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An Investigation of the Intensity of Weathering of Soils developed from Glacial and Glaciofluvial Deposits and their Relationship to the Glacial History of Central and Eastern Nepal

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An investigation of soil genesis on glacial and glaciofluvial deposits was carried out in order to quantify the intensity of soil development. The degree of weathering was for a relative estimation of the age of the deposits and subsequently for an interpretation of the glacial history of the landscape. In addition we want to reduce the great lack of information on soils and soil development in the areas mentioned above.

Our working areas included the Langtang Valley, the Helambu-Gosainkund region in Central Nepal and the Solu-Khumbu region in Eastern Nepal.

INTRODUCTION

The present study is based on work by *Heuberger* (1956, 1984, 1986) and *Heuberger & Weingartner* (1985) on Pleistocene and Holocene glaciation in Eastern and Central Nepal.

Former glaciations in the Langtang Valley have been discussed by various authors. *Franceschetti* (1968), *Vivian* (1971) and *Usselmann* (1980) described several moraines and associated terraces in this main valley. *Heuberger* (1984) first identified several glacial advances in the valley and assigned them to main- and late-glacial stages. *Ono* (1985, 1986) also differenciated three terrace systems with the associated moraines, which he thought to be of late-glacial origin. In addition, after his calculations the age of the maximum advances of the Little Ice Age in the Langtang Valley should have been 1815 AD, and he identified neoglacial moraine ridges probably dating from about 2800 yr BP.

Shiraiwa & Watanabe (1991) published the most recent work on glaciation in the Langtang Valley. By means of relative dating methods and ^{14}C-datings, they classified the moraines into five stages. The Ghora Tabela Stage is defined by the deeply weathered so called Lower Till extending down to 3200m a.s.l. . The Langtang Stage (3650-3000 ^{14}C yr BP) corresponds, according to *Shiraiwa & Watanabe* (1991), to the greatest advance in the Holocene, followed by a series of smaller advances in the Lirung Stage (2800-550 ^{14}C yr BP), and finally by the two smaller Little Ice Age advances (Yala I and II Stages).

The main difference between the authors concerns the dating of he glacial advances. *Heuberger* (1984) and *Ono* (1986) correlated the moraine remnants near Kyangjin to late glacial events, whereas *Shiraiwa & Watanabe* (1991) dated them to Neoglacial or Little Ice Age. All authors are of the opinion that the maximum extent of the last main glaciation reached down to 2400-2600 m, marked by a clear bending point of the valley. There the glacial trough configuration ends.

The glacial history of the Khumbu region has also been discussed by several authors. The first observations were published by *Heuberger* (1956), with reference to the valleys of Nangpo Tsangpo and Imja Dranka. He found that in the Nangpo Tsangpo valley the main valley glacier stopped a long distance upvalley during the late glacial period. Therefore the moraine ridges at Thame were deposited by tributary glaciers of the Thame Valley from Kongde Ri. *Fushimi* (1977, 178) investigated the moraine ridges near Pheriche (4243 m). He distinguished between three moraine systems corresponding to different advances: After a minimum date of 1200 years BP at the top he supposed the moraine to be of Holcene age. *Heuberger* (1956) estimated the same wall system to be late glacial, whereas *Röthlisberer* 1986) supposed that it corresponded with the advances of the main glaciation. Further, *Heuberger & Weingartner* (1985) give an overview of the extent of the last main glaciation in the Khumbu area. The maximum advance reached the village Ghat (2500 m). In addition, *Heuberger* (1986) found several signs of a second and perhaps third main glaciation in this area.

WORKING AREAS

Langtang valley

The Langtang Valley is located about 60 km north of Kathmandu. It is surrounded by mountains ranging in elevation from 5000 to 7200 m and belongs to the Inner Himalaya. The Langtang Khola drains the area to the west and flows into the Bhote Kosi at 1480 meters.

The geological conditions are largely uniform. The parent rock of the whole valley are gneisses (*Shiraiwa & Watanabe* 1991).

A monsoom climate is predominant with the highest precipitation from June to September. In the winter and spring season further important rainfalls are registered. At Kyangjin annual precipitation is about 1220 mm, the mean annual temperature is +2.7°C. The climatic snow line is at about 5300 m (*Miehe* 1990).

Because of intensive pasturing and the cutting of firewood, the forest vegetation in the upper part of the valley has been destroyed, and the vegetation cover now consists of dwarf bushes.

A small population of about 570 people lives in the valley. Agriculture (barley, buckwheat, potato) reaches heights of 3540 m, but the main source of living consists of pasturalism (dairy farming) and tourism.

Helambu and Gosainkund

The Helambu and Gosainkund regions are situated to the south of the Langtang Valley. They are separated from the Langtang Valley by a mountain range with peaks of between 5000 and 6800 m. With respect to the geographical situation and the climate, Helambu and Gosainkund belong to the 'Himalayan South Side'.

Helambu

The investigation area extended over the upper part of the Melamchi Khola valley. The uppermost part of the valley is formed by a geest called Pemdang (3550 m) and it was dammed by a huge moraine in the south, consisting of big boulders. Downvalley the Melamchi Khola becomes more narrow. The steep slopes are partly interrupted by small terraces between 2500 and 2900 m.

Acid gneisses are dominant. The climate is humid with an estimated annual precipitation of about 3500 mm. The highest precipitation is during the monsoon period in the summer. The mean annual temperature is +4-5°C at Pemdang with a temperature gradient of 0,58°C/100 m (*Miehe* 1990). The highest permanent settlement is the monastery of Neding (3000 m). The region is covered by forest vegetation. In the lower parts Abies spectabilis and Rhododendron specc. are dominant. Places which have been destroyed by fire have a bamboo-vegetation. In the upper part (Pemdang) Betula utlis, Juniperus recurva and Rhododendron campanulatum become more abundant.

Gosainkund

The area of Gosainkund consists of three stepped cirque lakes at an altitude of between 4080 and 4380 m. The surrounding peaks reach altitudes of between 4800 and 5100 m. Each lake is dammed by a moraine ridge. Additional moraine ridges can be found around the upper lake (Gosain Kund, 4380 m). There is also a roche moutonnée south of the Gosain Kund lake.

Climatic data are not available for this region. The climatic conditions are, presumably, comparable to those of Helambu, but precipitation and annual mean temperature are probably lower because of the altitude. The precipitation is estimated at about 2500 mm and the mean annual temperature is around 0°C. The working area is situated above the limit of forest growth. The vegetation consists of low bushes, grass, moss and lichens. The area is intensively grazed. The small village of Gosainkund with 2-3 households is a permanent settlement. At the end of July there is a big festival in honour of of Shiva, attended by thousands of Hindu and Buddhist pilgrims.

Solu-Khumbu

The high mountain landscape to the south of Mt. Everest consists of a main valley system and a few side valleys draining the area to the south. The relief is formed by Pleistocene glaciation and by tectonic-lithological structures, which have been affected by the river system. (*Vuichard* 1986). Our working area includes the upper part of the high valleys of Dudh Kosi, Beni Khola and Basa Dranga (Solu) and their respective spring valleys of Imja Drangka, Nangpo Tsangpo and Dudhkunda Khola.

The landscape is characterized by deeply carved valleys with steep slopes. A monsoon climate is predominant with a rainy season from June to September. In our working area precipitiation decreases from the south (2742 mm near Luglha; *Haffner* 1979) to the north (1030 mm at Namche Bazar; *Dobremez* 1976). Temperature mainly depends on height and local climatic conditions. At Namche Bazar, the mean annual temperature is +7°C (1964-1968; *Dobremez* 1976). The climatic snow line is at about 5700 m. In this region migmatitic igneous and basal paragneisses are the dominant initial rocks (*Vuichard* 1986).

MATERIALS AND METHODS

The locations of all soil profiles were selected according to morphological criteria. They are described in detail in *Bäumler* (1988), *Bäumler et al.* (1991), *Siebert* (1992) and *Kemp* (1992).

Langtang Valley

The working area was situated near Kyangjin at 3980 m in the upper part of the valley, where a tributary glacier (Lirung glacier) meets the main valley. Samples were taken from the high end moraine of the Lirung glacier and from two moraine ridges belonging to the moraine wall system in front of the end moraine. Further profiles were situated on the Kyangjin terrace, a moraine ridge near the airstrip deposited by the main glacier (Langtang glacier) and a further moraine ridge situated 120 m above the valley floor on the southern slope, believed to be a lateral moraine of the Langtang glacier.

Helambu and Gosainkund

In the area of Helambu three locations were studied. One was the moraine at Pemdang, the second was the soil on a terrace at Badja, a summerhut at 2950 m, and the third was a ridge between Badja and Neding. In the Gosainkund area, the moraine damming the lowest lake, Saraswati Kund (4080 m), a moraine on the east slope 80 m above the Gosain Kund lake and a medial moraine on the north side of the roche moutonnée were investigated.

Solu-Khumbu

25 soil profiles, mainly developed from glacial and glaciofluvial deposits, were sampled at different locations between 2670 m and 4900 m. Part of the working area is covered by eolian material of recent and Pleistocene origin.

ANALYSES

Analyses were carried out on air dried samples of the fine earth fraction <2mm. They included the pH, content of organic carbon and nitrogen, cation exchange capacity, exchangeable cations, fractionation of pedogenic iron oxides and particle size distribution. In addition, an analysis of the total element contents was made by X-ray-fluorescence. Further, several fossil soil horizons in the Langtang valley were sampled for radiocarbon dating (^{14}C).

The content of total pedogenic iron oxides, compared with the total Fe-content (Fed/Fet) and the content of well-crystallized Fe oxides compared with the total Fe content (Fed-o/Fet) were used to characterize the main weathering zone in the soil profiles.

The degree of soil weathering was quantified by a weathering index according to *Kronberg and Nesbitt* (1981). This index describes the degree of mineral weathering (cation leaching and desilication). It is applied to a cartesian coordinate system, where abscissa and ordinate are defined as follows:

$$\text{Abscissa} = \frac{(SiO_2 + CaO + K_2O + Na2O)}{(Al2O3 + SiO2 + CaO + K2O + Na2O)}$$

$$\text{Ordinate} = \frac{(CaO + K2O + Na2O)}{(Al2O3 + CaO + K2O + Na2O)}$$

RESULTS

Langtang Valley

All profiles show low pH-values between 4 and 5, thus reflecting the climatic conditions and the acid substratum. Due to the former forest cover, the contents of organic carbon are high (8-15% organic material). Particle size analysis show a clear dominance of sand fractions. Several profiles are covered by eolian material with high contents of fine sand and very coarse silt. Fe-fractions of the more intensively weathered soils clearly show podzolisation by maxima in the illuvial horizons.

The radiocarbon datings dated the deposits to between 3100 and 450 yr BP, which agrees very well with the datings given by *Shiraiwa & Watanabe* (1991). Three glacial advances could be distinguished during this period. By means of the results of the weathering indices and the ^{14}C datings, the following conclusion could be drawn according to soil development and the age of the glacial deposits: The profile on the end moraine of the Lirung glacier, classified as a Dystric Regosol, clearly represents the least developed soil profile. It shows the lowest content of organic carbon, the lowest cation exchange capacity, and the degree of acidification measured by the exchangeable cations is low as well as the degree of formation of pedogenic iron oxides. These results are confirmed by the results of the weathering index. According to the glacial chronology of *Shiraiwa & Watanabe* (1991), the moraine wall dates from advances of the Little Ice Age, probably around 1815 AD.

The profiles on the two moraine ridges situated just in front of the described end moraine, both classified as Dystric-Regosols, show a very similar degree of weathering. Compared with the profile on the end moraine, they show the initial development of a brown coloured B-horizon. The weathering index also classifies these two soil profiles as very young soil formations. According to the glacial chronology, the two profiles developed on deposits of the Lirung Stage (2800-550 yr BP). To get a better idea of the age of the profiles, we compared them with the profile of a terminal moraine near the airstrip. The beginning of the development of this profile, classified as a Haplic Podsol, could be dated by ^{14}C to 2500±115 yr BP. In contrast with the profiles on the Lirung moraines, this soil shows clear signs of podzolisation. The weathering index also classifies it to be more developed. In consequence, the profiles on the Lirung moraines are considerably younger and thus probably date from the end of the Lirung Stage (around 550 yr BP).

The profile on the Kyangjin terrace shows a more pronounced development than the profiles on the Lirung moraines. This means that the accumulation of the terrace material is not correlated to the deposition of the Lirung moraines: it must be older. This corresponds with the results of *Shiraiwa & Watanabe* (1991), who correlated the terrace accumulation with the Langtang Stage.

The soil profile of the lateral moraine on the southern slope 120 m above the valley floor shows clear signs of podzolisation. The weathering index proves that it is significantly more intensively weathered than the other profiles of the Langtang valley. According to this, and to its location high above the valley floor, it can be deduced that this moraine has its origin in an older glacial advance. This corresponds with the studies of *Heuberger* (1984) who dated this moraine to be late glacial.

Helambu and Gosainkund

The pH-values of the profiles of the working areas of Helambu and Gosainkund are very low. They vary 3.9 to 4.8. The topsoil horizons of the Gosainkund soils are more acidic. The pH-values reach 3.5. The cation exchange capacity at soil-pH is low. In consequence to the acid pH-value, the exchangeable Al-content is very high. The Al-saturation amounts to 80-90%.

At Pemdang a Typic Haplorthod has developed. It is characterized by high iron content in the B-horizon. No clear maximum of the iron fraction could be shown. The Fe-translocation includes all subsoil horizons while the Al-fractions show a clear maximum in the upper part of the B-horizons. At Badja we could find a loamy profile with clay translocation and clay contents up to 33% in the B-horizons. However the low pH-value in the profile indicates that the translocation process cannot take place currently. This soil is classified as a Haplic Alfisol. At 3100 m at the ridge between Badja and Neding, another loamy textured profile is located. In spite of the loamy texture, this soil shows translocation of iron and aluminium and is classified as a Haplic Podzol.

The estimated snow line depression, which corresponds to the moraine of Pemdang, amounts to about 500 m. Snow line depressions of this extent have also been calculated for late-glacial advances in the Alps (*Maisch* 1982). This consideration agrees with the results of the iron fractionation and the weathering indices. Therefore the moraine of Pemdang is estimated to be late-glacial. The profiles at Badja and Neding are both intensively weathered. The weathering indices show a higher degree of soil development in comparison to the other soils of Helambu and Gosainkund. It is possible that both profiles have not been reached by the ice of the last main glaciation.

In the Gosainkund area all profiles show a surface layer of fine textured material, but the current dominant pedological process is podsolization. There are now two different possibilities to explain the origin of the surface layer. On the one hand, highly weathered material could have been deposited, e.g., by eolian transport. On the other, clay minerals could have been formed in situ during a warmer period.

The profiles of Gosain Kund lake are all presumably of late-glacial origin. This could be shown by the weathering indices as well as by considerations of the snow line depression in this area. It is possible that the profile on the moraine damming the lowest lake (Saraswati Kund), which contains 27% clay, might be older.

Solu-Khumbu

The pH values of all soils are very low (4.0-5.6) and normally increase with increasing soil depth. Because of the acid substratum, the cation exchange capacity values are also very low, depending on the content of clay and organic carbon. Part of the soils show second maxima of organic carbon and pedogenic oxides in the subsoil horizons indicating stratification of the solum or translocation processes, which are typical for podzolisation. Otherwise, they decrease continuously with increasing soil depth. Sand and silt fractions dominate mainly with

more than 80% in all soils. They are classified as Podzols, Acrisols, Leptosol, Cambisols, and Regosols.

According to the results of the iron fractionation and of the weathering indices, the soil profiles can be separated into two groups: one group of younger soils with their maxima of weathering in the topsoil horizons, and one group of intensively weathered soils with their main zone of weathering in the subsoil horizons. The position of the main zone of weathering of a greater depth indicate considerably longer, probably interglacial periods of soil development. This was in full agreement with higher clay contents (up to 40%) in the group of old soils.

Furthermore, a clear differentiation of the soils could be shown due to the altitude and bioclimatic zones, which strongly influence processes of physical and chemical weathering. Cambisols, Alfisols and Acrisols predominate in the hill and lower tropical mountain zones between 2000 and 3000 m. The subalpine and alpine zones with coniferous and Rhododendron forests and dwarf bush vegetation is characterized by podzolised soils. The alpine zone above the forest line (4000-4200 m) and sites of erosion normally yield shallow and stony Regosols or Leptosols.

Within the group of young soils, developed from deposits of the last main glaciation or even more recently, a linear correlation between soil development and altitude could be shown. There is an average decrease of 3.5% clay per 1000 m for the working area between 2500 m and 5000 m. This is parallel to the thermal gradient (0.54°C/100 m; *Dobremez* 1976) indicating that climate conditions are the main controlling factors of weathering processes and soil development in high mountain regions.

A clear indication of the history of the landscape is given by the location of soils with different ages and intensity of weathering near Monjo in the Dudh Kosi valley and opposite Ringmo in the Beni Khola valley. Intensively weathered soils of presumably interglacial origin were situated at higher altitudes than soils developed from deposits of the last ice age. This might give indications of ice marginal grounds, as the old deposits are completely preserved and were not truncated by ice erosion during the last main glaciation.

Acknowledgements

The author thanks the Deutsche Forschungsgemeinschaft (Bonn) and the Fonds zur Förderung der wissenschaftlichen Forschung (Wien) for financing the fieldwork and part of the analyses in 1987 and 1991. We are greatly indebted to Prof. Weber-Diefenbach, München, for the X-ray fluorescence analyses.

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