Fluvisols
	30 - 60	C1	5YR 7/3	Pink	5YR 5/3	Reddish Brown	
	60 - 90	C2	5YR 7/3	Pink	5YR 4/3	Reddish Brown	

Note: A – Accumulative horizon
B – Horizon show little or no evidence of the original sediment or rock structure
Bg – B horizon with gleyic properties
C – Horizon still keeps original sediment or rock structure
Cr – used for reduced C horizon Cg – C horizon with gleyic properties
Cgor – used for oxidized and reduced C horizon with gleyic properties

Id Sample	Depth (cm)	Hor-iozon	Munsell Color				WRB soil type
			Dry	Description	Wet	Description	
F1 formation - 3rd group							
F1-53	0 – 30	A	7.5YR 7/3	Pink	7.5YR 5/3	Brown	Areno Ochric Fluvisols
	30 – 75	C1	7.5YR 7/3	Pink	7.5YR 4/4	Brown	
	75 - 110	C2	7.5YR 6/3	Light brown	7.5YR 4/4	Brown	
	110 – 145	C3	7.5YR 6/4	Light brown	7.5YR 4/4	Brown	
F1-54	0 – 30	A	7.5YR 7/3	Pink	7.5YR 5/3	Brown	Umbric Fluvisols
	30 – 60	C1	7.5YR 7/3	Pink	7.5YR 5/3	Brown	
	60 - 85	C2	7.5YR 7/4	Pink	7.5YR 4/3	Brown	
F1-56	0 - 25	A	7.5YR 7/3	Pink	7.5YR 4/3	Brown	Umbric Fluvisols
	25 - 50	C1	7.5YR 7/4	Pink	7.5YR 5/3	Brown	
	75 - 100	C3	7.5YR 7/4	Pink	7.5YR 5/3	Brown	
F1-57	0 - 25	A	5YR 6/3	Light reddish brown	5YR 5/3	Reddish Brown	Umbric Fluvisols
	25 - 45	C1	5YR 6/3	Light reddish brown	5YR 4/4	Reddish Brown	
	50 - 75	C2	5YR 6/3	Light reddish brown	5YR 5/3	Reddish Brown	
F1-58	0- 30	A	5YR 6/3	Light reddish brown	5YR 5/3	Reddish Brown	Umbric Fluvisols
	30 - 60	C1	5YR 6/3	Light reddish brown	5YR 5/3	Reddish brown	
	60 - 90	C2	5YR 6/3	Light reddish brown	5YR 5/3	Reddish brown	
F2 formation – 1st group							
F2-37	0 - 30	A	7.5YR 7/4	Pink	7.5YR 5/3	Brown	Ochric Fluvisols
	30 - 60	C1	7.5YR 7/4	Pink	7.5YR 5/3	Brown	
	60 - 90	C2	7.5YR 7/4	Pink	7.5YR 5/3	Brown	
F2-41	0 - 30	A	7.5YR 8/3	Pink	7.5YR 5/3	Brown	Ochric Fluvisols
	30 - 60	C1	7.5YR 8/3	Pink	7.5YR 5/3	Brown	
	60 - 90	C2	7.5YR 8/3	Pink	7.5YR 5/3	Brown	

Id Sample	Depth (cm)	Hor-iozon	Munsell Color				WRB soil type
			Dry	Description	Wet	Description	
F2 formation – 1st group (continue)							
F2-42	0 - 20	A	10YR 7/3	Very pale brown	10 YR 5/3	Brown	Gleyic Ochric Fluvisols
	20 - 40	Cgor	10YR 8/1; 10YR 8/3	White; Very pale brown	10YR 6/4	Light yellowish brown	
	40 - 60	Cgor	10YR 8/3	Very pale brown	10YR 6/6	Brownish yellow	
F2-46	0 - 20	A	7,5YR 6/3	Light brown	7,5YR 5/3	Brown	Umbric Fluvisols
	65 - 90	C1	5YR7/6; 5YR 8/1	Reddish yellow; White	5YR 6/8	Reddish yellow	
F2-47	0 - 20	A	7,5YR 7/3	Pink	7,5YR 5/3	Brown	Gleyic Umbric Fluvisols
	25 - 45	Cg	7,5YR 7/4	Pink	7,5YR 5/4	Brown	
F2-48	0 - 30	A	7.5YR 6/3	Light brown	7.5YR 5/3	Brown	Umbric Fluvisols
	30 - 60	C1	7.5YR 6/3	Light brown	7.5YR 5/3	Brown	
	90 - 120	C2	7.5YR 7/4	Pink	7.5YR 5/4	Brown	
F2 formation - 2nd group							
F2-02	0-25	A	7.5 R6/4	Light brown	7.5 R4/4	Brown	Umbric Fluvisols
F2-38	0 - 30	A	7.5 YR7/3	Pink	7.5YR 5/3	Brown	Gleyic Ochric Fluvisol
	30 - 45	Cg	7.5YR 7/4	Very pale brown	7.5YR 5/3	Brown	
F3 Formation							
F3-03	0-25	A	7.5 YR 7/6	Reddish brown	7.5 YR 5/6	Strong brown	Ferralic Fluvisols
F3-04	0-35	A	7.5 YR 7/6	Reddish brown	7.5 YR 6/6	Reddish brown	Ferralic Fluvisols
F3-05	0-20	A	10 YR 7/4	Very pale brown	10 YR 5/4	Yellowish brown	Ferralic Fluvisols
F3-07	0 - 35	B1	7.5 YR 8/6	Reddish yellow	7.5YR 5/8	Strong brown	Ferralic Cambisol
	35 - 100	B2	7,5YR 7/6	Reddish yellow	7,5YR 5/6	Strong brown	
F3-10	15 - 40	C	10YR 7/6	Yellow	10YR 6/6	Brownish yellow	Ferralic Fluvisols
	70 - 140	B	10YR 7/6 10R 5/8	Yellow / Red	10R 5/8	Red	

Note: F2-46 (65 – 90 cm depth) belongs to F3 formation. It is put in row below of F2-46 (0 – 20 cm depth) for easy following.

Id Sample	Depth (cm)	Hor-iozon	Munsell Color				WRB soil type
			Dry	Description	Wet	Description	
F4 formation							
F4-02	40 - 110	C	10YR 7/6	Yellow	10YR 6/6	Brownish yellow	Ferralic Cambisol
	110 - 130	B	5YR 6/6	Reddish yellow	5YR 6/8	Reddish yellow	Plinthic Ferrasol
F4-03	0 -15	A	10YR 7/2	Light gray	10YR 5/3	Yellowish brown	Gleyic Ferrasols
	36 - 50	B	10YR 7/3	Very Pale brown	10YR 6/4	Light yellowish brown	
	60 - 72	Bg	5YR 6/6	Reddish yellow	5YR 5/4	Reddish yellow	
F4-04	0 - 15	A	10YR 7/2	Light gray	10YR 5/3	Yellowish brown	Gleyic Plinthic Ferrasols
	15 - 23	B	10YR 7/4	Very Pale brown	10YR 6/6	Brownish yellow	
	58 - 70	Bg	5YR 6/6	Reddish yellow	5YR 6/4	Reddish yellow	
F4-07	0-20	A	10 YR 6/4	Light yellowish brown	10 YR 5/4	Yellowish brown	Gleyic Plinthic Ferrasols
F4-08	85 - 100	B2	10 YR 5/6	Yellowish Brown	10 YR 5/6	Yellowish Brown	Plinthic Ferrasols
F4-09	0 - 43	A	10YR 6/6	Brownish yellow	10YR 5/4	Yellowish brown	Plinthic Ferrasols
F5 formation							
F5-05	40 - 55	C	10YR 7/6	Yellow	10YR 6/6	Brownish yellow	Ferralic Fluvisos
F5-06	0 - 35	A	10 YR 6/4	Light yellowish brown	10 YR 5/4	Yellowish brown	Plinthic Ferrasols

Note: A – Accumulative horizon
B – Horizon show little or no evidence of the original sediment or rock structure
Bg – B horizon with gleyic properties
C – Horizon still keeps original sediment or rock structure
Cr – used for reduced C horizon
Cg – C horizon with gleyic properties
Cgor – used for oxidized and reduced C horizon with gleyic properties

Appendix 2 - Physical soil property: Grain size distribution and USDA texture

Id Sample	Depth (cm)	Grain size (wt)				Ratio		Texture
		> 2mm	< 2mm (total 100 %)					
		Gravel	Sand	Silt	Clay	sa/si	si/cl	USDA-NRCS
F1 formation - 1st group								
F1-36	0 - 30	*0*	2	66	32	0.03	2.06	Silty clay loam
	30 - 60	*0*	0	41	59	0.00	0.69	Silty clay
	60 - 90	*0*	0	50	50	0.00	1.00	Silty clay
F1-49	0 - 45	*0*	1	71	28	0.01	2.54	Silty clay loam
	45 - 70	*0*	0	55	45	0.00	1.22	Silty clay
	70 - 90	*0*	0	51	49	0.00	1.04	Silty clay
F1-50	0 - 30	*0*	1	51	48	0.02	1.06	Silty clay
	30 - 60	*0*	1	53	46	0.02	1.15	Silty clay
	60 - 100	*0*	0	59	41	0.00	1.44	Silty clay
F1 formation - 2nd group								
F1-35	0 - 25	*0*	14	70	16	0.20	4.38	Silt loam
	50-75	*0*	0	70	30	0.00	2.33	Silty clay loam
F1-33	0 - 25	*0*	1	70	29	0.01	2.41	Silty clay loam
	25-55	*0*	8	68	24	0.12	2.83	Silt loam
	55-75	*0*	2	70	28	0.03	2.50	Silty clay loam
F1-01	0-25	*0*	4	58	38	0.07	1.53	Silty clay loam
F1-40	0 - 30	*0*	5	73	22	0.07	3.32	Silt loam
	30 - 60	*0*	2	71	27	0.03	2.63	Silty clay loam
	60 - 90	*0*	1	67	32	0.01	2.09	Silty clay loam

Id Sample	Depth (cm)	Grain size (wt) > 2mm	< 2mm (total 100)			Ratio		Texture
		Gravel	Sand	Silt	Clay	sa/si	si/cl	USDA-NRCS
F1 formation - 3rd group								
F1-53	0 - 30	*0*	61	31	8	1.97	3.88	Sandy loam
	30 - 75	*0*	65	29	6	2.24	4.83	Sandy loam
	75 - 110	*0*	46	43	11	1.07	3.91	Loam
	110-145	*0*	57	35	8	1.63	4.38	Sandy loam
F1-54	0 - 30	*0*	42	49	9	0.86	5.44	Loam
	30 - 60	*0*	27	55	18	0.49	3.06	Silt loam
	60 - 85	*0*	31	56	13	0.55	4.31	Silt loam
F1-56	0 - 25	*0*	36	49	15	0.73	3.27	Silt loam
	25 - 50	*0*	39	49	12	0.80	4.08	Loam
	75 - 100	*0*	15	61	24	0.25	2.54	Silt loam
F1-57	0 - 25	*0*	22	64	14	0.34	4.57	Silt loam
	25 - 45	*0*	6	70	24	0.09	2.92	Silt loam
	50 - 75	*0*	36	52	11	0.69	4.73	Silt loam
F1-58	0- 30	*0*	22	63	15	0.35	4.20	Silt loam
	30 - 60	*0*	21	63	16	0.33	3.94	Silt loam
	60 - 90	*0*	8	68	24	0.12	2.83	Silt loam
F2 formation - 1st group								
F2-37	0 - 30	*9*	14	61	25	0.23	2.44	Silt loam
	30 - 60	*1*	5	62	33	0.08	1.88	Silty clay loam
	60 - 90	*0*	3	59	38	0.05	1.55	Silty clay loam
F2-41	0 - 30	*2*	3	44	53	0.07	0.83	Silty clay
	30 - 60	*1*	2	43	55	0.05	0.78	Silty clay
	60 - 90	*1*	2	44	54	0.05	0.81	Silty clay

Id Sample	Depth (cm)	Grain size (wt) > 2mm	< 2mm (total 100 %)			Ratio		Texture
		Gravel	Sand	Silt	Clay	sa/si	si/cl	USDA-NRCS
F2 formation - 1st group (continue)								
F2-42	0 - 20	*0*	2	38	60	0.05	0.63	Clay
	20 - 40	*0*	1	31	68	0.03	0.46	Clay
	40 - 60	*0*	0	24	76	0.00	0.32	Clay
F2-46	0 - 20	*0*	9	49	42	0.18	1.17	Silty clay
	65 - 90	*0*	23	36	41	0.64	0.88	Clay
F2-47	0 - 25	*0*	0	37	63	0.00	0.59	Clay
	25 - 25	*0*	3	32	65	0.09	0.49	Clay
F2-48	0 - 30	*0*	3	46	51	0.07	0.90	Silty clay
	30 - 60	*0*	5	45	50	0.11	0.90	Silty clay
	90 - 120	*0*	8	60	32	0.13	1.88	Silty clay loam
F2 formation - 2nd group								
F2-02	0-25	*0*	36	30	34	1.20	0.88	Clay loam
F2-38	0 - 30	*0*	13	47	40	0.28	1.18	Silty clay
	30 - 45	*0*	43	33	34	1.30	0.97	Loam
F3 formation								
F3-03	0-25	*3*	10	31	59	0.32	0.53	Clay
F3-04	25-35	*0*	7	41	52	0.17	0.79	Silty clay
F3-05	0-20	*2*	6	30	64	0.20	0.47	Clay
F3-07	0 - 35	*2*	10	38	52	0.26	0.73	Clay
	35 - 100	*0*	11	41	48	0.27	0.85	Silty clay
F3-10	15 - 40	*0*	27	21	52	1.29	0.40	Clay
	70 - 140	*32*	19	34	47	0.56	0.72	Clay

Note: F2-46 (65 – 90 cm depth) belongs to F3 formation. It is put in row below of F2-46 (0 – 20 cm depth) for easy following.

Id Sample	Depth (cm)	Grain size (wt)				Ratio		Texture
		> 2mm	< 2mm (total 100 %)					
		Gravel	Sand	Silt	Clay	sa/si	si/cl	USDA-NRCS
F4 formation								
F4-02	40 -110	*0*	25	33	42	0.76	0.79	Clay
	110-130	*32*	22	31	47	0.71	0.66	Clay
F4-03	0 -15	*3*	18	56	26	0.32	2.15	Silt loam
	36 - 50	*10*	38	39	23	0.97	1.70	Loam
	60 - 72	*29*	23	42	35	0.55	1.20	Clay loam
F4-04	0 - 15	*0*	10	62	28	0.16	2.21	Silty clay loam
	15 - 23	*0*	14	57	29	0.25	1.97	Silty clay loam
	58 - 70	*19*	14	41	45	0.34	0.91	Silty clay
F4-07	0-20	*18*	35	40	25	0.88	1.60	Loam
F4-08	85 -100	*53*	45	6	49	7.50	0.12	Clay
F4-09	0 - 43	2	36	8	56	4.50	0.14	Clay
F5 formation								
F5-05	40 - 55	0	22	34	44	0.65	0.77	Clay
F5-06	0 - 35	39	39	28	33	1.39	0.85	Clay loam

Appendix 3 - Chemical soil property: pH (H_2O), Cation Exchange Capacity (CEC), Dithinonid and Oxalat Extractable

Id Sample	Depth (cm)	pH (H_2O)	CEC mMol / 100g	Dithionid (g kg^{-1})			Oxalat (g kg^{-1})			Feo/ Fed (%)
				Al_d	Fe_d	Mn_d	Al_o	Fe_o	Mn_o	
F1 formation - 1st group										
F1-36	0 - 30	7.7	17.57	0.96	22.64	0.80	0.48	2.13	0.72	9.4
	30 - 60	7.7	15.82	1.47	31.48	0.54	0.61	2.09	0.43	6.7
	60 - 90	7.7	17.52	1.42	31.46	0.74	0.58	2.30	0.70	7.3
F1-49	0 - 45	7.9	25.31	1.11	27.18	1.03	0.48	2.87	0.96	10.6
	45 - 70	7.9	23.48	1.35	30.48	0.96	0.58	2.57	0.82	8.4
	70 - 90	7.6	14.09	1.36	31.63	0.65	0.64	2.13	0.47	6.7
F1-50	0 - 30	6.6	13.67	1.28	27.89	0.74	0.70	3.85	0.67	13.8
	30 - 60	7.4	14.00	1.08	28.45	0.72	0.63	4.18	0.60	14.7
	60 -100	7.5	12.88	1.36	30.98	0.99	0.57	2.04	0.89	6
F1 formation - 2nd group										
F1-35	0 - 25	7.7	22.21	1.26	21.85	0.58	0.66	3.42	0.64	15.7
	50-75	7.8	25.28	1.49	30.57	0.95	0.65	3.76	0.43	12.3
F1-33	0 - 25	7.3	13.33	1.90	32.88	1.00	1.10	5.01	0.95	15.2
	25-55	7.7	12.35	1.25	24.02	0.72	0.55	2.99	0.6	12.4
	55-75	7.7	19.55	1.83	30.58	0.97	0.78	4.64	0.43	15.2
F1-01	0-25	7.5	-	1.30	21.32	0.79	0.65	3.65	0.71	17.1
F1-40	0 - 30	6.1	-	0.79	17.82	0.63	0.44	2.31	0.56	12.9
	30 - 60	6.7	-	0.85	19.18	0.70	0.46	2.10	0.62	10.9
	60 - 90	7.7	-	0.93	22.31	0.83	0.55	2.37	0.75	10.6
F1 formation - 3rd group										
F1-53	0 - 30	7.7	12.2	0.43	11.83	0.27	0.25	1.65	0.24	14.0
	30 - 75	7.9	18.81	0.43	12.48	0.36	0.25	1.70	0.30	13.6
	75- 110	7.8	20.95	0.58	15.23	0.40	0.38	2.79	0.33	18.3
	110-145	7.9	-	0.48	13.22	0.40	0.32	2.29	0.34	17.3
F1-54	0 - 30	7.6	-	0.46	13.11	0.31	0.26	1.37	0.27	10.4
	30 - 60	7.8	-	0.81	17.53	0.50	0.45	2.08	0.45	11.9
	60 - 85	7.9	21.87	0.57	14.85	0.38	0.30	1.60	0.36	10.8
F1-56	0 - 25	5.1	5.73	0.53	14.04	0.31	0.36	1.82	0.30	13.0
	25 - 50	5.2	5.64	0.48	13.89	0.31	0.32	1.67	0.30	12.1
	75 - 100	7.4	12.34	0.64	19.11	0.58	0.46	2.77	0.55	14.5
F1-57	0 - 25	6.5	-	0.76	15.53	0.47	0.47	1.97	0.40	12.7
	25 - 45	7.7	-	1.00	22.91	0.74	0.48	2.72	0.66	11.9
	50 - 75	7.8	-	0.64	15.57	0.43	0.31	1.65	0.35	10.6

Id Sample	Depth (cm)	pH (H_2O)	CEC mMol / 100g	Dithionid (g kg^{-1})			Oxalat (g kg^{-1})			Feo/Fed (%)
				Al_d	Fe_d	Mn_d	Al_o	Fe_o	Mn_o	
F1 formation – 3rd group (continue)										
F1-58	0- 30	7.0	-	0.68	15.99	0.53	0.36	1.61	0.46	10.1
	30 - 60	7.8	-	0.69	16.49	0.55	0.36	1.80	0.48	10.9
	60 - 90	7.8	-	1.01	22.09	0.84	0.35	1.87	0.47	8.5
F2 formation - 1st group										
F2-37	0 - 30	4.9	5.02	1.46	48.89	1.20	0.58	7.29	0.89	14.9
	30 - 60	4.9	6.43	1.61	24.86	1.19	0.73	4.14	1.00	16.7
	60 - 90	5	7.21	1.94	26.71	1.31	0.77	2.93	1.01	11.0
F2-41	0 - 30	6.1	12.30	2.07	35.64	1.09	0.68	2.69	0.66	7.5
	30 - 60	6.3	11.49	2.24	33.39	0.87	0.68	2.40	0.67	7.2
	60 - 90	6.4	11.47	2.81	33.97	1.15	0.72	1.68	0.84	4.9
F2-42	0 - 20	5.2	8.98	1.28	21.13	0.18	0.73	3.43	0.10	16.3
	20 - 40	6.9	9.23	3.56	47.02	0.23	0.68	0.60	0.11	1.3
	40 - 60	6.5	10.43	2.78	39.38	0.31	0.71	0.75	0.08	1.9
F2-46	0 - 20	6.7	7.09	1.35	27.24	0.12	0.6	1.24	0.08	4.6
	65 - 90	5.4	6.05	2.61	31.54	0.05	0.55	0.71	0.04	2.3
F2-47	0 - 25	7.0	12.35	2.2	31.53	0.45	0.68	0.85	0.37	2.7
	25 - 25	7.0	14.15	1.63	24.73	0.18	0.8	0.73	0.23	3.0
F2-48	0 - 30	5.7	12.37	2.27	29.33	1.03	0.85	2.50	0.76	8.5
	30 - 60	5.7	11.91	2.13	28.29	1.01	0.82	2.64	0.69	9.3
	90 -120	6.6	10.30	2.00	24.07	0.76	0.65	1.53	0.57	6.4
F2 formation - 2nd group										
F2-02	0-25	6.8	8.63	0.61	14.89	0.46	0.37	5.54	0.37	37.2
F2-38	0 - 30	6.1	8.33	0.87	20.56	0.29	0.52	2.47	0.14	12.0
	30 - 45	6.5	6.33	1.56	24.14	0.95	0.54	1.52	0.78	6.3
F3 formation										
F3-03	0-25	6.4	8.15	2.97	33.65	0.29	0.5	3.77	0.24	11.2
F3-04	25-35	5.3	3.50	2.45	19.88	0.04	0.8	1.63	0.02	8.2
F3-05	0-20	7.1	6.89	1.85	20.65	0.15	0.33	3.13	0.11	15.2
F3-07	0 - 35	4.5	4.93	5.15	50.24	0.24	0.82	0.95	0.13	1.9
	35 -100	4.5	5.50	6.51	60.7	0.15	1.06	0.9	0.06	1.5
F3-10	15 - 40	4.8	4.81	4.20	31.85	0.04	0.95	1.92	0.03	6.0
	70 -140	4.3	0.92	12.86	153.83	0.04	0.82	0.73	0.01	0.5
F4 formation										
F4-02	40-110	4.0	0.69	4.54	33.63	0.04	1.25	2.18	0.02	6.5
	110-130	4.1	0.76	16.01	133.25	0.14	0.96	1.00	0.02	0.8
F4-03	0 -15	4.5	2.34	3.63	40.58	0.06	0.72	3.67	0.04	9.0
	36 - 50	4.0	0.83	2.88	21.3	0.02	1.18	2.87	0.01	13.5
	60 - 72	4.2	0.88	9.31	140.8	0.04	0.86	1.39	0.01	1.0

Note: F2-46 (65 – 90 cm depth) belongs to F3 formation. It is put in row below of F2-46 (0 – 20 cm depth) for easy following.

Id Sample	Depth (cm)	pH (H_2O)	CEC mMol / 100g	Dithionid (g kg^{-1})			Oxalat (g kg^{-1})			Feo/ Fed (%)
				Al_d	Fe_d	Mn_d	Al_o	Fe_o	Mn_o	
F4 formation (continue)										
F4-04	0 - 15	4.3	-	1.41	17.06	0.01	0.64	2.91	0.01	17
	15 - 23	4.3	-	1.79	24.61	0.02	0.51	1.93	0.01	7.8
	58 - 70	4.3	-	6.04	111.44	0.01	0.75	0.83	0.01	0.7
F4-07	0-20	5.2	-	2.46	16.25	0.04	0.87	4.58	0.02	28.2
F4-08	85 -100	4.9	-	11.8	65.28	0.09	1.36	1.44	0.03	2.2
F4-09	0 - 43	4.6	0.53	14.38	84.22	0.50	1.49	1.31	0.21	1.6
F5 formation										
F5-05	40 - 55	4.5	3.08	3.79	33.22	0.03	1.15	2.52	0.01	7.6
F5-06	0-35	5.3	-	3.19	30.58	0.19	0.45	1.88	0.16	6.1

Appendix 4 - Bulk Minerals

Id Sample	Depth (cm)	BULK MINERALS										
		Mica	Amp.	Sheet Silicate	Quar-tz	Goe-thite	KFSP	Plag.	Cal-cite	Dolo-mite	Pyr-ite	Hem-atite
F1 formation - 1st group												
F1-36	0 - 30	+	-	**	**	-	+	*	-	-	-	+
	30 - 60	+	-	**	*	+	+	*	+	-	-	+
	60 - 90	+	-	**	*	+	+	*	-	-	-	+
F1-49	0 - 45	+	+	**	**	-	+	*	+	-	-	+
	45 - 70	+	-	**	*	+	+	*	-	-	-	+
	70 - 90	+	-	**	*	+	+	*	-	-	-	+
F1-50	0 - 30	+	-	**	*	+	+	*	-	-	-	+
	30 - 60	+	-	**	*	+	+	*	-	-	-	+
	60 - 100	+	-	**	**	+	+	*	-	-	-	+
F1 formation – 2nd group												
F1-35	0 - 25	+	+	**	**	-	+	*	+	-	-	+
	50-75	+	-	**	*	-	+	*	+	+	-	+
F1-33	0 - 25	+	?	**	**	-	+	*	+	-	-	+
	25-55	+	-	**	*	-	+	*	?	?	-	+
	55-75	+	-	**	**	-	+	*	?	?	-	+
F1-01	0-25	+	-	**	*	+	-	*	+	-	-	+
F1-40	0 - 30	+	-	*	**	?	+	*	-	-	-	+
	30 - 60	+	?	**	**	?	+	*	-	-	-	+
	60 - 90	+	-	**	**	?	+	*	-	-	-	+
F1 formation – 3rd group												
F1-53	0 - 30	+	+	*	*	+	+	*	+	?	-	+
	30 - 75	+	+	*	**	?	*	*	+	?	-	+
	75 - 110	+	+	*	*	?	*	*	?	?	-	+
	110-145	+	+	*	**	?	*	*	?	?	-	+
F1-54	0 - 30	+	+	*	**	+	?	*	-	-	-	+
	30 - 60	+	-	*	*	+	+	*	+	-	-	+
	60 - 85	+	-	*	**	+	+	*	+	+	-	+
F1-56	0 - 25	+	-	*	*	+	+	*	-	-	-	+
	25 - 50	+	+	*	**	+	+	*	-	-	-	+
	75 - 100	+	-	**	**	+	+	*	-	-	-	+

Note: Mineral quantity

*** High amounts
** Medium amounts
* Small amounts

+ Traces
? Unsure
- None

Amp. – Amphibolite
KFSP - Potassium Feldspar
Plag.- Plagioclase

Id Sample	Depth (cm)	BULK MINERALS										
		Mica	Amp.	Sheet Silicate	Quar-tz	Goe-thite	KFSP	Plag.	Cal-cite	Dolo-mite	Pyr-ite	Hem-atite
F1 formation – 3rd group (cont.)												
F1-57	0 - 25	+	+	*	*	?	+	*	-	-	-	+
	25 - 45	+	-	**	**	?	+	*	+	-	-	+
	50 - 75	+	+	*	**	?	+	*	+	-	-	+
F1-58	0- 30	+	+	*	**	?	+	*	-	-	-	+
	30 - 60	+	+	*	*	?	+	*	?	?	-	+
	60 - 90	+	-	*	**	?	+	*	+	?	-	+
F2 formation – 1st group												
F2-37	0 - 30	+	-	*	**	?	+	*	-	-	-	+
	30 - 60	+	?	*	**	?	+	*	-	-	-	+
	60 - 90	+	?	**	**	?	+	*	-	-	-	+
F2-41	0 - 30	+	-	**	**	+	+	*	-	-	-	+
	30 - 60	+	-	**	**	+	+	*	-	-	-	+
	60 - 90	+	-	**	**	+	+	*	-	-	-	+
F2-42	0 - 20	+	-	***	**	+	+	+	-	-	-	+
	20 - 40	+	-	***	*	*	+	+	-	-	-	+
	40 - 60	+	-	***	*	*	+	+	-	-	-	+
F2-46	0 - 20	+	-	**	**	+	+	*	-	-	-	+
	65 - 90	+	-	**	**	*	-	+	-	-	-	+
F2-47	0 - 25	+	-	**	**	+	+	+	-	-	-	+
	25 - 25	+	-	**	*	+	+	+	-	-	-	+
F2-48	0 - 30	+	-	**	*	?	+	*	-	-	-	+
	30 - 60	+	-	**	**	?	*	+	-	-	-	+
	90- 120	+	-	**	**	?	*	*	-	-	-	+
F2 formation – 2nd group												
F2-02	0-25	+	-	*	**	+	*	**	-	-	-	*
F2-38	0 - 30	+	-	**	**	?	*	*	-	-	-	+
	30 - 45	+	-	**	**	?	+	*	-	-	-	+
F3 formation												
F3-03	0-25	+	-	**	**	+	+	+	-	-	-	+
F3-04	25-35	-	-	**	**	+	-	-	-	-	-	+
F3-05	0-20	-	-	*	**	+	+	-	-	-	-	+
F3-07	0 - 35	+	-	**	*	*	-	-	?	-	-	+
	35- 100	+	-	**	**	*	-	+	+	-	-	+

Note: F2-46 (65 – 90 cm depth) belongs to F3 formation. It is put in row below of F2-46 (0 – 20 cm depth) for easy following.

Id Sample	Depth (cm)	BULK MINERALS										
		Mica	Amp.	Sheet Silicate	Quar-tz	Goe-thite	KFSP	Plag.	Cal-cite	Dolo-mite	Pyr-ite	Hem-atite
F3 formation (cont.)												
F3-10	15 - 40	-	-	**	**	*	+	-	-	-	-	+
	70- 140	-	-	*	+	**	-	-	-	?	-	*
F4 formation												
F4-02	40- 110	-	-	*	**	*	+	-	-	-	-	+
	110-130	-	-	*	*	**	+	-	-	-	-	*
F4-03	0 -15	-	-	*	**	*	+	-	-	-	-	+
	36 - 50	-	-	**	**	+	+	-	-	-	-	+
	60 - 72	-	-	*	**	**	+	-	-	-	-	*
F4-04	0 - 15	-	-	*	**	*	+	-	-	-	-	+
	15 - 23	-	-	*	**	+	+	-	-	-	-	+
	58 - 70	-	-	*	***	**	+	-	-	-	-	*
F4-07	0-20	-	-	*	**	**	+	-	-	-	-	*
F4-08	80-100	-	-	*	*	**	-	-	-	-	-	**
F4-09	0-43	-	-	*	**	**	+	-	-	-	-	*
F5 formation												
F5-05	40 - 55	-	-	**	**	+	+	-	-	-	-	+
F5-06	0-35	-	-	*	**	**	+	-	-	-	-	*

Appendix 5 - Clay Minerals

Id Sample	Depth (cm)	CLAY MINERALS							
		Vermiculite		Illite	Kaolinite		Chlorites		Mixed layer
		14 Å	18 Å		Well	Poorly	Primary	Secondary	
F1 formation - 1st group									
F1-36	0 - 30	+	+	**	*	*	*	-	+
	30 - 60	+	+	**	*	*	*	-	+
	60 - 90	+	-	**	*	*	*	-	+
F1-49	0 - 45	+	-	**	*	*	*	-	+
	45 - 70	+	+	**	*	*	*	-	+
	70 - 90	+	+	**	*	*	*	-	+
F1-50	0 - 30	+	+	**	*	*	*	-	+
	30 - 60	+	+	**	*	*	*	-	+
	60 - 100	+	+	**	*	*	*	-	+
F1 formation – 2nd group									
F1-35	0 - 25	+	+	**	*	*	*	-	
	50-75	+	+	**	*	*	*	-	-
F1-33	0 - 25	+	+	**	*	*	*	-	-
	25-55	+	+	**	*	*	*	-	-
	55-75	*	+	**	*	*	*	-	-
F1-01	0-25	*	*	**	*	*	*	-	+
F1-40	0 - 30	*	*	**	*	*	*	-	+
	30 - 60	*	*	**	*	*	*	-	+
	60 - 90	+	+	**	*	*	*	-	
F1 formation – 3rd group									
F1-53	0 - 30	+	+	**	*	*	+	-	+
	30 - 75	+	+	**	*	*	+	-	+
	75 - 110	+	+	**	*	*	+	-	+
	110-145	+	+	**	*	*	+	-	+
F1-54	0 - 30	+	?	**	*	*	*	-	+
	30 - 60	+	+	**	*	*	*	-	+
	60 - 85	+	+	**	*	*	*	-	+
F1-56	0 - 25	+	+	**	*	*	*	-	+
	25 - 50	+	+	**	*	*	*	-	+
	75 - 100	+	+	**	*	*	*	-	+

Note:

*** High amounts   * Small amounts   ? Unsure

** Medium amounts   + Traces   - None

Id Sample	Depth (cm)	CLAY MINERALS							
		Vermiculite		Illite	Kaolinite		Chlorites		Mixed layer
		14 Å	18 Å		Well	Poorly	Primary	Secondary	
F1 formation – 3rd group (cont.)									
F1-57	0 - 25	+	+	**	*	*	*	-	+
	25 - 45	+	+	**	*	*	*	-	+
	50 - 75	+	+	**	*	*	*	-	+
F1-58	0- 30	+	+	**	*	*	*	-	+
	30 - 60	+	+	**	*	*	*	-	+
	60 - 90	+	+	**	*	*	*	-	+
F2 formation – 1st group									
F2-37	0 - 30	+	?	**	**	+	*	-	+
	30 - 60	+	?	**	**	+	*	-	+
	60 - 90	+	?	**	**	+	*	-	+
F2-41	0 - 30	+	-	**	**	*	*	-	+
	30 - 60	+	-	**	**	*	*	-	+
	60 - 90	+	-	**	*	*	*	-	+
F2-42	0 - 20	+	-	**	**	*	*	-	+
	20 - 40	+	-	**	**	*	*	-	+
	40 - 60	+	-	**	**	*	*	-	+
F2-46	0 - 20	*	-	*	**	*	*	-	+
	65 - 90	*	-	*	**	**	*	-	-
F2-47	0 - 25	+	+	**	*	*	*	-	-
	25 - 25	+	+	**	*	*	*	-	+
F2-48	0 - 30	*	-	**	*	*	*	-	+
	30 - 60	*	-	**	*	*	*	-	+
	90 - 120	*	+	**	*	*	*	-	+
F2 formation – 2nd group									
F2-02	0-25	*	*	**	*	*	*	-	-
F2-38	0 - 30	+	-	**	*	*	*	-	+
	30 - 45	+	-	**	*	*	*	-	+
F3 formation									
F3-03	0-25	?	+	+	**	**	*	-	*
F3-04	25-35	+	-	+	**	**	*	-	*
F3-05	0-20	*	*	*	**	**	*	-	+
F3-07	0 - 35	*	+	+	*	*	*	-	-
	35- 100	*	-	*	**	**	*	-	-

Note: F2-46 (65 – 90 cm depth) belongs to F3 formation. It is put in row below of F2-46 (0 – 20 cm depth) for easy following.

Id Sample	Depth (cm)	CLAY MINERALS							
		Vermiculite		Illite	Kaolinite		Chlorites		Mixed layer
		14 Å	18 Å		Well	Poorly	Primary	Secondary	
F3 formation (cont.)									
F3-10	15 - 40	*	-	-	*	***	-	+	-
	70- 140	+	-	-	**	**	+	+	+
F4 formation									
F4-02	40 - 110	*	-	-	**	**	-	**	-
	110-130	*	-	-	**	***	-	**	-
F4-03	0 -15	*	-	-	+	***	-	**	-
	36 - 50	*	-	-	*	***	-	**	-
	60 - 72	*	-	-	*	***	-	**	-
F4-04	0 - 15	*	-	-	*	**	-	**	-
	15 - 23	*	-	-	*	**	-	**	-
	58 - 70	*	-	-	*	**	-	**	-
F4-07	0-20	+	-	-	*	***	-	*	+
F4-08	80-100	-	-	-	*	***	-	+	+
F4-09	0-43	-	-	-	**	**	-	+	-
F5 formation									
F5-05	40 - 55	*	-	-	+	***	*	**	+
F5-06	0-35	*	-	-	*	**	+	*	*

Appendix 6 – The correlation between spectral image-data (end-member) and spectral lab-data

End-members for **Ochric Fluvisols**

Wavelength (nm)	**Lab-data**	Image-data			**Lab-data**	Image-data
	F2-37	118	141	144	**F1-36**	8362
556	**0.1900**	0.0828	0.0537	0.0838	**0.1965**	0.0778
661	**0.3062**	0.1181	0.0912	0.0978	**0.3086**	0.0964
807	**0.4020**	0.1344	0.1039	0.1311	**0.3761**	0.1449
1656	**0.4995**	0.1892	0.1156	0.1806	**0.4023**	0.1892
2167	**0.5050**	0.1517	0.1491	0.1111	**0.4209**	0.1398
2209	**0.4731**	0.1597	0.0878	0.1341	**0.3976**	0.1313
2262	**0.4982**	0.1689	0.0950	0.1224	**0.4138**	0.1333
2336	**0.4893**	0.1354	0.0875	0.0936	**0.4125**	0.1021
2400	**0.4818**	0.0782	0.0702	0.0562	**0.4131**	0.0515
NDVI	-	0.0645	0.0375	0.1457	-	0.2009
r (RSQ)	**-**	**0.37**	**0.32**	**0.11**	**-**	**0.15**

Note: * F2-37 and F1-36 are field soil samples. The values in “Lab-data” columns are the soil spectra measured by spectroradiometer in the laboratory.

* 118, 141, 144 and 8362 are Id of end-members. The values in “Image-data” columns are spectral reflectance value in ASTER image (acquired on 13 Jan 2003).
* Normalized Difference Vegetation Index (NDVI) is calculated from ASTER image.
* r value is value of the square of the Pearson product moment correlation coefficient (RSQ) through Lab-data and Image-data.

End-members for **Ochric Fluvisols** *(continue)*

Wavelength (nm)	**Lab-data**	Image-data
	F1-01	7012
556	**0.1697**	0.0753
661	**0.2693**	0.0933
807	**0.3294**	0.1134
1656	**0.3449**	0.1956
2167	**0.3520**	0.1339
2209	**0.3333**	0.1369
2262	**0.3512**	0.1452
2336	**0.3469**	0.1021
2400	**0.3431**	0.0515
NDVI	-	0.0973
r (RSQ)	**-**	**0.20**

End-members for **Umbric Fluvisols**

Wavelength (nm)	**Lab-data**	Image-data		**Lab-data**	Image-data	
	F2-48	116	137	**F1-33**	8332	120
556	**0.1889**	0.0853	0.0853	**0.2033**	0.0728	0.0912
661	**0.3043**	0.1026	0.0995	**0.3104**	0.0902	0.1191
807	**0.3897**	0.1292	0.1239	**0.3772**	0.1029	0.1414
1656	**0.4101**	0.1892	0.2148	**0.4209**	0.1508	0.2058
2167	**0.4100**	0.1160	0.1339	**0.4318**	0.1160	0.1520
2209	**0.3776**	0.1256	0.1369	***0.4047***	0.1085	0.1676
2262	**0.4030**	0.1215	0.1393	**0.4234**	0.1156	0.1573
2336	**0.3937**	0.0926	0.1021	**0.4204**	0.0926	0.1216
2400	**0.3864**	0.0439	0.0477	**0.4187**	0.0477	0.0749
NDVI	-	0.1145	0.1092	-	0.0658	0.0858
r (RSQ)	**-**	**0.12**	**0.18**	**-**	**0.15**	**0.23**

End-members for **Umbric Fluvisols** *(continue)*

Wavelength (nm)	**Lab-data**	Image-data	**Lab-data**	Image-data	**Lab-data**	Image-data
	F1-54	119	**F1-57**	8572	**702**	7023
556	**0.1732**	0.0961	**0.2129**	0.0862	**0.1938**	0.0778
661	**0.2652**	0.1252	**0.3353**	0.1008	**0.2952**	0.0902
807	**0.3266**	0.1260	**0.4171**	0.1466	**0.3622**	0.1292
1656	**0.3639**	0.1995	**0.4571**	0.2184	**0.3945**	0.1700
2167	**0.3844**	0.1695	**0.4827**	0.1520	**0.4057**	0.1160
2209	***0.3626***	0.1843	**0.4553**	0.1731	**0.3793**	0.1085
2262	**0.3785**	0.1748	**0.4760**	0.1573	**0.3995**	0.1215
2336	**0.3759**	0.1497	**0.4727**	0.1263	**0.3943**	0.0831
2400	**0.3766**	0.0861	**0.4728**	0.0712	**0.3922**	0.0477
NDVI	-	0.0031	-	0.1850	-	0.1775
r (RSQ)	**-**	**0.30**	**-**	**0.23**	**-**	**0.11**

End-members for **Gleyic Umbric Fluvisols**

Wavelength (nm)	**Lab-data**	Image-data		
	F2-47	8472	114	136
556	**0.2752**	0.1103	0.0953	0.1157
661	**0.3871**	0.1398	0.1088	0.1374
807	**0.4516**	0.1606	0.1082	0.1414
1656	**0.4792**	0.0803	0.0739	0.0925
2167	**0.4713**	0.0566	0.0388	0.0586
2209	**0.4328**	0.0461	0.0347	0.0671
2262	**0.4633**	0.0504	0.0385	0.0584
2336	**0.4523**	0.0355	0.0260	0.0375
2400	**0.4445**	0.0210	0.0172	0.0300
NDVI	-	0.0693	-0.0030	0.0146
r (RSQ)	**-**	**0.14**	**0.23**	**0.20**

End-members for **Gleyic Ochric Fluvisols**

Wavelength (nm)	**Lab-data**	Image-data		**Lab-data**	Image-data
	F2-42	122	136	**F2-38**	8383
556	**0.2617**	0.1451	0.1157	**0.2480**	0.1132
661	**0.3568**	0.1770	0.1374	**0.3664**	0.1313
807	**0.4221**	0.1724	0.1414	**0.4417**	0.1414
1656	**0.4768**	0.0610	0.0925	**0.4947**	0.0862
2167	**0.4713**	0.0469	0.0586	**0.4942**	0.0469
2209	**0.4373**	0.0336	0.0671	***0.4579***	0.0448
2262	**0.4631**	0.0293	0.0584	**0.4875**	0.0467
2336	**0.4532**	0.0328	0.0375	**0.4776**	0.0328
2400	**0.4465**	0.0263	0.0300	**0.4698**	0.0188
NDVI	-	-0.0132	0.0146	-	0.0372
r (RSQ)	**-**	**0.48**	**0.34**	**-**	**0.35**

End-members for **Areno Ochric Fluvisols** *(continue)*

Wavelength (nm)	**Lab-data**	Image-data
	F1-53	8532
556	**0.1669**	0.0753
661	**0.2582**	0.0933
807	**0.3174**	0.1239
1656	**0.3473**	0.1636
2167	**0.3643**	0.1160
2209	***0.3416***	0.1256
2262	**0.3578**	0.1215
2336	**0.3540**	0.0926
2400	**0.3545**	0.0477
NDVI	-	0.1409
r (RSQ)	**-**	**0.12**

End-members for **Ferralic Fluvisols**

Wavelength (nm)	**Lab-data**	Image-data	**Lab-data**	Image-data	**Lab-data**	Image-data
	F3-04	7042	**F3-03**	146	**F3-10**	131
556	**0.2975**	0.0953	**0.2672**	0.0878	**0.3121**	0.0936
661	**0.4654**	0.1150	**0.3731**	0.1026	**0.4328**	0.1008
807	**0.5425**	0.1711	**0.4420**	0.1344	**0.5096**	0.1208
1656	**0.6019**	0.1892	**0.5476**	0.2212	**0.5400**	0.1554
2167	**0.5608**	0.1042	**0.5420**	0.1398	**0.4367**	0.0994
2209	**0.5138**	0.1029	**0.5061**	0.1483	**0.3747**	0.1006
2262	**0.5598**	0.1156	**0.5368**	0.1452	**0.4617**	0.0991
2336	**0.5369**	0.0783	**0.5248**	0.1069	**0.4255**	0.0702
2400	**0.5202**	0.0363	**0.5133**	0.0553	**0.3975**	0.0450
NDVI	-	0.1961	-	0.1341	-	0.0902
r (RSQ)	**-**	**0.11**	**-**	**0.20**	**-**	**0.39**

End-members for **Gleyic Plinthic Ferrasols**

Wavelength (nm)	**Lab-data**	Image-data	
	F4-07	7070	125
556	**0.1582**	0.0986	0.1255
661	**0.2346**	0.1108	0.1435
807	**0.3102**	0.1160	0.1620
1656	**0.4609**	0.1414	0.2813
2167	**0.4282**	0.2499	0.1987
2209	**0.3934**	0.1637	0.2178
2262	**0.4332**	0.1899	0.2097
2336	**0.4155**	0.1748	0.1637
2400	**0.3980**	0.1310	0.0899
NDVI	-	0.0749	0.0608
r (RSQ)	-	0.48	0.33

End-members for **Plinthic Ferrasols**

Wavelength (nm)	**Lab-data**	Image-data		**Lab-data**	Image-data	
	F5-06	7061	134	**F4-09**	7093	124
556	**0.2060**	0.1034	0.1059	**0.1373**	0.1034	0.1230
661	**0.2907**	0.1191	0.1160	**0.2025**	0.1130	0.1526
807	**0.3530**	0.1311	0.1311	**0.2629**	0.1569	0.1620
1656	**0.4573**	0.2247	0.2058	**0.3896**	0.2310	0.3128
2167	**0.4136**	0.1578	0.1228	**0.2744**	0.1403	0.2045
2209	**0.3799**	0.1731	0.1341	***0.2300***	0.1452	0.2178
2262	**0.4162**	0.1573	0.1282	**0.2867**	0.1282	0.2156
2336	**0.3972**	0.1263	0.0983	**0.2552**	0.1076	0.1590
2400	**0.3788**	0.0712	0.0525	**0.2326**	0.0600	0.0861
NDVI	-	0.0048	0.0610	-	0.1627	0.0300
r (RSQ)	**-**	**0.36**	**0.15**	**-**	**0.56**	**0.64**

There are one “sand” and one “Gleysols” (WRB soil type) end-member in the process of WRB soil mapping. The correlation of these members is not described in the appendix because the present study does not have these field soil samples.

End-members for **Gleysols**

Wavelength (nm)	Image-data
	115
556	0.1003
661	0.1212
807	0.1396
1656	0.0547
2167	0.0329
2209	0.0234
2262	0.0326
2336	0.0260
2400	0.1340
NDVI	0.0706
r (RSQ)	**-**

End-members for **Sand**

Wavelength (nm)	Image-data
	108
556	0.1751
661	0.2111
807	0.2183
1656	0.3365
2167	0.2824
2209	0.2960
2262	0.3111
2336	0.2400
2400	0.1353
NDVI	0.0168
r (RSQ)	**-**

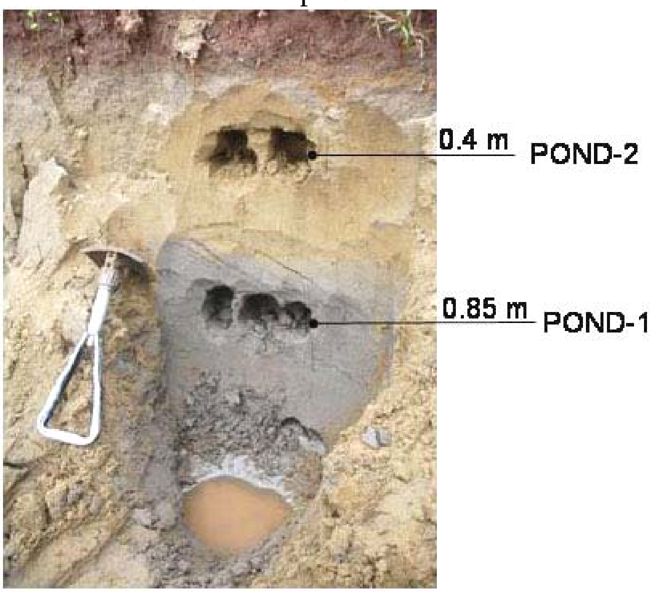
Appendix 7 – Optically Stimulated Luminescence (OSL) sample information

Datasheet 1: POND sample

1. **Collector**:
Name: Prof. Dr. Markus Fiebig
Institution: Institute of Applied Geology - BOKU
Address: Peter Jordan Str. 70, 1190, Vienna, Austria
Tel:

2. **Sample description**:
Name: POND
Country: VIETNAM
Province/district, town, region: Phuctho town, Hanoi province
Long / Lat: 105^{o} 32’ 33” 21^{o} 07’ 03”
Date of collection: 19 January 2008
Weather condition: Little rain
Relief: Paleochannel. The floor of the paleochannel is lower ≈ 1 m than surround surface. Attitude 7 m (above sea level).
Geology: Holocene fluvial sediment
Land cover: paddy rice

3. **Context of sample**
Depth of sample (above sea level): POND-2: 6.5-6.7m
POND-1: 6m -6.2m
Moisture of sample: 100%
Ground water table level: in the time of acquisition samples – dry season, the water table is about 1.5 m depth. As the figure below, the ground water table can be increased till 0.75 m depth.



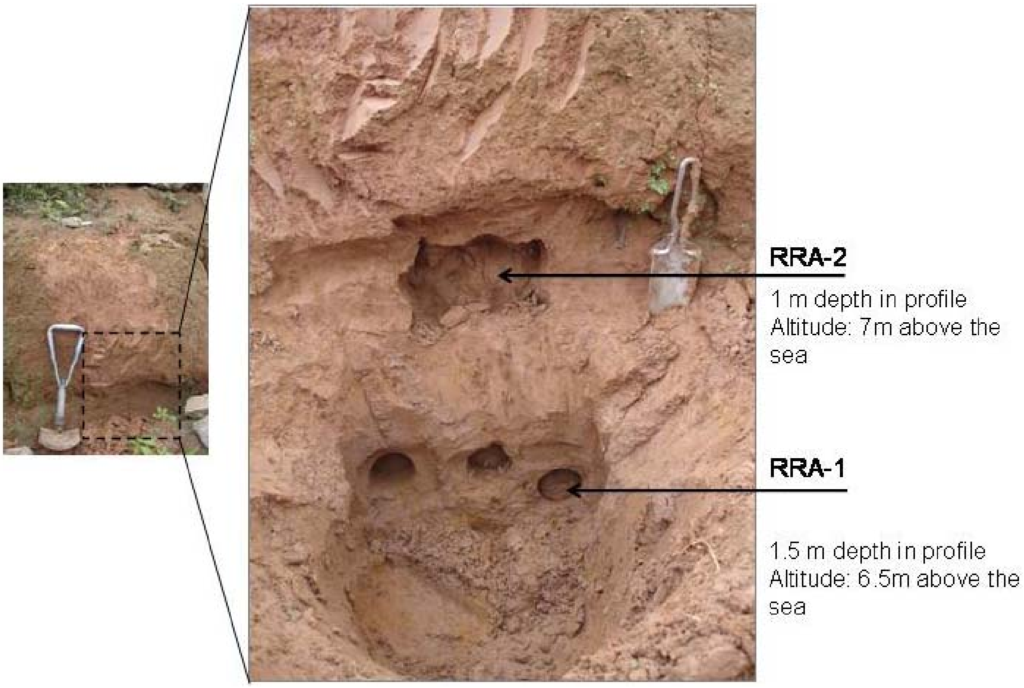
In figure in the left side: the position of POND 1 and 2 in the profile.The value in the right of picture is the depth of sample from the surface.

Datasheet 2: RRA sample

1. **Collector**:
Name: Prof. Dr. Markus Fiebig
Institution: Institute of Applied Geology - BOKU
Address: Peter Jordan Str. 70, 1190, Vienna, Austria
Tel:

2. **Sample description**:
Name: RRA
Country: VIETNAM
Province/district, town, region: Sontay city, Hanoi province
Long / Lat: 105^{o} 30’ 29” ” 21^{o} 09’ 14”
Date of collection: 17 January 2008
Weather condition: Dry, however it has little rain in the day
Relief: at the bank of the Red River. Altitude 10m (above sea level) - consideration to the top position of bank river
Geology: Holocene fluvial sediment
Land cover: Grass

3. **Context of sample**
Depth of sample (above sea level): RRA-2: 6.8 – 7.0m
RRA-1: 6.3 – 6.5m
Moisture of sample: 30 %
Water river level: the RRA-1 position is higher than Red river water about 1.2 - 1.5 m (at the time of taken samples). Obviously, the profile can be covered by water river in the monsoon.



The profile of the sample (right) and the position of samples (middle). These samples were taken in two sandy layers. Each layer is from 25 – 40 cm thick

Appendix 8 – ^{14}C Sample Information

Datasheet 1: Sample F2-44

1. Collector:

Name: Quoc Cuong Tran
Institution: Institute of Applied Geology - BOKU
Address: Peter Jordan Str. 70, 1190, Vienna, Austria
Telephone................ ....
Fax...
E-mail : *qcuong77@yahoo.com* ; quoc-cuong.tran@boku.ac.at

2. Sample description: (in case where several sample come from the same site, please describe them all in one sheet, and insert an appropriate sample list in the "sample name" box)

Sample name: **F2-44**

Date of collection: 19 February 2008
Material of sample:

✓ charcoal	☐ gyttja	☐ bone(s)
☐ wood	☐ grain(s)	☐ humus
☐ peat	☐ terrestrial shell	☐ plant remains
☐ organic sediment	☐ fresh-water shell	☐ detritus
☐ mud	☐ marine shell	☐ tufa
☐ soil	☐ speleothem	☐ other............

Additional information about material of sample:
(botanical or lithological identification, species etc.)
....
....
Contamination:

✓ none	☐ organic detritus
☐ probable	☐ humic
☐ roottlets	☐ organic preservatives (impregnants)
☐ carbonate	☐ other......

3. Sample location:

Country VIETNAM
Province/district, town, region: Thach That town, Hanoi province
Geographical coordinates vs. Greenwich:
Lat **21^o 04' 22"** ***N*** *Long* **105^o 34' 29"** ***E***
Altitude 8.0 *m a. s. l.*
Short geographical description of the environment of site (the nearest lake, mountain etc.):
Close to the Red River;

4. Context of sample:
Depth below surface: 4.0 *m*
Short description of the geomorphological and stratigraphical context of sample, details about position of sample within site:
In the edge of Red River delta – North of Vietnam; Fluvial terrain; Sample located in Holocene stratum

Type of site:
☐ exposure ☐ trench ☐ core
☐ museum ☐ finding ✓ excavation ☐ other

5. Field of study:
☐ archeology ✓ geology
☐ geography ☐ geomorphology ☐ geochemistry
☐ oceanography ☐ history ☐ botany
☐ limnology ☐ calibration

6. The sketch with scale and position of sample within site, pollen diagram

The profile F2-44 and the charcoal samples in the profile.
The ^{14}C sample is located at 4.0 m in depth

Datasheet: Sample ECP

1. Collector:
Name: Prof. Dr. Markus Fiebig
Institution: Institute of Applied Geology - BOKU
Address: Peter Jordan Str. 70, 1190, Vienna, Austria
Telephone.+43 6991030 79 77
Fax..
E-mail : qcuong77@yahoo.com ; quoc-cuong.tran@boku.ac.at

2. Sample description: (in case where several sample come from the same site, please describe them all in one sheet, and insert an appropriate sample list in the "sample name" box)

Sample name: **ECP**

Date of collection: 18 January 2008
Material of sample:

☐ charcoal	☐ gyttja	☐ bone(s)
☐ wood	☐ grain(s)	☐ humus
☐ peat	☐ terrestrial shell	☐ plant remains
✓ organic sediment	☐ fresh-water shell	☐ detritus
☐ mud	☐ marine shell	☐ tufa
☐ soil	☐ speleothem	☐ other.............

Additional information about material of sample:
(botanical or lithological identification, species etc.)
....
....

Contamination:

✓ none	☐ organic detritus
☐ probable	☐ humic
☐ roottlets	☐ organic preservatives (impregnants)
☐ carbonate	☐ other......

3. Sample location:
Country VIETNAM
Province/district, town, region: Danphuong town, Hanoi province
Geographical coordinates vs. Greenwich:
Lat **21° 08' 03"** ***N*** *Long* **105° 40' 49"** ***E***
Altitude 11.0 *m a. s. l.*
Short geographical description of the environment of site (the nearest lake, mountain etc.):
Samples located in the cliff of bank of Red River. Close to the connection between Day River and Red River.

4. Context of sample:
Depth below surface: 3 *m*
Short description of the geomorphological and stratigraphical context of sample, details about position of sample within site:
Sample is in Holocene stratum. At the cliff of the Red River bank.

Type of site:
✓ exposure ☐ trench ☐ core
☐ museum ☐ finding ☐ excavation ☐ other

5. Field of study:
☐ archeology ✓ geology
☐ geography ☐ geomorphology ☐ geochemistry
☐ oceanography ☐ history ☐ botany
☐ limnology ☐ calibration

6. The sketch with scale and position of sample within site, pollen diagram (use additional sheet if necessary).

ECP samples in the profile.
The top of the outcrop is the garden with bamboo tree

CURRICULUM VITAE

Full name: **TRAN QUOC CUONG**
Date of birth: 04 December 1977 in Hanoi, Vietnam
Nationality: Vietnamese
Marital status: Married

E-mail qcuong77@yahoo.com
quoc-cuong.tran@boku.ac.at

Main Research Field
Application Remote Sensing and GIS in Geosciences, Quaternary Geology and Geomorphology

Education

2006 - 2009	PhD student with North-South dialogue scholarship by OeAD at Institute of Applied Geology (IAG), BOKU, Vienna, Austria
2000 - 2003	MSc. Geology, University of Mining and Geology, Hanoi, Vietnam
May 2000	Trained in remote sensing field in Ho Chi Minh city by PCI International
1994 - 1999	BSc. Geology, University of Mining and Geology, Hanoi, Vietnam

Experience record

July 1999 to date	Researcher at Centre of Remote Sensing & GIS (VTGEO) - Institute of Geological Science (IGS) – Vietnam Academy of Science and Technology (VAST)
Mar. 2004 to Feb. 2005	GIS & database Assistant for "*UXO/Landmine Impact Assessment and Technical Survey*" Project – Vietnam Veterans of America Foundation (VVAF)
May 2002	Instructor - course for GIS and Remote Sensing for authorities in Binh Thuan Province.
Dec 2001	Instructor - course: "*How to import GPS data into GIS database*" for staffs of Yokdon National Park, sponsored by Fauna and Flora International (FFI)
2000 - 2001	Participating in National Project in "*Using RadarSat data to study the relationship between Rice Repartition and Biosophysic and Socio-economic features in Mekong Delta*". National Centre for Natural Science & Technology (NCST) and Center for Remote sensing and Geomatic (VTGEO).
1999 - 2000	Member of SAR Processing Team - project "*Rice crop monitoring in Vietnam*", RadarSat International, Centre formation Remote Sensing and Geomatics

Award

Mar. 2004	First prize in the 3rd Conference of Youth Scientist – Vietnam Academy of Science and Technology (VAST)
Oct. 27th 1998	Award for excellent student by WUS, awarded at Ministry of Training and Education of Vietnam.

Vienna, July 01st, 2009