Soils on Glacial and Glaciofluvial Deposits in Central and Eastern Nepal in Relation to Classification and Landscape History

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Abstract

Forty types of soils developed from glacial and glaciofluvial deposits between 2,700 and 5,000masl were investigated in the Langtang Valley (Central Nepal) and in the Mt. Everest region (Eastern Nepal) to obtain information about their classification, zonal distribution, changes with elevation and climatic conditions, and their relation to landscape history. They were classified as entisols, inceptisols, ultisols, and spodosols according to the US Soil Taxonomy (Soil Survey Staff 1994). The analytical results indicate an influence of the elevation on soil types and soil-forming processes due to climatic conditions and bioclimatic zones. Fe fractionation and weathering indices resulted in a differentiation of the soils into different soil development groups. Three groups of younger soils with their main zone of weathering in the top horizons were mainly developed from deposits of the last glaciation and the Holocene (Late Holocene, Middle Holocene, and Early Holocene-Late Pleistocene). The relative age estimates could be supported by radiocarbon analysis. The other group of considerably older, highly weathered soils was presumably derived from Middle Pleistocene deposits. Their location and slope position give indications on the history of the landscape and the climate over at least two interglacial periods.

Introduction

The aim of the present study is to obtain information about the soils of the Dudh Kosi River system and of the Langtang Valley concerning soil types, their zonal distribution, and soil development with regard to landscape history and the history of the climate. Our studies are part of the interdisciplinary research on Pleistocene and Holocene glaciation and soil development of the Khumbu Himal south of Mt. Everest in eastern Nepal (Heuberger 1986, Bäumler et al. 1991, Bäumler and Zech 1994) and of the Langtang region in western Nepal (Bäumler et al. 1996).

Besides human activities, the main soil-forming factors are climate, geology and parent material, the orographic situation, vegetation cover, and time. Within similar local conditions, i.e., climate, topography, and parent material, soil development is mainly subject to time-controlled processes. The rates of soil-forming processes generally decrease with increasing time; the trend normally fits a logarithmic curve (Colman and Pierce 1986, Reheis 1990). The state and course of soil development can be characterised by the extent of accumulation or decrease of geogenic or pedogenic minerals or elements. This includes a rapid transformation of easily weatherable minerals, formation of new products, eluviation of alkali or alkaline earth cations, and accumulation of residuals.

When different soils are compared with regard to soil-forming factors, the main zone of weathering within the solum usually shows the best results (Harden and Taylor 1983, McFadden and Hendricks 1985). This zone, which may enclose several horizons, is characterised by maxima of clay and free Fe- or Al-oxides. Young soils show these maxima in the topsoil horizons followed by a continuous shift to subsoil B-horizons with increasing soil age (Levine and Ciolkosz 1983). In high mountain areas, soil development is furthermore strongly influenced by the orographic situation (Righi and Lorphelin 1986) and by the elevation (Drever and Zobrist 1992).

Materials and Methods

Study Areas

The soils of two study areas were investigated, namely the Langtang Valley in Central Nepal, and the Solu/Khumbu region in eastern Nepal. The Langtang Valley is located about 60km north of Kathmandu and belongs to the Inner Himalayas. The valley drains to the south-west. The locations of the soil profiles were near the village of Kyangjin (3,980masl; 28° 12'N, 85° 33'E; Bäumler et al. 1996). The working area in the Solu/Khumbu region included the upper part of the high valleys of the Dudh Kosi and Solu *Khola* (Beni *Khola*) together with the associated spring valleys of the Imja Drangka, Nangpo Tsangpo, Dudhkunda *Khola*, and Basa Drangka.

The geology of the working areas is largely uniform. Parent materials are metamorphic rocks rich in mica (migmatitic, igneous, and basal paragneisses and mica schists). A monsoon climate is predominant, with the highest precipitation from June to September. Convective rainfall occurs in the winter and spring season. At Kyangjin (Langtang Valley), the annual precipitation is about 1,200mm. In the Dudh Kosi Valley in eastern Nepal, precipitation decreases from the south (2,700mm near Lukla, 2,800masl) to the north (1,031mm at Namche Bazaar, 3,440masl; Dobremez 1976). The temperature mainly depends on elevation and local climatic conditions (+2.7°C at Kyangjin). The climatic snow-line is between 5,300m (Langtang Valley) and 5,700m (Khumbu Himal). Due to intensive grazing and the use of firewood and timber, the forest vegetation has been largely destroyed. The present vegetation cover consists mainly of dwarf bushes and turf. Parts of the two study areas are covered with eolian sediments.

Methods

All analyses were carried out on air-dried samples of the <2mm fraction. For a determination of the organic carbon and the nitrogen and for a total element analysis, an aliquot was ground to <100µm. Corg and Ntot were measured by gas chromatography (Carlo Erba ANA 1500). Soil pH was determined in 0.01 M

CaCl2 at a soil:solution ratio of 1:2.5 (Avery and Bascomb 1974). For particle size fractionation, the samples were pretreated with an acid ammonium oxalate solution to remove Fe+Al compounds followed by a treatment with H_2O_2 (30% solution) to destroy organic material. Sand fractions were determined by wet sieving; silt and clay fractions were measured by sedimentation. Total element analyses were carried out by X-ray-fluorescence analysis (TEFA 6111, EGandG Instruments Ortec) after ignition of the ground samples at 975°C for 2h. Cation exchange capacity (CEC) was determined with an unbuffered 0.5 N NH^4Cl solution (soil-solution ratio 1:20; Trüby and Aldinger 1989). Pedogenic Fe-compounds (Fed) were extracted with dithionite-citrate-bicarbonate (DCB) solution (Mehra and Jackson 1960). The extraction of non- or poor crystalline Fe-oxides, hydroxides, and associated gels (Feo) was carried out with an acid ammonium oxalate solution (Schwertmann 1964).

Relative Age Estimation

An important tool to quantify the degree of weathering is the release of silicate-bound Fe and the formation of pedogenic oxides during the process of soil formation. The ratio between well-crystallised Fe-oxides and the total Fe (Fed-o/Fet) was used as a relative measure of the main zone of weathering in the soil profile as well as a measure of the degree of weathering (Arduino et al. 1984).

Another way of quantifying the intensity of soil development is by element calculations. We used a weathering index according to Kronberg and Nesbitt (1981), which describes the degree of mineral weathering, i.e., Si-hydrolysis, accumulation of Al-oxides (A), and cation release and subsequent leaching (B). It is applied to a Cartesian coordinate system in which A and B are defined as below. During the process of weathering, the values of the indices A and B follow the characteristic weathering, paths shown in Figure 1.

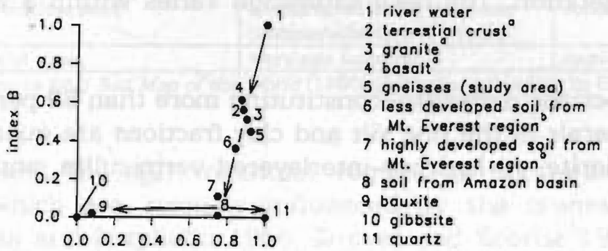

Figure 1: Theoretical Paths of Soil and Rock Weathering (from: Kronberg and Nesbitt 1981; a) data from Wedepohl 1969; b) data from Bäumler et al. 1991.)

$$A = (SiO_2 + CaO + K_2O + Na_2O) / (Al_2O_3 + SiO_2 + CaO + K_2O + Na_2O)$$
$$B = (CaO + K_2O + Na_2O) / (Al_2O_3 + CaO + K_2O + Na_2O)$$

Results and Discussion

Basic analytical data of the investigated soil profiles are given in Table 1. The soil pH is very acid in all horizons (3.6 - 5.6), and this is due to the parent material. The pH usually increases with increasing soil depth. The upper soil horizons are characterised by high contents of organic carbon (2 - 14%) and total nitrogen (0.1 - 1.1%), and this is mainly due to the former forest cover of almost all sites. Some of the soil profiles show a second maximum of C_{org} or N_{tot} in the subsoil horizons, indicating translocation processes, which are typical of podsolization.

Table 1: Analytical Results of the Soils from Central and Eastern Nepal

Parent material	glacial and glaciofluvial deposits of metamorphic rocks (gneisses, migmatites, mica schist), partly covered by eolian deposits
Soil types	Regosols and leptosols (entisols), cambisols (inceptisols), podzols (spodosols), acrisols/alisols (ultisols/alfisols), ferralic paleosols
% Carbon in Ah	2-14 %
C/N-ratio	13-25
Soil reaction	very acid to moderate acid (pH between 3.6 - 5.6)
Base saturation	topsoil horizons: <10 - 96 %; subsoil horizons: <10 - 97 %
Cation exchange capacity	topsoil horizons: 20-220 mmolc kg^{-1}; subsoil horizons: 4-62 mmolc kg^{-1}
Exchangeable cations	Dominance of Al in almost all horizons; in the topsoil horizons, in addition, Ca, K, and Mg
Minerals of the clay and fine silt fractions	quartz, feldspars, mica (illite), chlorite, Al-interlayered vermiculite, mixed-layer minerals

The cation exchange capacity varies between 4 - 220 mmolc kg^{-1}. Its depth function corresponds to the behaviour of C_{org} and clay. Aluminium is the dominant cation at the exchange sites of almost all horizons, while, in addition, Ca, K, and Mg show comparatively high concentrations in the top horizons due to the influence of vegetation. The base saturation varies within a wide range of <10 - 97 per cent.

The sand and silt fractions dominate, constituting more than 80 per cent of most soils. Dominant minerals of the fine silt and clay fractions are quartz, feldspars, mica (illite), and chlorite, Al-hydroxe-interlayered vermiculite, and mixed-layer minerals.

The analytical results show a clear differentiation of the investigated soils due to elevation. In both study areas, brown-coloured inceptisols (cambisols) dominate below 3,000masl, while the region above 4,500m and erodible sites are characterised by shallow and stony entisols (regosols/lepsotols) at initial stages of development. Podzolised soils are mainly located between 3,000m and 4,500masl. This is in good agreement with the results of Hormann (1974), Franz and Müller (1978), and Righi and Lorphelin (1986) who also demonstrated a relationship between soil types and altitude in other regions of the Himalayas.

Soil type distribution corresponds well to altitudinal zones of vegetation, being the result of climatic differences, especially temperature, which strongly influence processes of physical weathering and clay mineral formation (Table 2). The hill region between 1,500 and 2,000m, with deciduous mixed forests of different *Quercus* species, and the deciduous and evergreen mixed tropical mountain forests are characterised by brown-coloured inceptisols (US Soil Taxonomy 1994) and cambisols (FAO 1990) respectively. Ultisols/alfisols (alisols or acrisols according to FAO 1990), which are characterised by clay migration and argillic B-horizons, can additionally be found in the hill region. Podzolised soils dominate in the sub-alpine and alpine zone with coniferous and *Rhododendron* forests and dwarf bush vegetation. The upper tropical mountain zone marks a transitional zone. Shallow, stony soils with initial soil formation dominate in the alpine mountain zone above the forest line and in the zone of alpine turf vegetation. According to our own observations and to the studies of Hormann (1974) and Franz and Müller (1978), the tropical and sub-tropical zone below 1,500-2,000m with coniferous mixed forests of *Pinus roxburghii* and semi-deciduous forests of *Shorea robusta* are mainly characterised by red-coloured soils, rich in clay and iron oxides (oxisols/ferralsols).

Table 2: Bioclimatic (altitudinal) Zones with Characteristic Soils and Vegetation Cover

Altitude	Bioclimatic Zonation	Soils*	Vegetation
6,000m	climatic snowline (5,000-6,000m)	frost debris	
5,000m	alpine zone	regosols and leptosols (entisols)	alpine turf vegetation
	alpine zone forest line (3,800-4,200m)	regosols and podzols (entisols, spodosols)	dwarf bush vegetation
4,000m	Sub-alpine zone	podzols (spodosols)	coniferous forests
	upper tropical mountain zone	cambisols and podzols (inceptisols, spodosols)	mixed forests
3,000m	lower tropical mountain zone	cambisols (inceptisols)	deciduous and evergreen mountain forests
2,000m	hill zone	cambisols and alisols/acrisols (inceptisols and ultisols/alfisols)	deciduous mixed forests
	Sub-tropical zone	alisols/acrisols and ferralsols (ultisols/alfisols and oxisols)	coniferous mixed forests
0-1,000m	tropical zone	ferralsols (oxisols)	semi-deciduous forests

* Soil types according to FAO *Soil Map of the World* (1990); soil types according to US Soil Taxonomy (1994) in parenthesis

Soil development in high mountain regions is controlled by processes of weathering, which are strongly influenced by the orographic situation and elevation (Righi and Lorphelin 1986, Drever and Zobrist 1992), i.e., the lower the location of the soil profiles, the more intensive the conditions of weathering. This is clearly shown in Figure 2 by the relationship between elevation and the clay content of the main zone of weathering in the solum of soils developed from Holocene deposits and deposits of the last glaciation. It can be described by the equation y=29.71-5.27*10-3.x (r=-0.77**; n=36 (y: clay content, x: elevation). This means an average decrease of the clay content of 5.3 per cent per 1,000m for the two study areas between 2,500m and 5,000masl. By comparison, the thermal gradient amounts to 5.4°C per 1,000m (Dobremez 1976).

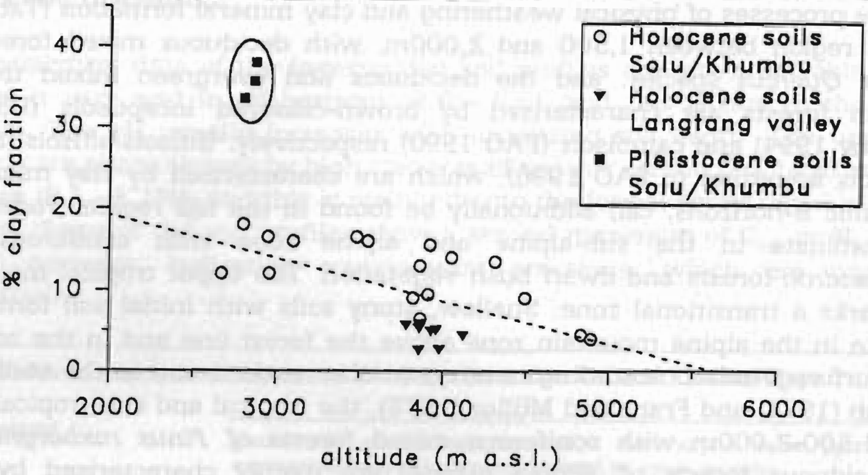

Figure 2: Correlation between Clay Content in the Main Zone of Weathering of the Examined Soils and the Elevation of the Corresponding Locations

The results indicate a significant influence of the elevation on soil development in the high mountain areas of Khumbu and Langtang Himal. Physical (increasing clay content) as well as chemical alterations (podzolisation) influence soil development even at higher elevation. Temperature variations are probably the main agency of physical weathering and, in combination with monsoon precipitation during the warm summer months, the main agency of chemical weathering processes. This is confirmed by Drever and Zobrist (1992) who demonstrated a decrease in the intensity of silicate hydrolysis and Si-leaching as a function of soil thickness and temperature with increasing elevation in the mountains of the southern Swiss Alps. Silicate hydrolysis is also one of the main chemical weathering processes in Central Nepal between 2,700m and 4,000masl (Righi and Lorphelin 1986). The two studies and our present results show that an application to other regions of the Himalayas and to high mountain areas in general seems possible.

To compare different soils or locations with regard to soil development and relative age, the zone or the horizon exhibiting the maximum intensity of weathering within soil profile can be used. This maximum is characterised by the highest degree of formation of pedogenic or crystalline Fe-oxides. Topsoil maxima are typical of an early or short period of soil formation, as is shown for soils developed after the last main glaciation (Arduino et al. 1984). With increasing soil age, the main zone of weathering moves downwards to subsoil B horizons (Levine and Ciolkosz 1983).

Based on iron fractionation and weathering indices, the examined soils can be separated into different soil development groups independent of the influence of elevation. The results are shown in Figures 3, 4, and 5. The soils developed on the right slope of the Beni *Khola* (Solu Valley) opposite the village of Ringmo were used as representative examples (profiles 6-8). The soil depth as a function of the iron fractions and the Fe-index of crystalline oxides to total iron.

$Fe_{d\text{-}o}/Fe_t$, are illustrated in Figure 3. Within profile 6 (typic ustochrept), developed from glacial deposits and located at a downslope position, the highest Fe-index value is in the A horizon. In contrast, profiles 7 (dystric ustochrept over red-coloured paleosol) and 8 (typic haplustult), which are located at a middle slope position about 200m above profile 6, show higher contents of Fe_t and Fe_d. In addition, their index maximum is located in the subsoil Bt horizons.

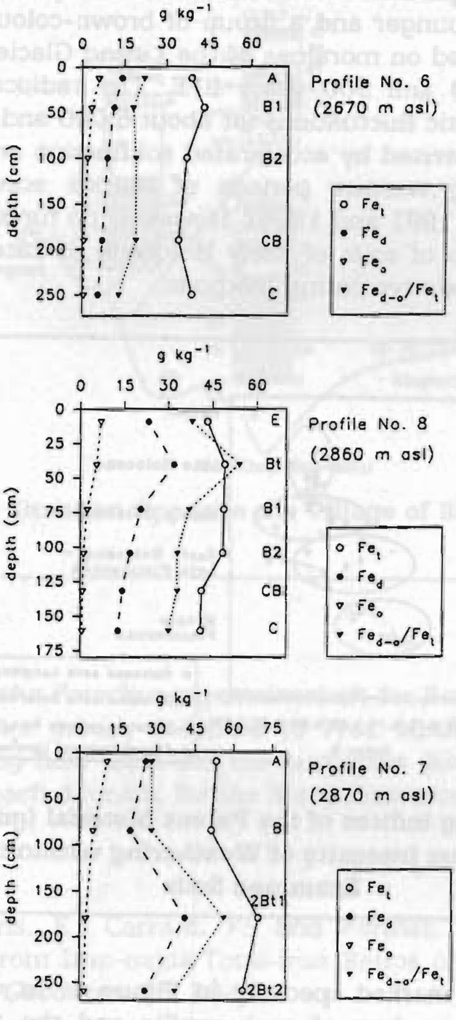

Figure 3: Soil Depth Function of Total (Fe_t), DCB-soluble (Fe_d), Oxalate-soluble (Feo) Iron, and the Ratio of $Fe_{d\text{-}o}/Fe_t$ of Three Soil Profiles in the Solu Valley Opposite Ringmo Village

The results indicate a differentiation into two groups of soils with different soil development: one group of younger soils with their main zone of weathering in the top horizons, represented by profile 6, which were developed from deposits from the last main glaciation or from the Holocene, and another group of considerably older, highly weathered soils-presumably of interglacial origin (Bäumler et al. 1991).

Similar results are obtained using the weathering indices A and B (Fig. 4). Comparable to the results of the Fe-index, and in combination with absolute age dating by radiocarbon analysis, four generations of soils can be differentiated: soils developed from the Late Holocene, Middle Holocene, Early Holocene/Late Pleistocene, and from Middle Pleistocene deposits. The radiocarbon analyses were carried out on charcoal and buried A horizons. According to them the group of young soils could be separated into initial soils developed from deposits of the 'Little Ice Age' or even younger and a group of brown-coloured inceptisols and spodosols. Those developed on moraines of the Lirung Glacier (Langtang Valley) deposited between 3,100 and 500 years BPE. The radiocarbon data provide further evidence on climatic fluctuations (at about 6,000 and 4,000 years BPE in both study areas) characterised by accelerated solifluction and the deposition of eolian material following warmer periods of humus accumulation and soil formation (Bäumler et al. 1991 and 1996). However, no further differentiation is possible within the group of soils of Early Holocene to Late Pleistocene origin according to the applied relative dating methods.

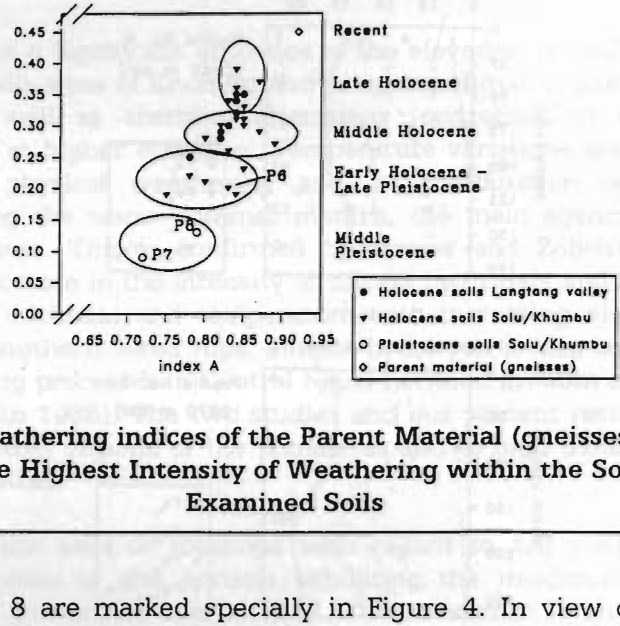

Figure 4: Weathering indices of the Parent Material (gneisses) and the Horizons of the Highest Intensity of Weathering within the Solum of the Examined Soils

Profiles 6, 7, and 8 are marked specially in Figure 4. In view of the horizon differentiation within the solum of each profile and the theoretical paths of physical and chemical weathering shown in Figure 1, the location of the indices of the three soils in Figure 4 indicate three different age generations, with profile 6 as the youngest and profile 7 as the most intensively weathered soil.

The significance of these results becomes clearer in light of the location of these three soils on the slope opposite Ringmo illustrated in Figure 5. We found the most intensively, extremely-weathered deposits (red-coloured paleosol/oxisol) at the highest slope position, just ten metres above the next younger generation of soils (ultisol), represented by profile 8. Only 200m downslope we found the least developed of the three soils (profile 6; inceptisol) derived from moraine deposits presumably of the last main glaciation. The special situation of this site provides clues about the history of climate and landscape, given that profiles 7 and 8 are preserved and were not truncated or completely destroyed by ice erosion. Based on the assumption that the moraine deposits from which profile 6 developed were deposited during the maximum extent of the last glaciation, the results and the intensity of weathering of profiles 7 and 8 point to at least two interglacial periods.

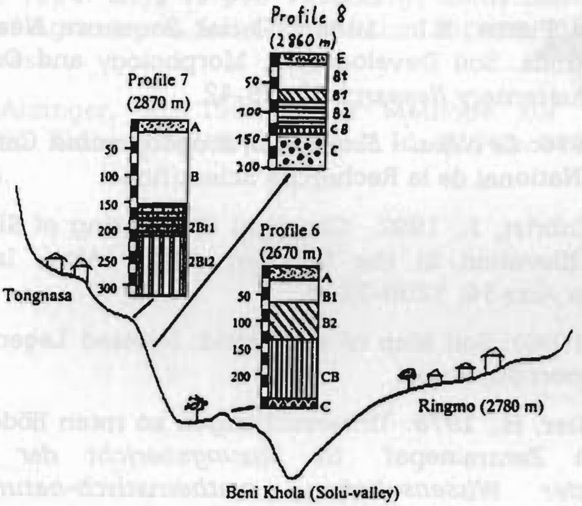

Figure 5: Site Situation Opposite the Village of Ringmo (Solu Valley)

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