

LANDFORM DEVELOPMENT AND BIOTURBATION ON THE KHORAT PLATEAU, NORTHEAST THAILAND

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ABSTRACT

Landforms and soils of the Khorat Plateau have been explained as largely resulting from fluvial action and subsequent terrace formation since the pioneering work of MOORMAN ET AL., (1964) some three decades ago. However, new research shows that neither this terrace concept nor the newly favoured concept of widespread aeolian activity with extensive loess-like deposition is generally applicable. The Khorat Plateau represents an erosional surface that developed in two main phases under different climatic conditions. In the early Tertiary an extensive plain associated with deep weathering was formed under humid tropical conditions extending from the Plateau westwards into the present mountain ranges. The uplands with Rhodic Ferralsols (Yasothon soils) and the often associated gravel horizons are relics of this plain.

In a second phase, probably during the Pliocene or early Pleistocene, the plain was dissected and much of the weathering mantle stripped off due to relief rejuvenation initiated by tectonic uplift. On the new land surface Xanthic Ferralsols developed in conjunction with a thick laterite horizon, indicating climatic conditions with pronounced seasonality and fluctuating ground water tables. Laterisation continues to the present as shown by pisolithic layers in young alluvial soils.

Research of the authors shows that an additional and so far neglected factor in landform and soil development is bioturbation by termites. This activity is responsible for differentiating the soil and weathering mantle into layers of coarser and finer material through continuous upward movement of fine particles, thus producing a pseudo-stratification. This is particularly evident where the Rhodic Ferralsols are underlain by a gravel horizon. These gravel layers and the sharp boundary between the overlying sandy material are therefore neither due to fluvial nor aeolian processes as previously assumed, but to bioturbation. The great expanse of sandy soils on the plateau is also most probably the result of bioturbation and not of widespread loess deposition during a period of dessication.

The significance of bioturbation is substantiated by investigations on recent termite mounding. Average rates of mounding in different reforestation areas vary between 0.11 and 0.34 mm/yr; this shows that termites are capable of reworking a soil profile of a few metres within several thousand years.

Bioturbation appears to be not only responsible for altering sediment structures but also for changing the position of dateable material such as tektites within the soil profile, and their usefulness for dating particular horizons is therefore limited.

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INTRODUCTION

There have been several attempts to explain the landforms of the Khorat Plateau, Northeast Thailand, and the history of their development. The earliest was by CREDNER (1935) who considered the Khorat Plateau to be an erosional plain, a peneplain, formed by long lasting erosional and denudational processes. Due to the war years and because his publication was written in German, this pioneering work has been all but forgotten. It was therefore largely the terrace concept of MOORMANN ET AL. (1964), developed during a nation wide soil survey, that has dominated the discussion on the geomorphology of the Khorat Plateau. MOORMANN ET AL. (1964) tried to explain the strikingly different soils at various levels in the landscape as the result of fluvial deposition and subsequent incision. In fact, they considered the majority of the soils and therefore also the general relief of the plateau to be of fluvial origin. Except for the strike and hogback ridges and cuestas bordering the Khorat Plateau to the south and west and the Phu Phan Ranges in the centre of the plateau the present landforms were assumed to have originated from a vast alluvial plain which subsequently was dissected in different stages. MOORMANN ET AL. (1964) thus distinguished an "upper terrace" (oldest) with deeply weathered red sandy soils (Yasothon Series), a "middle terrace" with pale brown to yellow soils (predominantly Khorat and Udon Series) and a "lower terrace" (predominantly Roi Et Series) close to the recent flood plains which are characterized by young alluvial soil. This terrace concept has remained the standard geomorphological concept for the explanation of the landforms of the Khorat Plateau and is also still widely used in soil descriptions.

Even though research into the geomorphology of Northeast Thailand is still very much in progress and we are far from having a complete answer as to the geomorphic history of the area, there is mounting evidence to show that the terrace concept is not valid. Although several authors have pointed out that the "terraces" are not fluvial in origin (BOONSENER, 1983, 1985; MICHAEL, 1982, LÖFFLER ET AL., 1984, PRAMOJANEE ET AL., 1985, DHEERADILOK & CHAIMANEE, 1986, KUBINIOK, 1989; TAMURA, 1992), considerable disagreement exists about the formation of these terrace-like landforms. MICHAEL (1982) considers them to be erosional features caused by lateral etching, while BOONSENER (1983, 1985) argued that aeolian activity must have played an important role since his grain size analyses of the sands of the high terrace showed a degree of sorting typical for aeolian deposits. BOONSENER's loess concept has recently been taken up by KY (1991), ŠIBRAVA (1993) and ŠIBRAVA & SHIMANOVICH (1994) to explain similar landforms in Vietnam. The weakness of BOONSENER's (1983, 1985) explanation, however, is the great similarity in grain size distribution between the sandy surface soils and the original bedrock as shown by PRAMOJANEE ET AL., (1985) and the fact that the distribution of the presumed loess sands is virtually identical with the occurrence of the sandstones and conglomerates of the Mahasarakham and Khok Kruat Formations. Another important factor not recognized by BOONSENER is the increase in coarser sand down the soil profile and the subsequent decrease in the degree of sorting as will be shown later.

LÖFFLER & KUBINIOK (1991) argued that the key to the understanding of the geomorphic development of the Khorat Plateau lies in finding a satisfactory explanation for the Rhodic Ferralsols (Yasothon soils) of the "upper terrace". These soils occur in a great semicircle around the southern Khorat Plateau (Fig. 1) and are characterized by their bright red

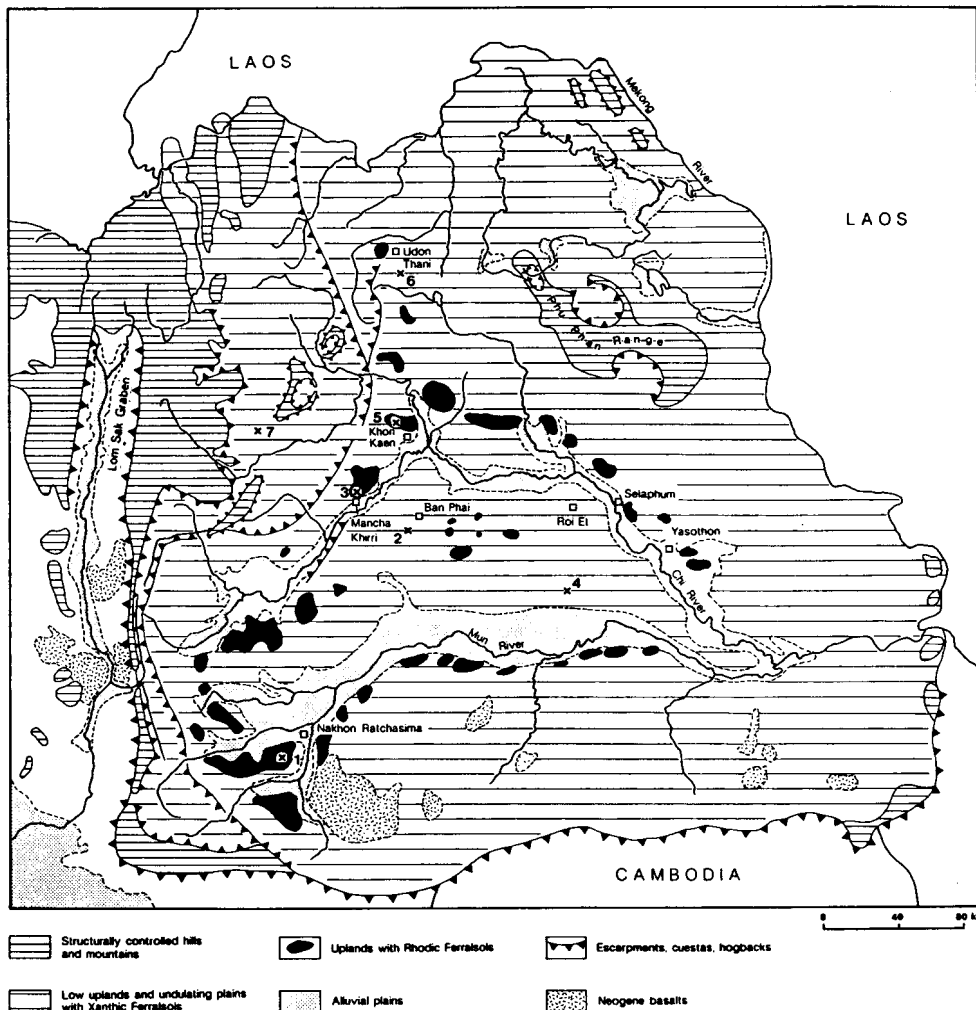


Figure 1. Generalized geomorphological map of the Khorat Plateau. Numbers indicate the location of test sites and exposures. 1 gravel pits south of Khorat, 2 Casuarina plantations south of Ban Phai, 3 Eucalyptus plantations north of Mancha Khirri, 4 Eucalyptus plantations at Ban Dong Krang Noi, 5 gravel pits near Ban Fang, 6 large Termite mounds south of Udon, 7 large Termite mounds near Chum Phae.

colour, their sandy texture and the fact that they are frequently underlain by a poorly sorted gravel horizon. Because of the presence of these gravels, the fluvial origin of this horizon has never been questioned by previous authors (MOORMANN ET AL., 1964, BOONSENER, 1985; MICHAEL, 1982; NUTALYA ET AL., 1989; TAMURA ET AL., 1988; TAMAURA, 1992). The maximum age of the gravel deposits was considered to be 700,000 years as tektites (Australites) for which this age is generally accepted (FLEISCHER ET AL., 1969; GENTNER, ET AL., 1969; TAMURA, 1992), occur in the gravel layer.

FIELD OBSERVATIONS AND METHODS

The present authors have been engaged geomorphological and pedological research in the Northeast for over a decade (ADAB, 1983; LÖFFLER ET AL., 1984; LÖFFLER & KUBINIOK, 1988; KUBINIOK, 1989; LÖFFLER, 1995) and during this work doubts arose as to the general validity of the above cited concepts on landform development. This applies in particular to the widely accepted terrace concept and also the newly postulated aeolian origin of the wide spread sandy deposits. Our recent investigations of numerous gravel layers around Khon Kaen, Selaphum, Yasothon and Nakhon Ratchasima, however, show that many lack the typical features of fluvial sorting and bedding (Figs. 1, 2 a, b). Fluvial action also does not explain the striking differentiation between the gravel horizon and the overlying sandy soils unless one postulates completely different depositional environments such as fluvial deposition for the gravels and aeolian deposition for the sands (BOONSENER, 1985). An important finding was made by the authors in 1989 in a gravel pit south of Nakhon Ratchasima airport along the road connecting highways No. 304 and 224 (site 1, Fig. 1). This exposure was revisited several times as it was gradually enlarged through quarrying for road building material. The main feature of this exposure is that it gives proof that the red sandy soil (Yasothon soil) and the underlying gravels are genetically related and that the sands must have originated from the weathered conglomeratic sandstone. Upward transport of sandy material from weathered conglomeratic sandstone must have occurred. The exposure shows a uniform, red sandy soil about 2.5 m thick underlain by largely unsorted and non-stratified gravels, typically associated with the Yasothon soils (Figs. 2 a, b). The gravel layer merges into the underlying conglomeratic sandstone which consists of alternating, partly cross-bedded layers of gravel and consolidated sand. In some sections of the exposure the unweathered conglomeratic sandstone protrudes into the gravel horizon and it is obvious that there is no continuity between the two units. Not only does the gravel horizon contain much more gravel than the conglomeratic sandstone, the bedding which is quite apparent in the sandstone is entirely missing in the gravel horizon. The gravel layer, therefore, cannot simply represent a weathered part of the conglomeratic sandstone, there must have occurred a relative concentration of the gravel through removal of finer material. This process of removal also must have been responsible for destroying the bedding structure. The only process which can account for the removal of the sand has to be upward transport through bioturbation most probably by termites as already presumed in a previous publication (LÖFFLER & KUBINIOK, 1991). However, no proof was given and in particular no evidence for the capacity of the termites to achieve this was supplied.

Our interpretations are based on profile investigations and descriptions of numerous exposures in soil pits, road cuts and quarries, supplemented by laboratory analysis of selected soil and sediment samples. The profiles were described using the method and format outlined by the "BUNDESANSTALT FÜR GEOWISSENSCHAFTEN UND ROHSTOFFE" (1982) and the soils have been classified using the FAO soil classification system (FAO, 1988). Soil and sediment samples were analyzed for grain size distribution, heavy metal content and clay mineralogy. Grain size analysis followed the method of Köhn (MÜLLER ET AL., 1970) and the heavy metal content was analyzed from an aqua regia digestion of the <2 mm fraction using an Perkin Elmer 3100 AAS (Atomic Absorption Spectrometer).



Figure 2a. Exposure south of the airport of Nakhon Ratchasima (site 1 Figure 1) with red sandy soil (top) underlain by largely unsorted and non-stratified gravels (left and right). Because of the removal of material for road construction the sand layer is not preserved in its full thickness. Conglomeratic sandstone (centre right and fig. 2b) with alternating partly cross-bedded layers of gravel and consolidated sand underlies and partly protrudes into the gravel horizon. The lithological composition of the gravels in the conglomeratic sandstone and the gravel horizon is identical and it is obvious that the gravel horizon must have formed through removal of fine material from the the conglomeratic sandstone.

Figure 2b. Close-up of fig. 2a showing the structure of the conglomeratic sandstone and the transition to the gravel layer. There is no continuity between the two units even though the lithological composition of the gravels in the sandstone and in the gravel layer is identical.



Figure 3. Within reforestation areas (here *Casuaria equisetifolia* reforestation near Ban Phai) termite mounds are located around the base of the trees; the mounds must have developed during the lifetime of the trees, thus giving a maximum age for the mound.



Figure 4. Large tree-covered termite mounds form a characteristic element in the rice fields of the Northeast.

The clay mineralogy of the fraction $<2 \mu\text{m}$ was analyzed with a Siemens X-Ray Diffraktometer D500 following the method of the US Geological Survey (CARROL, 1970). The soil structure and weathering status were assessed by microscopic analysis of thin sections as described by SCHNÜTGEN (1981) and MÜLLER & RAITH (1981).

QUANTIFICATION OF BIOTURBATION

In order to assess the rate of termite activity, termite mounds of known ages had to be found. These occur in reforestation areas where prior to planting all termite mounds had been removed or levelled. All parts of the mounds that are above surface within these plantations must have been constructed since planting. The great majority of mounds found in these plantations occur around the base of the tree trunks which is a further indication that the mounds cannot be older than the trees (Fig. 3).

A total of 637 termite mounds over 60 ha in the North and Northeast were surveyed. As a termite mound approximates a stump of a cone its volume (V) can be calculated by the following equation.

$$V = (A_2 + \sqrt{A_1 A_2} + A_1) h/3$$

where A_1 and A_2 represent the cross sectional areas at the base and top respectively. The areas have been calculated from parameters that are relatively easy to measure in the field namely, base circumference (c), height above ground (h) and longitudinal and lateral top diameters (d_1 and d_2).

$$A_1 = \pi (c/2\pi)^2 \quad \text{and} \quad A_2 = \pi (d_1/2) (d_2/2)$$

The total volume of earth accumulated in the mounds (Fig. 5) varied between 14 and 32 m^3/ha (average 18.8 m^3/ha) for 13 year old *Casuarina* plantations (site 2, Fig. 1) and 5 and 21 m^3/ha (average 11 m^3/ha) for *Eucalyptus* plantings of similar age (sites 3 and 4, Fig. 1). As no plantations older than about a decade exist in the Northeast a 30 year old teak plantation near Lampang in Northern Thailand was included in the investigations for comparison. The values here ranged from 60 to 285 m^3/ha (average 101 m^3/ha). If the soil material is spread out evenly over the surface the rate of accumulation in the three test areas corresponds to 0.11–0.24 mm/year (average 0.14 mm/yr) for the *Casuarina* sites, 0.05–0.16 mm/year (average 0.11 mm/yr) for the *Eucalyptus* plantations and between 0.2 and 0.95 mm/year (average 0.38 mm/yr) for the teak forests. Within a freshly harvested Cassava field near Mancha Khirri small termite mounds had developed within a year producing a total volume of 1 m^3 which corresponds to an accumulation rate of similar magnitude of 1 mm/year. In addition to the dateable mounds, a number of areas were investigated to demonstrate the enormous capacity of termites to accumulate earth material.

In addition to the dateable mounds a number of areas were investigated to demonstrate the enormous capacity of termites to accumulate earth material (Fig. 6). These were a mature forest in the uplands west of Hot and agricultural fields in the Northeast around Udon and Chum Phae (sites 6 and 7 on Fig. 1). Most impressive are the large termite

mounds within the low lying rice fields (including former rice fields converted into other crops) in the Northeast (Fig. 4). Here the volume of a single mound can reach over 100 m³ and the total volume per hectare can amount to nearly 800 m³ (Fig. 6). These mounds form characteristic elements of the agricultural landscape of the Northeast and probably developed over a long time in connection with rice growing. The seasonal ponding of water seems to have led to a concentration of termites in slightly higher positions within the fields. For the farmers these mounds are not unwanted; they often serve as sites for small huts and rest places at times of work in the fields. Unfortunately no indications have as yet been found for the age of these mounds.

Although there are a number of possible errors in the calculations such as the coarseness of the measuring technique, the varying shape of the mounds and the presence of cavities in the mounds, they do give an order of magnitude which is comparable with data from other parts of the world where average rates of termite mounding of 0.025–0.300 mm/yr have been reported (WILLIAMS, 1968, 1978; HUMPHREYS & MITCHELL, 1988; GOUDIE, 1988; THOMAS, 1995). The extrapolation of the rates of soil transport over a long time period is of course also risky, but the results demonstrate the impressive capacity of termites to move material upwards within a soil profile. In a time period of 10,000 years a layer of soil of 1 to 3 m could be totally reworked.

Since the termites move only finer textured material, this process necessarily leads to sorting of the soil and weathering profile with a gradual loss of fine material from the lower horizon and its accumulation in the upper horizon.

Further evidence for a sorting process can be observed in pits where the contact between gravel layer and the overlying red sand is well exposed (sites 1 and 5, Fig. 1). The upper 10 cm of the soil show a similar grain size distribution as the termite mounds and their surrounding soil; they consist predominantly of well-sorted fine sand and roughly equal portions of coarse silt and fine medium sand (Fig. 7). This is, of course, also the reason that an aeolian origin has been postulated (BOONSENER, 1985; SONSUK & HASTINGS, 1984). With increasing depth, however, the coarser fractions increase continuously. At Ban Fang west of Khon Kaen (site 5 in Fig. 1), for instance, the coarse sand fraction increases from 7% near the surface to 15%, 26% and 39% in 1 m, 2.4 m and 3.5 m depth respectively (Fig. 7). The coarse sand fraction increases in a similar fashion in an exposure south of Khorat from 4–6% at the surface to 10–20% in 1 m and 14–24% in 2.5 m depth near the boundary to the gravel.

The conglomeratic sandstone underlying the gravel horizon and partly protruding into it showed a very heterogeneous grain-size pattern. Medium sand (35–40%) is present in roughly equal proportions; the coarse sand varied greatly from 13% in one sample to 40% in the other (the coarse quartz pebbles within the conglomeratic sandstone were ignored).

Although the grain size analyses do not give a direct answer as to the origin of the sands, they do show the following facts. The sands overlying the gravel horizon are characterized by a continuous upward decrease in the coarse sand fraction with a simultaneous increase of finer fractions and degree of sorting. An aeolian origin can therefore be ruled out and the lack of any bedding and stratification makes a fluvial origin also unlikely.

To further verify the genetic relationship between the sand and gravel horizons, we analyzed the heavy metal content within 26 profiles. If sediments are of similar origin,

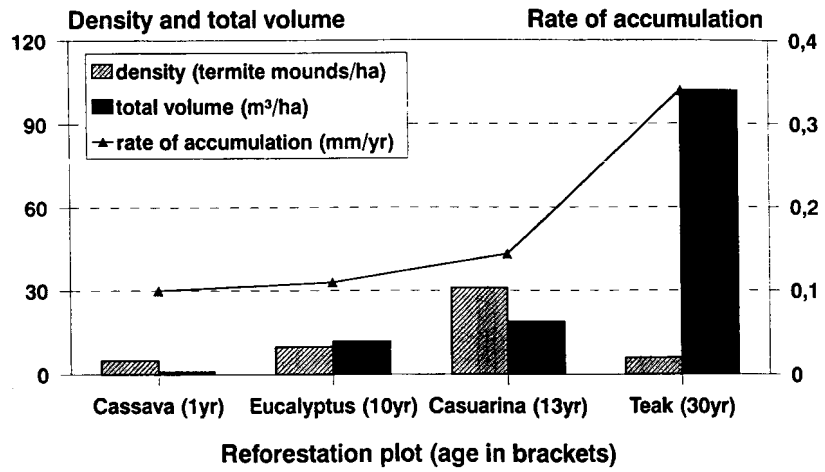


Figure 5. Density, total volume and rate of accumulation of dateable termite mounds under different types of vegetation.

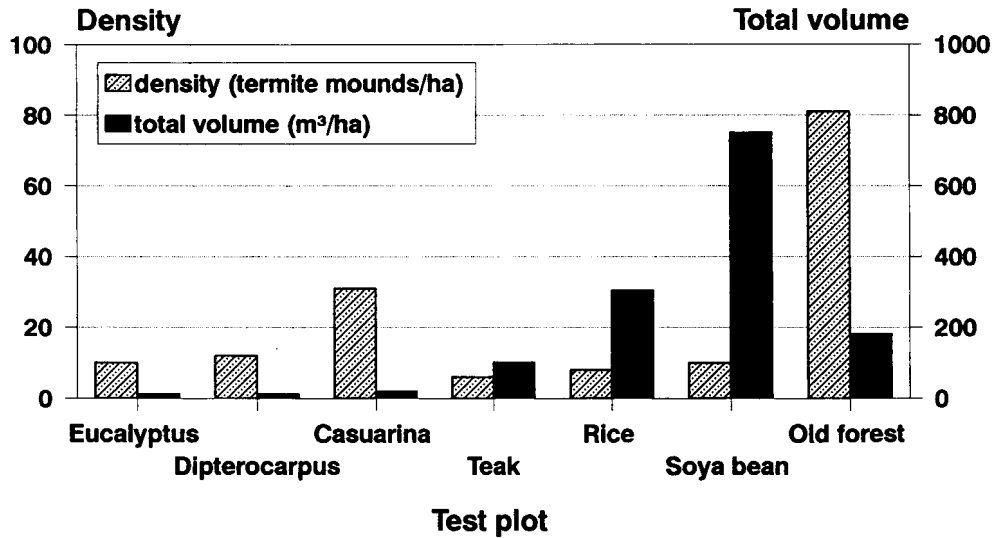


Figure 6. Density and total volume of all termite mounds surveyed in relation to land cover.

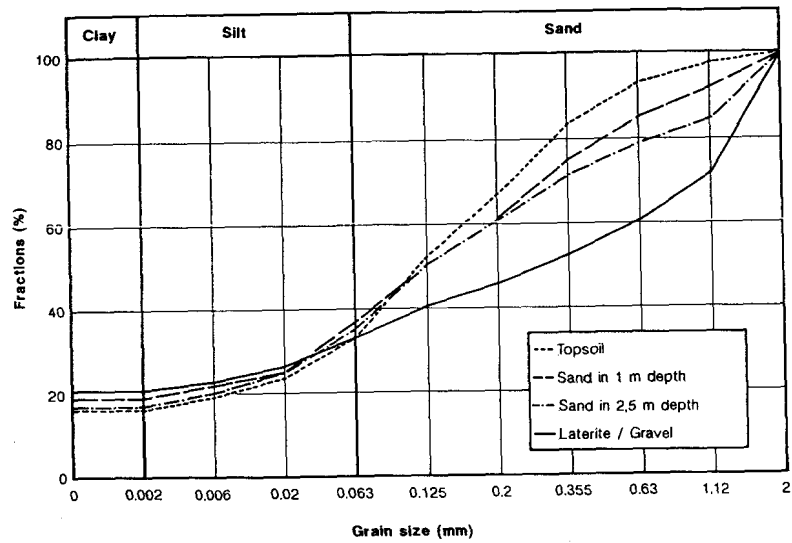


Figure 7. Grain size distribution of red soils (Rhodic Ferralssols) in exposure near Ban Fang west of Khon Kaen (site 5 in Fig. 1). The diagram clearly shows the increase in coarse sand fractions with depth and the decrease in the degree of sorting which is incompatible with aeolian deposition.



Figure 8. Within the Xanthic Ferralssols a more or less continuous laterite horizon between 0.2 and 0.5 m thick, is developed at 0.5–1.5 m depth. This laterite crust is well exposed along road and railway cuts as here along the railway line north of Khon Kaen.

they usually have a similar suite of heavy metals. The samples were analysed for Ni, Cu, Pb, Cr and Zn and their distribution throughout the profiles was homogenous. Neither the conglomeratic sandstone nor the overlying or adjacent gravel horizon nor the overlying sand differed in their suite of heavy metals. This can be taken as an indication that these three horizons are of similar origin and do not represent deposits of different age and provenance.

Having found an explanation for the widespread gravel layers and the sharp boundary between the gravel and the sandy soil still leaves the question how this fits into a general history of landform development of the Khorat Plateau. To discuss this we have to briefly describe the major geomorphic/pedological units of the plateau.

MAJOR LANDFORM UNITS

The major landform units of the Northeast (Fig. 1) are as follows:

1. Structurally controlled hills and mountains (homoclinal ridges, hogback ridges, anticlinal ridges) with shallow Lithosols and Cambisols.
2. Uplands with red sandy soils (Rhodic Ferralsols) rising between 10 and 50 m above the surroundings (the "upper terrace" of MOORMAN ET AL., 1964).
3. Low uplands and undulating plains with grey to yellow sandy soils (Xanthic Ferralsols) making up the major part of the plateau ("middle" and "lower terraces" of MOORMAN ET AL., 1964).
4. Broad alluvial plains up to 40 km wide along the major rivers draining the plateau (for example the central Mun River plain known as the Tung Kula Ronghai Plain) with Planosols, Gleyic Solonchaks and Albic Arenosols.

Structurally Controlled Hills and Mountains

These landforms fringe the plateau to the south and west and separate it not only from the low-lying central plains, but also from the mountain areas to the northeast. Within the plateau the northwest-southeast running Phu Phan Range forms a prominent anticlinal ridge splitting the plateau into a larger southern and smaller northern part.

Dating these landforms is difficult. Basalt flows which erupted on to an existing land surface some 11 m.y. ago (BARR & McDONALD, 1981) occur in the Lom-Sak Graben directly to the west of the plateau. This indicates that both the graben and the nearby cuesta escarpment must have been in existence at that time; otherwise one would expect the Cretaceous sediments forming the cuesta also to be covered by the lava flow. The presence of the lava, however, also indicates that there has not been any significant scarp retreat since eruption of the lavas 11 m.y. ago.

Uplands with Rhodic Ferralsols

This unit is identical with the "upper terrace" or the "Yasothon soil" series and is most widespread in the southern Khorat Plateau where it forms a rough semicircle (Fig. 1). Some isolated patches are also found in the northern part of the plateau and west of the

Lom-Sak Graben in the vicinity of Highway Nr. 12. While some of these upland ridges are associated with quartz gravels, there are also some occurrences that are gravel free.

From the distribution of these soils and associated landforms an old land surface can be reconstructed, sloping gently from west to east from about 200 m above present sea level to about 130 m. The general slope of the surface is slightly higher than the present gradient of the major flood plains and the height of the uplands above the present flood plains therefore decreases eastward. Near the towns of Yasothon and Selaphum the uplands are only a few metres above the flood plain of the Chi River; they do not continue further east.

The most prominent feature of the soils of these uplands is their bright red colour. They are of a sandy loamy texture and show little profile differentiation. Lateritic concretions are rare despite their high iron content. They have only been found in areas where the recent groundwater table is close to the surface as east of Selaphum and Yasothon. Here the uplands are only about 10–12 m above the surrounding plains and the lateritic concretions probably developed as a result of groundwater influence in the same way as it did for the Xanthic Ferralsols in the nearby plains.

Much of the soil matrix consists of iron oxide and iron hydroxide embedding quartz and some feldspar minerals. The topsoils of the Rhodic Ferralsols often show evidence of "browning" and, where this has occurred, clay coatings have been found in the pore spaces up to a depth of 1.5 m. The matrix of these soils is made up of an iron oxide/iron hydroxide mixture with a relatively low clay content. Some of the quartz and feldspar minerals show signs of "cavernous" weathering (i.e., tiny pits in the minerals), with the caverns filled with secondary silica. These are indications for an advanced stage of weathering usually associated with a humid tropical climate. The Rhodic Ferralsols are therefore considered to be relict features on the Khorat Plateau where present climatic conditions are strongly seasonal with a pronounced dry season (KUBINIOK, 1989).

Low uplands and undulating plains with Xanthic Ferralsols

By far the major part of the plateau is made up of low broad ridges and hills with gentle slopes rarely exceeding 3°, merging without any sharp break into undulating plains. This landscape encompasses the "middle" and "lower terraces" of MOORMANN ET AL. (1964) and its vast expanse alone makes it highly improbable that it constitutes remnants of former alluvial terraces. This landscape is underlain over its entire expanse by the Mahasarakham and Khok Kruat Formations which occasionally crop out along road cuts or can be observed in quarries or dried up fish ponds.

The soils on this landform type are again of sandy loamy texture, but in striking contrast to the Rhodic Ferralsols they are pale yellow to light brown in colour and they are invariably associated with a lateritic horizon at a depth of 0.5–1.5 m. This laterite is often well developed, between 0.20 and 0.50 m thick and follows the ups and downs of the relief more or less parallel to the land surface. Where it is exposed along road cuts or along the railway line it forms a hard lateritic crust (Fig. 8).

This lateritic horizon is relatively well developed throughout the plateau except for the western part where the Mesozoic sediments are more strongly folded. In this area the Rhodic Ferralsols are absent and the bedrock is at very shallow depth, often cropping out

at the surface. Calcareous concretions are present in some bedrock exposures along the road from Phu Wiang to Ban Si Chomphu (west of Khon Kaen), indicating a relatively little advanced state of weathering and hence a relatively young age.

The Xanthic Ferralsols have mostly a sandy loamy texture with a high proportion of the fine sand fraction. The study of thin sections shows that quartz and orthoclase minerals are present within a clay matrix of kaolinite (according to X-ray analysis) and iron hydroxide. The minerals are etched along their margins, but weathering pits comparable to those of the Rhodic Ferralsols are missing.

Alluvial Plains

The alluvial plains are the youngest elements in the landscape. The thickness of the alluvial deposits varies according to the size of the rivers. Along the main rivers such as the Mun and Chi Rivers (Mae Nam Mun and Mae Nam Chi) the total thickness of the alluvial fill is over 100 m. It decreases to some tens of metres in the tributary valleys. Some ^{14}C dates from the central Mun River plain (Tung Kula Ronghai) indicate that the upper 10 to 15 m are between 30,000 and 20,000 years old, with the uppermost clay layer being less than 20,000 years old (LÖFFLER ET AL., 1984).

The reason for the considerable thickness of the alluvial fills lies in the geomorphic development of the rivers. According to LÖFFLER ET AL. (1984) the main rivers incised well below their present flood plains at a time when base level was lower and the present series of rapids along the lower course of the Mun River did not exist. Subsequently the incised valleys were filled up with sediments due to uplift along the eastern part of the Khorat Plateau. For this reason the transition between the erosional plain and the alluvial plain is often difficult to establish in the field without drilling.

The soils of the alluvial plains are Planosols, Gleyic Solonchaks and Albic Arenosols. In some areas such as the central Mun River plain and near Nakhon Ratchasima there is a strong tendency for secondary soil salinisation in these soils due to a saline groundwater table at shallow depth (ARUNIN, 1984; LÖFFLER & KUBINIOK, 1988). Within the soil profile there are often two thin pisolithic layers consisting of iron and manganese nodules. The upper layer is at a depth of 0.30 m and is virtually horizontal over great distances. It defines the lower limit of the plough pan and as such the lower limit of the perched water table during the rainy season. The lower pisolithic layer, in contrast, is irregularly developed. It can be observed as wide undulations at a depth between 0.40 and 2.00 m in the numerous drainage channels that have been dug in the Tung Kula Ronghai plain to improve water control. It is obvious that it represents the upper limit of the main aquifer which moves under artesian pressure upwards into the alluvial clay during the rainy season (LÖFFLER & KUBINIOK, 1988).

If these soils are not used for rice cultivation they are virtually structureless. Thin sections show that the single sand and silt grains mostly consist of quartz and are either completely unweathered or show only slight signs of weathering at the grain surface. These soils are obviously poorly developed and hence pedogenically very young.

DISCUSSION

The present landforms of the Khorat Plateau essentially originated from an extensive erosional plain that developed during the Tertiary over the Mesozoic rock formations. This plain must have existed for a considerable time and continued westward into the area where at a later stage the Petchabun Ranges were uplifted and the Lom-Sak Graben developed. Relics of this plain are the deeply weathered Rhodic Ferralsols (Yasothon soils) that are present both in the plateau area and at higher elevations in the Petchabun Ranges. The deeply weathered Ferralsols on summit surfaces in the mountain ranges of northern Thailand probably also belong to this plain (KUBINIOK, 1992). The degree of weathering of the single mineral grains and the composition of the weathering material indicate that climatic conditions during the formation of this plain must have been wet tropical. The lack of well developed laterite horizons further shows that there could not have been a significant fluctuation in groundwater table. The rather homogenous distribution of iron oxide/hydroxide also demands a rather uniform soil moisture regime in contrast to the present situation where laterite formation is still in progress in the young alluvial sediments.

The Xanthic Ferralsols always occur in topographic positions below the Rhodic Ferralsols if there is a direct contact between the two units. This can be observed along road cuts south of the Mun River where there is a transition from the Xanthic Ferralsols on lower and middle slope positions to the Rhodic Ferralsols on top of the ridges. It is therefore obvious that the Xanthic Ferralsols are considerably younger and must have developed after the destruction of the landscape on which the Rhodic Ferralsols had formed. The less advanced degree of weathering further supports this. The fact that the laterite horizon is developed more or less parallel to the present relief and its considerable thickness are indications that it must have formed over a long time of tectonic stability and that this process is still going on. Only in the west of the plateau do we find geological evidence of tectonic uplift and here the widespread laterite is missing. Mesas with lateritic caps which would indicate phases of uplift and subsequent lowering of the plain are also missing.

The fact that laterite formation has not yet come to an end is also indicated by observations in the young alluvial soils. Here the laterite horizon is usually only present in the form of a thin band of iron and manganese pisoliths. The alluvial soils are pedogenically poorly developed and the single grains hardly show any signs of weathering. The soil development is similar to that of European "brown soils". The leaching near the surface and clay eluvation of the Rhodic and Xanthic Ferralsols also seem to be features of recent weathering.

The lack of dateable material in the sediments of the various relief units makes it difficult to come up with precise ages for the landform units. The maximum age for the oldest relief units must be the early Tertiary since the youngest formation in which these landforms are developed is the upper Cretaceous Mahasarakham Sandstone. The easterly-oriented drainage system must have developed on a landscape where the present north-south trending strike ridges in the west were not yet exposed. In other words the landscape on which the Rhodic Ferralsols developed must have been of lower relief than the present one. The Lom-Sak Graben also did not yet exist as relics of the old deeply weathered land

surface with well developed Rhodic Ferralsols can be found on the west side of the Graben at altitudes between 650 and 800 m. Since basalts erupted into the southern Lom-Sak Graben 11.3 m.y. ago, the Graben must have existed at that time. The relict surface with the Rhodic Ferralsols must therefore predate this and an age of at least lower Miocene and probably older must be assumed for it. This assumption is further supported by the fact that the weathering profiles and soils on the Quaternary basalts found on the Khorat Plateau have no similarity with the Ferralsols. In fact they are surprisingly little weathered; the soils here are shallow, dark brown to black basalt soils with a high content of montmorillonitic clay minerals. The suggested young Pleistocene age for the Rhodic Ferralsols (SONSUK & HASTINGS, 1984) is therefore impossible as we have pointed out previously (LÖFFLER & KUBINIOK, 1991).

The formation of the low and undulating plains with the Xanthic Ferralsol and the associated laterite horizon must be considerably younger. Following uplift, the old landscape was dissected. There is evidence from the Mun River Basin in the Tung Kula Ronghai area that the Mun River incised 130 m below its present surface and also some larger tributaries like the Lam Sieo Yai were well below their present level (LÖFFLER ET AL., 1984). This must have led to widespread stripping of the old surface and only remnants survived partly because they were situated in watershed positions and partly because of lithological reasons. Closure of the Mun River drainage basin due to uplift near the confluence of the Mun and Mekong Rivers led to filling up of the Mun Valley and its tributaries, including the Chi Valley, with alluvial deposits, leading to the extensive flat plains that today characterize the two river systems. This filling up of the broad valleys had little direct effect on the uplands where soil development and erosional processes continued.

The presence of the relatively thick laterite horizon indicates that a seasonal climate prevailed during much of the time when Xanthic Ferralsols were forming. We have no information as to exactly when the dissection of the old land surface started and when the present relief was formed. The position of the tektites for which an age of 700,000 yrs. B.P. has been established by K/Ar and fission track dating (FLEISCHER ET AL., 1969; GENTNER ET AL., 1969; TAMURA, 1992) gives some clues as to the minimum age of the laterite horizon. The tektites occur as rare, singular, glassy rock fragments over a wide area in the northwestern part of the plateau. They are present in both the Rhodic and the Xanthic Ferralsols. If they occur in a lateritic profile they are always situated on top of, or are cemented into the uppermost part of the laterite horizon. They never occur within or underneath the laterite. The same applies to their position with respect to the gravel horizon. The tektites therefore must have fallen onto a land surface where the laterite and the gravel horizon already existed. As it is unlikely that on impact, all tektites penetrated the then existing soil profile, there must have been relative movement of the tektites down the profile through bioturbation until the laterite and/or gravel horizon was reached. Since laterite formation is still in progress the tektites were sometimes cemented into the uppermost part of the laterite. It is therefore reasonable to assume that both the laterite formation and the development of the gravel horizon predate this tektite fall by a considerable time. A relatively great age for the laterite is also indicated by its thickness and the fact that micromorphological observations show that there are several generations of iron-filled cracks within the laterite nodules.

According to our observations the landform and soil development in the Northeast took place in two main phases.

In the first phase, in the early Tertiary, an extensive erosional plain developed over the more or less flat-lying Cretaceous sediments. This plain continued westward into the present mountain ranges. Climatic conditions were humid tropical resulting in deep weathering with Rhodic Ferralsols.

In the second phase this plain was destroyed and much of the weathering mantle removed in conjunction with tectonic processes that led to uplift of the plateau and its margins as well as to the formation of the Lom-Sak Graben. The relief on the plateau was accentuated since the base level of erosion for the Mun River catchment lay some 130 m lower than at present. On the slopes and undulating plains, Xanthic Ferralsols developed in conjunction with a thick laterite horizon. This process continues to the present. In the wide valleys of the Mun and Chi Rivers alluviation was caused by the formation of the rapids near the mouth of the Mun River resulting in partial closure of the drainage basin. In the accumulated sediments, which are up to 130 m thick, weathering and soil development is poor. Thin bands of lateritic concretions show that laterite formation still goes on. The soils resemble European "brown soils".

An important and, till now, neglected factor in soil and landform development is the process of bioturbation by termites and other invertebrates. According to our observations, termites are responsible for differentiating the soil and weathering mantle into layers of coarser and finer material through continuous upward movement of the finer particles (mostly fine sand), thus producing a pseudo-stratification. In the same way dateable material such as tektites is gradually moving down the profile as a kind of lag. Their present position is therefore not necessarily identical with their original one and their usefulness for dating is limited. The only conclusion they permit is that the tektite fall occurred when both the thick laterite horizon and the gravel layer already existed; the laterite and gravel horizons are therefore considerably older than the tektites. The same applies to the overlying sands. They, too, must predate the tektite fall. Neither the gravel layer associated with the Rhodic Ferralsols nor the uniform sandy Xanthic Ferralsols are of fluvial or aeolian origin, but have derived from weathered bedrock through relative accumulation of fine-textured material over time through bioturbation. Neither the terrace concept nor the newly favoured hypothesis of widespread loess deposition are therefore valid.

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