ORIGIN AND PROPERTIES OF

THE SOILS OF

PHOBJI-GANGTEY VALLEY

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Royal Government of Bhutan

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<td>Description</td>
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<tr>
<td>AMS</td>
<td>Accelerator Mass Spectrometry, special kind of $^{14}$C measurement</td>
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<tr>
<td>a.s.l.</td>
<td>above sea level</td>
</tr>
<tr>
<td>BET</td>
<td>laboratory measurement for determining the specific surface area</td>
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<td>BGS</td>
<td>Bhutan Geological Survey</td>
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<td>BHU</td>
<td>Basic Health Unit</td>
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<tr>
<td>BNC</td>
<td>Black-necked Cranes (<em>Grus nigricollis</em>)</td>
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<tr>
<td>BNPP</td>
<td>Bhutan National Potato Program</td>
</tr>
<tr>
<td>BP</td>
<td>before present</td>
</tr>
<tr>
<td>BSS(P)</td>
<td>Bhutan Soil Survey (Project)</td>
</tr>
<tr>
<td>CEC</td>
<td>cation exchange capacity</td>
</tr>
<tr>
<td>DANIDA</td>
<td>Danish International Development Assistance</td>
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<td>FAO</td>
<td>Food and Agricultural Organisation of the United Nations</td>
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<tr>
<td>FYM</td>
<td>farmyard manure</td>
</tr>
<tr>
<td>GNH</td>
<td>Gross National Happiness</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>ICDP</td>
<td>Integrated Conservation and Development Programme of the RSPN</td>
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<tr>
<td>ICP-OES</td>
<td>Inductively coupled plasma optical emission spectroscopy</td>
</tr>
<tr>
<td>LGM</td>
<td>Last Glacial Maximum</td>
</tr>
<tr>
<td>Ma</td>
<td>million years</td>
</tr>
<tr>
<td>MoA</td>
<td>Ministry of Agriculture, Thimphu</td>
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<td>NAA</td>
<td>Neutron Activation Analysis</td>
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<td>NCS</td>
<td>Nature Conservation Section</td>
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<td>NSSC</td>
<td>National Soil Services Centre, Simtokha</td>
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<tr>
<td>PSD</td>
<td>particle size distribution</td>
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<tr>
<td>RGoB</td>
<td>Royal Government of Bhutan</td>
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<td>RNR(RC)</td>
<td>Renewable Natural Resources (Research Centre)</td>
</tr>
<tr>
<td>RSPN</td>
<td>Royal Society for the Protection of Nature, Thimphu</td>
</tr>
<tr>
<td>SPAL</td>
<td>Soil and Plant Analytical Laboratory, Simtokha</td>
</tr>
<tr>
<td>TUM</td>
<td>Technical University of Munich, Germany</td>
</tr>
<tr>
<td>WRB</td>
<td>World Reference Base for Soil Resources (FAO)</td>
</tr>
<tr>
<td>XRA</td>
<td>X-ray attenuation (laboratory measurement for determining the PSD)</td>
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<tr>
<td>XRD</td>
<td>X-ray diffraction (laboratory measurement for identifying clay minerals)</td>
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SUMMARY

In autumn 2001, a detailed soil survey was conducted in the Phobji-Gangtey valley under Wangdue-Phodrang district as part of the ongoing collaboration between the National Soil Services Centre (NSSC) in Simtokha, Bhutan and the Technical University of Munich (TUM), Germany. The soils in this region are of special interest, because they constitute Bhutan’s main potato cropping area, and the unusual morphology of the valley system might allow insights into its landscape and climate history.

21 soil profiles were established, described and sampled. A total number of 128 samples was transferred to Germany where most of the geochemical measurements were conducted.

The local geology is dominated by low grade crystalline sediments of Precambrian age (Chekha formation); remnants of fossiliferous marine sediments occur close to Taphu. During our study, no evidence for glacial activities could be found, however periglacial features like blockfields and asymmetric valley profiles were observed.

Most of the material representing today’s soils has been deposited during the Quaternary period (since 2 Ma). The influx of aeolian material by strong up-valley winds during dry seasons and the counteracted discharge with monsoonal rainfall, lead to a “local cycle” of aeolian sediments which appears to have been the dominant factor in soil formation. This process only slowed down when a dense forest cover was in place during the Holocene climate optimum (approx. 5000 years BP), leaving evidence in the form of impressive, now buried topsoil horizons in many parts of Phobji-Gangtey valley. The subsequently colder climate but also human appearance and associated deforestation, agricultural and grazing activities, resulted in the re-establishment of the aeolian cycle and rendered grassland as the climax vegetation outside of the forests. Clay mineral analyses and evaluation of soil texture data have shown that the subsoil and topsoil properties are similar, suggesting that the material’s source is more or less local.

Typical main characteristics of the Phobji-Gangtey soils include

- low bulk densities (often below 0.7 g cm$^{-3}$)
- low pH and CEC, reflecting the acid nature of the underlying granitic and phyllitic schists
- shallow A horizons but high $C_{org}$ contents often down to more than 1 m depth
- bright orange subsoil colours, and
- frequent occurrence of thixotropic features.

Below the buried topsoil horizons, translocation of clay and sometimes also organic material was commonly observed.

Within the WRB system most of the analysed soils would qualify for Andosols, and regarding their presumably aeolian origin, an additional reference soil subgroup named “Aeolic Andosols” is proposed.

Regarding their agricultural use, the above characteristics generally provide favourable conditions. To buffer the increasing pressure on the soils resulting from population growth and land use changes, sustainable development of the valley’s soil resources should be the focus of all development efforts. Beneficial indigenous techniques like high organic matter input will have to be maintained and supplemented by erosion control, careful liming and reconsidering the current use of pesticides. Educating farmers and providing them with additional sources of income are also among the priorities.

It is concluded that Phobji-Gangtey valley with its unique natural setting (e.g. Black-necked Cranes) and income-generating agricultural activities may even become an exemplary region, where conflicts between agricultural production and environmental conservation are resolved, thus coming a step closer to the overall aim of Gross National Happiness.
ACKNOWLEDGEMENTS

The field work was done by Dr. Rupert Bäumler, Kado Tshering, Thomas Caspari and Phub Tshering, with active physical support by the local farmer Lemi. We are grateful to the Ministry of Agriculture for granting the necessary permissions and to the people of Phobji and Gangte for facilitating our field work with their help and friendliness.

The credits for the bulk density measurements go to Jamyang from SPAL and his colleagues. The geochemical analyses were performed at the Soil Science Institute of the Technical University of Munich, Germany, by Thomas Caspari with support from Ulrike Maul and student helpers.

This report was prepared by Thomas Caspari. He is grateful to Chencho Norbu, Tshering Dorji, Austin Hutcheon, Ian Baillie and Rupert Bäumler for their reviews and helpful comments.

Sarah Harding is kindfully acknowledged for her information on the cultural history of Bhutan.
1 INTRODUCTION

1.1 Bhutan Soil Survey Project

The Bhutan Soil Survey Project (BSSP) was set up by an agreement signed in September 1996 by the Royal Government of Bhutan (RGoB) and the Danish International Development Assistance (DANIDA). It was initiated because of a perceived need for systematic information about the nature and distribution of the soils of Bhutan. The project is part of the National Soil Services Centre (NSSC) of the Research, Extension and Irrigation Division (REID) in the Ministry of Agriculture (MoA). It began field activities in June 1997.

The emphasis in the initial stages of the project was on training of Bhutanese nationals as soil surveyors, and the establishment of a functioning soil survey organisation. The main method of training is on-the-job instruction and close supervision of actual soil surveys, carried through from initial planning to final presentation. In the early stages detailed surveys are best for instruction purposes. They enable soil patterns to be worked out by direct observation and with the minimum of extrapolation and assumptions.

During the initial phase of fieldwork, which included soil sampling, basic analyses and soil survey on selected sites, more and more questions arose: Where does the material for soil formation come from? Which processes have lead to the soils we observe today? What can the soils tell us about former environmental and climate changes in Bhutan?

1.2 Cooperation between BSSP and Technical University of Munich

To clarify aspects of soil genesis of high altitude and alluvial soils in Bhutan, a collaborative research was initiated in 1999 between the BSSP and the Soil Science Institute of the Technical University Munich (TUM), Germany. The soils of Bajo RNR-RC and soils developed on fluvial terraces in the Chamkhar Chhu valley north of Jakhar were subject of the first joint research trip in autumn 2000. The present report contains the findings and interpretation of the second excursion which lead to the Phobji-Gangtey valley system, central Bhutan. A final expedition in 2002 lead to the eroded landscape around Tshogompa, Wamrong, East Bhutan (Wangchuck 2003).

1.3 Aims of the soil survey in the Phobji-Gangtey valley

The Phobji-Gangtey valley belongs to the southern part of the “North-South valleys and ranges of western and central Bhutan” as defined by Norbu et al. (2003). Typical valleys in this section were formed by the main rivers draining the southern slopes of the Himalaya, and would have wide lower reaches and moderate slopes within the inner basins at an altitude between ca. 2000 and 3000 m a.s.l. Here lies the Bhutanese cultural heartland and at the same time one of the main zones of agricultural activity within Bhutan, making use of the sediments on the river terraces and floodplains which have accumulated over time.

Phobjikha is insofar unusual, as it is not connected to one of the major river systems. Nevertheless it is of considerable agricultural significance: after having traditionally been used for grazing, it has now become the main area for potato farming within Bhutan, since the crop was introduced by the Swiss Helevetas in 1968-1970. Until the late 1980s, Phobjikha was the only potato seed multiplication centre in Bhutan.

In this context, it is of high interest, not only to classify and analyse the current state and fertility of the local soils, but also to understand the underlying processes of landscape and soil formation: What are the soil forming materials? Which processes have formed the present soils? What can they tell us about past environmental changes (e.g. the Ice Age) and even human activities within the valley?

Answers to these questions might be able to make a contribution towards the appropriate and sustainable management of the local soils.
2 SURVEY AREA

2.1 Location and general description

Phobji-Gangtey valley is situated in Central Bhutan, a few kilometres south of the Pele La and near the periphery of the north-western tip of the Black Mountains National Park. The geographical coordinates are 27°23’-27°30’ N and 90°10’-90°14’ E.

Two geogs in the Wangdue-Phodrang district, namely Phobji and Gangtey, cover nearly all of the area and therefore we decided to call it the Phobji-Gangtey valley system (Fig. 1). The North-Eastern edge of the examined area already belongs to Sephu geog, and some of the soil profiles in the western part were established in Bjena and Athang geog.

Fig. 1: location of the examination area within Wangdue-Phodrang district

The Phobji-Gangtey valley system is located between 2800 - 4000 m a.s.l., with the bottom of the main valley being at approx. 2900 m a.s.l. and the closest surrounding mountains reaching heights of about 3900 m.

Until the mid-1980’s, the valley was reachable only by horseback or on foot. In the meantime, an unpitched road that diverts at Dhungdhung Nyesa on the Wangdue – Tongsa highway is the main access to the valley. The road continues along the western side of the valley and diverges at Tabiting (see section 6.1). One part carries on further south and ends at Gongpha and the other passes the primary school across to the other side of the valley and ends at Taphu.

The total population within the valley is estimated at 4125, comprising of about 500 households in 37, mainly clustered, villages and an average family size of eight (RSPN 2003). Farmers and students constitute 53% of the population.
Government facilities in the area include a primary school, a newly-built community school at Taphu, a forest beat office, and an upgraded BHU. The Druk Seed Corporation, which has replaced the BNPP (Bhutan National Potato Program), deals with potato farming, distribution of seeds and marketing of the product. Apart from the above there is also an agricultural extension center that includes animal husbandry and pasture development components. At Khebethang, which is located at the southern end of the valley, the Nature Conservation Section (NCS) of the Forestry Services Division has established a nature study centre.

2.2 Climate

There are no meteorological data available yet, and the climate cannot be compared to the much warmer one in Wangdue-Phodrang, where the next meteorological station is situated. The climate can be generally described as cool temperate, and is characterised by moderately warm summers and frosty winters with minimum temperatures around -12°C (RSPN 2003), Fig. 2. July is regarded as the wettest and warmest month, January the coldest.

The mean annual precipitation is around 1500 mm, of which 75% occur during the monsoon, i.e. June-September, mostly as falls of low or moderate intensity. The area receives substantial snowfall in winter.

![Climate chart for Phobji-Gangtey valley](image)

During our presence in autumn 2001, the conditions were dry and warm. Temperatures reached at least 20°C during daytime and towards end of November frost occurred regularly during the nights. Snowfall was observed only once.

2.3 Geology and soil parent materials

So far, only rough accounts of the underlying geology exist. Jangpangi (1978) assigned most of the area between Mo Chhu in the west and Chamkar Chhu in the east to the “Tethyan zone”, consisting of Tethyan geosynclinal sediments upon basement (low grade) crystallines. This he named Chekha formation.

Gansser (1983) further distinguishes between different grades of metamorphism and divides the area into higher grade crystalline units (= Paro metasediments) and lower grade Precambrian sediments (= Chekha formation, incl. Sangsing La formation). The centre of the latter unit consists of the Tang Chu basin, showing a preserved sedimentary section of Palaeozoic age. The southern
extension of these sediments obviously occurs in our research area in a synclinal position between the Pele La pass and the Black Mountain range. Singh (1973) describes strongly weathered fossiliferous sediments discovered south of Taphu, which may have formed during widespread marine transgressions invading the Lesser Himalaya during Upper Permian age (230 Ma). However, the outcrops of this material seem to be rare and therefore of no major influence on soil formation in the Phobji-Gangtey valley.

In 2001, an extensive field survey has been conducted within the examination area by the Bhutan Geological Survey (BGS). However, at the time of finishing this report their results were not yet available.

2.4 Topography and drainage

The valley is aligned along a northwest-southeast axis with two major lateral valleys on the eastern side. The upper lateral valley we called the “Thang/Hal” side valley according to the two major villages. The lower one is referred to as the “Taphu” side valley. Both side valleys show asymmetric profiles, meaning that the S- and W-exposed slopes are significantly steeper in comparison to the ones facing north and east. The formation of this feature can be explained by the differences in insolation, resulting in moisture differences. As a consequence of higher moisture, hanging material on the N- and E-exposed slopes is more likely to slide and thus form gentler slopes. This mechanism is especially active in a permafrost environment, and it is also responsible for the fact that features like paleosols, river terraces or glacial deposits are usually preserved on the W- and S-facing slopes only.

Whereas the bottoms of the lateral valleys are considerably sloped, the upper part of the valley floor (south of Gangtey Goempa) is wide and flat. Especially during monsoon time, water accumulates and it is difficult to cross from one valley side to the other. This mid-valley wetland is composed of marshes vegetated by dwarf bamboo (*Yushania microphylla*).

During fieldwork in November 2001, we observed that the (even small) local streams were constantly supplied with considerable amounts of water, although the last rainfall event had been several weeks (months?) ago, and the watershed area being rather small. This may point to high water holding capacity of the local soils. The frequent occurrence of repository horizons (geological layers associated with frequent occurrence of water springs) may also be another indication for permafrost activities in the course of which the subsurfaces were compacted by solifluction.

2.5 Flora and fauna

Phobji-Gangtey valley offers a wide range of habitats: pristine coniferous forests along the hillslopes, grazed grassland in the lower reaches of the slopes, marshy wetland along the valley bottom and blockfields above 3500 meters offering comparatively dry and sunny conditions. As a result, a high degree of floral and faunal diversity can be assumed.

The following account is based on RSPN (2003), supplemented by our own observations: the valley floor is largely composed of marshes vegetated by dwarf bamboo (*Yushania microphylla*). In the northern valley region, the lower slopes adjacent to the valley floor, are dominated by blue pine (*Pinus wallichiana*) with hard woods such as birch (*Betula utilis*) and several species of rhododendron and maple (*Acer spp.*) in the understory. Higher upslope, the species composition changes to spruce-fir with suppressed hemlock (*Tsuga Dumosa*) and rhododendron in the midstory. The areas of sparse canopy are dominated by hemlock. The understory regeneration comprises of blue pine, dwarf bamboo (*Arundinaria maling*), *Pteridium* fern and herbaceous species such as *Primula sp.*, *Robus sp.*, and *Fragaria sp.* Forests in the southern valley region are richer in hardwoods dominated by birch, maple and rhododendron. On forest edges and along trails, *Daphne*, *Piptanthus*, *Rosa*, *Berberis*, *Vaccinium*, *Enkianthus*, *Euphorbia*, *Cotoneaster*, *Primula* and *Osmunda* species can be found.

The local fauna includes wild boar (*Sus scrofa*), sambar deer (*Cervus unicolor*), muntjac (*Muntiacus munjac*), Himalayan black bear (*Selenarctos thibetanus*), leopard (*Panthera pardus*),
dhole (*Cuon alpinus*), red fox (*Vulpes vulpes*) and red panda (*Ailurus fulgens*). The valley is also supposed to accommodate over 62 species of birds and officially declared as conservation area due to its importance as a wintering ground for the rare and endangered Black Necked Cranes (*Grus nigricollis*) whose summer habitat is in Tibet. Other common bird species observed during fieldwork e.g. include the Himalayan griffon (*Gyps himalayensis*), Common Kestrel (*Falco tinnunculus*), Red-billed Chough (*Pyrrhocorax pyrrhocorax*), Yellow-billed Chough *Pyrrhocorax graculus*, Black-billed Magpie (*Pica pica*), Large-billed Crow (*Corvus macrorhynchos*), Spotted Cracker (*Nucifraga caryocatactes*), Nuthatch (*Sitta sp.*), Tree Creeper (*Certhia sp.*), Little Forktail (*Enicurus scouleri*), several Redstart species (e.g. *Chaimarrornis leucocephalus*, *Phoenicurus frontalis*), Winter Wren (*Troglodytes troglodytes*) and Green-backed Tit (*Parus monticolus*). RSPN (2003) additionally mentions Darjeeling Woodpecker (*Dendrocopos darjellensis*), Rosefinch (*Carpodacus sp.*), Broad-billed Warbler (*Tickellia hodgsoni*), Dark-sided Flycatcher (*Muscicapa sibirica*), Grey-backed Shrike (*Lanius tephronotus*), Mrs Gould’s Sunbird (*Aethopyga gouldiae*), Oriental Turtle Dove (*Streptopelia orientalis*), Blood Pheasant (*Ithaginis cruentus*), Satyr Tragopan (*Tragopan satyra*), Chestnut-breasted Partridge (*Arborophila mandellii*), Hill Partridge (*Arborophila torqueola*), White-tailed Robin (*Myiomela leucura*), Hoary-throated Barwing (*Actinodura nipalensis*), Red-tailed Minla (*Minla ignotincta*) and Laughing Thrush (*Garrulax sp.*).

### 2.6 Land use

The livelihood of almost all households in Phobji-Gangtey valley is based on subsistence agriculture and livestock rearing. Wheat flour and rice constitute the main diet of most people. Livestock products supplement the dietary requirements and wool from sheep is used for clothing products.

The people of Gangtey *geog* are known as *gangteps*. They migrate to lower altitudes during winter as most of the households have land holding and houses at lower altitudes. This is the time when the famous black necked cranes (*Grus nigricollis*) inhabit the valley and live from the animals they find in the swampy parts of the valley bottom. During summer, members of many households are still on a move between their two residences in order to accomplish farm works at both places. Farm works at lower altitude are mainly associated with rice cultivation, which supplements their subsistence and cash crops grown at the alpine altitudes. According to Kado Tshering, the migration is now constantly decreasing, as the availability and use of firewood is increasing.

The people of Phobji *geog* are known as *phobjibs*. They do not migrate and instead cultivate on the slopes that surround the valley. Their livelihood is based on dryland farming and livestock rearing. The major crops grown are wheat, buckwheat, millet and potato. Potato is the most important cash crop and came into the valley in 1972 by Swiss help (Foundation Pro Bhutan). Until late 1980s, Phobjikha was the only potato seed multiplication centre in Bhutan. Today, about 86.3% of the households depend on potato as the main source of income. The harvest is transported all the way to Phuentsholing in southern border to India for auction. Before the introduction of the potato, livestock rearing has been the main agricultural activity, not at least owing to the alpine climate. Livestock is still important for *phobjibs* and *gangteps*. A recent survey of the livestock population in Phobji (RNR Census Statistics 2000) yielded 2061 cattle, 129 horses, 798 pigs, 1110 poultry and 2605 sheep. Yaks are also owned by few of the households. The area is one of the livestock priority areas of Wangdue Phodrang Dzongkhag. The wide-open valley is thought to have a great potential for pasture development. Recently, a new RNR centre with artificial insemination service has been constructed.

Barter is still prevalent amongst the non-migrating residents who barter cane products for rice and chili from people of lower altitudes.
3 PREVIOUS SOILS INFORMATION

To our knowledge, there has been no scientific soil survey within Phobji and Gangte geog prior to our study.

Some general remarks on the local soils can be found in the Ninth Plan geog documents for Phobji and Gangte (RGoB 2002a/b): the soil types in Phobji are described as “sandy loam to clayey loam” and in Gangte as “sandy to sandy loam”. In both geogs the soils are regarded as “generally fertile and good for cropping”.

In the first comprehensive paper on the soils of Bhutan, Baillie et al. (2004) summarised the main soils up to approx. 3000 m in the inner valleys as “moderately weathered and leached” and having “bright subsoil colours and thin dark topsoils”. They note that “above these” (corresponding to the transition from temperate broadleaf or blue pine to mixed conifer forests) “there is a zone of bright orange-coloured, non-volcanic andosolic soils” showing “very pronounced crumb structure, friable consistence” and which “are very porous to below one meter”. The authors mention (daily) freeze-thawing cycles as a main process leading to the observed friability. “Subsoil contents of organic carbon are moderate, possible due to complexation and stabilization of labile aluminium”.

It is finally pointed out that these soils “are similar to the non-volcanic andosols described in Eastern Nepal (Bäumler & Zech 1994) and to cryptopodzolic soils on the southern slopes of the European Alps (Blaser et al. 1996).”

Regarding the role of aeolian deposits, Baillie et al. (2004) state that “many soils in Bhutan incorporate some aeolian deposits, and this contributes to the generally large contents of silt and fine sand, especially in surface layers. […] Deep aeolian deposits give distinctive stone-free soils with large contents of coarse silt and very fine sand, vesicular porous structures, and very low bulk densities. They are most common around valley heads at altitudes of about 2500 – 3000 m”.

Fig. 3: Archaeological site northwest of Gangyu
4 METHODS

An initial period of 3 days was spent to travel the study area (see section 6.1) in order to get a first impression on the local geomorphology and to determine extent and borders of our study area. Subsequently, a working program was set up together for the time of our stay.

4.1 Establishing, describing and sampling the soil profiles

Between 03 November 2001 and 17 November 2001, 21 soil profiles were established so as to cover the main valley incl. Kumbu Goempa, and the lateral valleys of Thang/Hal and Taphu. Most profiles were done in the form of soil pits, however road cuts and landslide sites have also been used where it seemed to be appropriate (Fig. 4). In order to avoid violating Buddhist beliefs, profiles were only situated in places which were decided to be acceptable by our Bhutanese colleagues, and all macroscopic animals detected during the digging process were brought to safety. It was taken care that the profiles were facing the sun to improve differences in colours and thus simplify horizon differentiation. Usually we would dig down until the parent material was reached. When we could not detect any changes at approx. 2 m depth, the ground below was tested using an auger with extension.

Fig. 4: Establishing soil pit PK 140A

For each profile, basic information like its geographic coordinates (using a Garmin GPS), height above sea level, inclination and exposition of the site, relief data, land use, vegetation, weather and signs of anthropogenic influence were gathered. Prior to its description, the profile was cleaned using a spatula and – if necessary – the surfaces moistened with water from a spray bottle. All procedures for describing and sampling were made according to FAO (1990). The first parameter determined during field survey was depth, shape and clarity of horizon borders. Horizon designations were made according to the World Reference Base (WRB 1998) and soil colours analysed using the Munsell Soil Color Charts (Munsell 1994). Further parameters included texture, structure of the soil aggregates, mottles & concretions, coatings, pores & cracks, distribution and frequency of stones and roots, estimates of humus and carbonate content.

The results of each description were recorded on the BSS profile form as well as the German form based on the German soil survey manual “KA4” (AG Boden 1994).
From each horizon, we took one bulk sample (approx. 1 kg) and replicate core samples (n = 3, V = 100 cm³), Fig. 5a/b. In a few cases, core samples could not be taken due to high stone contents in the subsoil. The samples were hand-crushed and filled into double-labelled plastic bags. Whereas the core samples were analysed by SPAL. Simtokha, the bulk samples were sieved to 2 mm and air-dried as long as possible before being transferred to Germany. There, all geochemical analyses were performed in the labs of the Soil Science Institute of the Technical University of Munich.

4.2 Physical and chemical analyses

For the measurement of bulk density, the core samples were dried at 105°C and subsequently weighed.

The pH values were measured in deionised water and 1M KCl at a soil-solution ratio of 1:2.5. For particle size distribution, the samples were pre-treated with H₂O₂ to destroy organic matter. After dispersion by shaking with tetrasodium pyrophosphate (Na₄P₂O₇) and ammonium oxalate solution for 16 hours, the sand fractions were separated by wet sieving (2000-630 µm, 630-200 µm and 200-63µm). The fraction <63 µm was freeze-dried, suspended in water and subjected to X-ray attenuation (XRA) measurement (Micromeritics Sedigraph 5100) for determining the amount of silt (63-2 µm) and clay (<2 µm). Particle sizes below 0.5 µm cannot be quantified.

Organic carbon (Corg) and total nitrogen were measured by dry combustion (975°C) in duplicates, using a Vario EL Elementar analyser (minimum detection levels of 0.4 µg for C and 1.0 µg for N).

Total element contents (e.g. Fe) were measured by neutron activation analysis (NAA) at the University of Missouri, USA. The sample is first made radioactive by bombardment with neutrons, then the radioactive isotopes created are identified and the element concentrations are determined by the gamma-rays they emit. NAA is capable of detecting many elements at extremely low concentrations.
For the determination of the cation exchange capacity (CEC), unbuffered 0.5M NH₄Cl solution was used to extract exchangeable cations from 2.5 g air-dried soil (Trüby & Aldinger 1989) at a soil-solution ratio of 1:20. Concentrations of extracted Na⁺, K⁺, Ca²⁺, Mg²⁺, Mn²⁺ and Al³⁺ were measured by ICP-OES (Perkin Elmer Optima 3000). Clay fractions (< 2μm) were separated by sedimentation. The clay mineralogical composition was examined by X-ray diffraction analysis (Philips PW 1830 diffractometer) of oriented preparations after saturation of the clay fraction with Mg²⁺ (at 25°C), employing cobalt-Ka radiation and operating at 35 kV and 35 mA. The samples were irradiated between 2° and 18° at a scanning rate of 0.02° and intervals of 5 s.

The surface area of the air-dried fine earth was determined by the N₂-adsorption BET approach (Brunauer et al. 1938), using an Quantachrome Autosorb 1 surface area analyser. Prior to the measurements the samples were outgassed under vacuum (40 mbar) at 70°C for 24 hours, and then analysed by multiple-step adsorption of N₂ at 77° K in the relative pressure (p/p₀) range of 0.05 to 0.30.

¹⁴C-AMS (accelerator mass spectrometry) measurements of subsoil organic matter were performed at the Leibniz laboratory for radiometric dating and isotope research (Kiel, Germany). Pre-treatments of the samples included extraction by 1% HCl, 1% NaOH and 1% NaOH at 60°C, combustion at 900°C and reduction of the generated CO₂ to graphite.

4.3 Data analysis and statistics

To take into account the varying horizon thickness, weighted means of the analytical parameters were calculated for each profile according to the equation:

\[ x_m = \frac{\sum (x_i \cdot d_i)}{\sum d_i} \]

\( x_m \) = profile-weighted mean
\( x_i \) = parameter x of horizon i
\( d_i \) = depth of horizon i

We used the one-tailed Student’s t-test to detect if correlations were significant at the 0.05 (*), 0.01 (**) or 0.001 (***) probability level.
5 RESULTS AND DISCUSSION

5.1 Soils and the Past

When India collided with the Asian continent between 55-50 million years ago, it was the birth hour of the Himalayas. Whereas the Indian plate was subducted (and still moves into Asia with 5 cm/a), the continental area was uplifted, forming the Himalayan chain and the Tibetan highland. During this process, the sediments and geological material were not only uplifted but often transformed and metamorphosed under high temperatures and pressures. As a result, the main part of the Himalayas nowadays consists of crystalline metamorphic rocks. In Bhutan, they are e.g. represented by the Paro Metasediments and the Thimphu Gneis formation.

However, in some particular regions, marine sediments - having evolved from the Cambrian to the middle Carbon times in the Thethyan sea - were uplifted on top of crystalline units without being transformed/ metamorphosed. They can be found in various sites in the Himalayas, even on top of Mount Everest (Yang & Hsia 1975). Gansser (1983) mentions that the Tethyan sediments form “a normal cover above the crystalline” and are usually of “platform type”. Within Bhutan, they mainly occur in basins: Lingshi basin (NW), Toma La and Lunana belt, and Tang Chu basin (central Bhutan).

Singh (1973) was the first to mention a possible southern extension of the Tang Chu sediments within the Phobji-Gangtey valley. He had detected badly preserved remnants of brachiopod species (shell-like marine animals living on the sea bottom) in layers of compact green shale and thinly bedded limestone south of Taphu during field work between 1958 and 1966. Gupta (1971) examined similar fossils collected by A. Gansser in the Tang Chu basin and suggested Devonian age (approx. 370 Ma). On a sketch map drawn by Jangpangi (1978), the Tethyan sediment outcrop near Taphu is shown and mentioned as outliers over the Chekha rocks (Fig. 6).

During fieldwork in autumn 2001, Kado Tshering mentioned that students from Kanglung had also found fossils within the valley. Our soil scientific work did not reveal any fossiliferous material, but – in this context – profile PK 139 showed some interesting features: unlike all other profiles, the subsoil showed a dark brown (10 YR 2/2) horizon just above and between boulders of blocky granite and quartzite. The detection of Manganese crusts and a large Mn nodule in 1.2 m depth was the final hint: macroscopic Mn nodules can only form under marine sedimentary conditions, their growth rates being of the order of a few millimetres per million years (Dubinin & Sval’nov 2003). Total element analyses (NAA) not only show extremely high Mn contents as expected, but also the highest As, Ce, Co, Sb, Sc, Sr contents of the whole valley system. The extraordinary high Ce values can be explained with the fact, that Ce is easily incorporated into Mn nodules. Sc and Sr are conservative elements and indicate that the PK 139/6 horizon is older than any other weathered material found in the study area. The high BET value of 60 m² g⁻¹ gives further support to this hypothesis. This Palaeozoic marine layer seems to outcrop only in the Taphu lateral valley, and as this parent material does not play any significant role in the formation and properties of the Phobji-Gangtey soils, it will not be further discussed in chapters 5.2 and 5.3.

Nevertheless, it has to be pointed out in this context, that the unique Phobji-Gangtey landscape with its wide valley bottom and gentle slopes, was shaped by strong weathering of the comparatively “soft” Precambrian sediments. Most other NS valleys in Bhutan at this altitude are V-shaped with steep slopes. On the other hand, prior to our research it has often been discussed that these features may result from glacial activities within the valley. What is true about this claim?
The geology was not the only thing which was altered during the uplift of the Himalayas. It also triggered a climatic change, which dramatically strengthened the Asian monsoon. Since that time, the main wind direction has been from south to north. Over millions of years, the monsoonal rains will have eroded the marine sediments from the slope areas into the valley beds and from there further downslope into the Brahmaputra and finally the Indian Ocean. Strong up-valley winds will have caused aeolian deposits at the same time. The ongoing struggle of the two tectonic plates has lead to the maximum uplift of the Tibetan plateau at around eight million years ago (Harrison et al. 1993). This is evidenced from climatic changes and the initiation of normal faulting after this rapid pulse of uplift (see Fort 1996 for a comprehensive summary).

During fieldwork, we discovered conglomerates in the form of well-rounded pebbles set in a finer-grained matrix and consolidated mainly by silicic acid. Sites include the Tabedin g guesthouse and the opposite side of the valley, where they constitute the parent material for PK 155. Evidence for impressive sediment movements during late Pleistocene / early Holocene was found in the form of pebble layers in PK 143/8 (BC horizon) and PK 150/7 (CB).

Towards the end of the Tertiary, the climate had gradually cooled. It is not completely clear yet if a global cooling event or the uplift of the Tibetan plateau itself (or maybe the increased dust transport by the strengthened winter monsoon) was responsible for this development which culminated in the period of Pleistocene (1.6 Million years – 10,000 BP), the “Ice Age”, characterised by repeated and rapid temperature fluctuations and the heaviest glaciation since the Cambrian period.

![Fig. 7: Remnants of highly dissected river sediments (right part of photo) in the Thang/Hal side valley, deposited during Tertiary and early Pleistocene](image)

Especially during late and middle Pleistocene, the Himalayas in general have been much more glaciated than today. Regarding the issue of the extent of this glaciation, there is considerable disagreement among scientists. Theories range from complete glaciation of the Himalayas (Kuhle 2002) to much more careful estimates (Bäumler 2001). Meyer et al. (2003) examined the current and past glacial situation of Eastern Lunana. By examining glacial deposits they could show that the glaciers extended as far downslope as 3550 m a.s.l. during the Last Glacial Maximum (LGM). At this height, they also assigned the transition between glacial erosion (U-shaped cross profiles) and fluvial erosion (V-Shaped morphology). This corresponds well with our own findings in Central Bhutan (Caspari et al. 2004a).

The highest mountain peaks within the watershed of Phobji-Gangtey valley reach heights of about 3900 m and are situated along the northeastern and southwestern boundaries. However it seems unlikely that glaciers were able to evolve within these comparatively small catchments, which are moreover surrounded by clearly lower altitudes (i.e. have no connection to higher landscapes). Another evidence that major glaciation did never exist within the valley is given by the already mentioned conglomerates from Tertiary times. Together with all other fluvial (Fig. 7) and aeolian
sediments accumulated within the valley bottom until then, they would have been dislodged and deposited further south. There are some “wavy” morphological features within the valley, especially east of Takche Goempa, which could be wrongly interpreted as lateral and/or terminal moraines (Fig. 8). Most probably, they represent hang slide material, amended by fluvial Tertiary sediments, covered by aeolian sediments and finally dissected by erosion. However, periglacial features can be observed within the valley, most prominent in the form of a) huge, autochthonous (consisting entirely of the products of in situ weathering of bedrock) blockfields in the cirque slopes north of Taphu, and b) asymmetric valley slopes of the side valleys. All these observations would favour the hypothesis that glaciation did not occur within the valley during the LGM.

During late Pleistocene, the glaciers will have retreated, and there is evidence from Bumthang that this happened earlier than previously assumed, namely starting from 27000 years BP or even earlier (Caspari et al. 2004a).

**Fig. 8: Moraine-like structures east of Takche Goempa**

Within the chronology of Phobji-Gangtey valley, we have now reached a point, at which the present soils start being formed. During and also following the LGM, the land surface was bare and without any major vegetation. Thus, the potential for aeolian transport of sediments must have been enormous. Following the main wind direction form S to N, material will have been “pushed” up the valley and finally sedimented at and around the obstacle in its way. With time, this not only caused an additional smoothening of the landscape, but also had its impact on soil formation. An obvious example can be found with the striking differences in soil depth throughout the valley: whereas in the very south of the study area, the profiles are “only” about 2 meters deep (PK 135, PK 136), heavier sediment loads with up to 4 m exist north of Gangyu (PK 150) and particularly north of Taphu (PK 140, PK 140A). With 4.20 m, the deepest profile has been PK 151, situated on an east-orientated slope north of Gangtey. Hardly any material > 2 mm has been found within the profiles above the Cv (BvCv, CvBv) horizons, so that aeolian sediments indeed seem to be the major soil forming material in Phobji-Gangtey.

During early Holocene, the climate became gradually warmer and wetter, resulting in a floral succession from grassland to first vascular plants, bushes, trees etc. Around 5000 years BP a climate was reached which was warmer and wetter than today and referred to as “Holocene climate optimum”. Meyer et al. (2003) state a “decaying glacier system just around 4700 BP” for Eastern Lunana. Within the study area, a (maybe subtropical) forest ecosystem will have developed, leaving evidence for its existence in form of a massive A horizon, which was found in nearly all parts of the valley. In profiles PK 143 and PK 144 we sampled this organic horizon, lying in approx. 1 m depth, for $^{14}$C dating. The resulting conventional $^{14}$C ages were found to be 1667 years BP (PK 143/4) and 2024 years BP (PK 144/4). Translocation of organic material is an important process in the soils of this part of Bhutan (Baillie et al. 2004), so that younger C-containing material can infiltrate the sampled horizons from the overlying A horizon(s). The ages therefore represent minima for the main phases of pedogenesis and usually are underestimates for the ages of the parent materials.
was

So, in some way, grassland has been the climax vegetation for more than 2000 years. This fact bottoms and nearly all lower slopes), higher plants or even trees have not been able to re-develop.

during or after the Holocene climate optimum (i.e. in most areas of the main and side valley on the local soils. It can be observed that in places, where forest has been cleared at some stage the valley was even more intense than today. Terracing can be seen on steep slopes, which are also got dryer. As a consequence, the existing forests have changed from dense (presumably) subtropical to the more open stands of today’s pine forest. In places, where this development was undisturbed, the fossil A horizon is identical with or not separable from) the recent one (e.g. PK 155). Yet, in locations where the forests completely disappeared, another generation of airborne sediments can be observed on top of the fossil A horizons. In case of PK 143 and PK 144, these sediments account for approx. 1 m soil profile which – given the correctness of the \( ^{14} \text{C} \) dating – would give a mean annual airborne sediment load of about 0.5 mm. This does not seem to be unrealistic, as during our stay we have been witnessing impressive accumulations of silt-sized particles (about 1-2 mm) during the course of only one day in vicinity to wind shelters set up during the Black necked crane Festival 2001.

One of the most interesting but at the same time most difficult questions to answer refers to the when and how of deforestation. This issue is closely connected to the human settlement within this area. Only few things are known about the early history of Bhutan. Monoliths and skillfully made stone axes (one exemplar dated to 4000–3500 BP, Aris 1979) from Central Bhutan indicate the presence of a lithic culture. The huge, flat stones covering the entrance to the central temple of Gangtey monastery (see insertion “Gangtey Monastery – then and now” on page 18) might be evidence for this early culture. Charcoal found on top of the fossil A horizons all over the valley indicates that from at least 2000 years BP some kind of slash and burn land use in connection with “primitive agriculture” was being practised in the Phobji-Gangtey area. At this time, wooded hills between 2000-3000 m a.s.l. in an transect from Nepal in the west to Arunachal Pradesh in the east of Bhutan, were inhabited by the \( m(o)\)enpa people, a hunter and gatherer tribe with dependence on forest for their livelihood. In Tibetan literature, the term \( \text{mon(g)} \) referred to something similar as “southern or western mountain-dwelling non-Indian non-Tibetan barbarian” (Aris 1979). The region which we now call \( \text{druk yul} \) (Bhutan) was referred to as \( \text{Iho mon} \), meaning “\( \text{Mon} \) people of the South” (Sarah Harding, personal communication). Within Bhutan, \( \text{monpa} \) communities have once settled in all major villages of Central Bhutan, but today have been pushed to the hinterland of the Black Mountain range forests. Regarding their settlements within Phobji-Gangtey valley, nothing evident is left over, except maybe the three round “mini-hills” north of Gangyu (Fig. 3), which may have served as special places during Bon rituals. However, they might as well present the remaining basements of \( \text{chorten} \)-like structures erected in the time period directly after Guru Rinpoche’s arrival in Bhutan, when terminal parts of stretched alluvial terraces were often thought to represent snakeheads and had to be tamed by putting sacred buildings directly on top (= philosophy behind the placement of Gangtey and Rukubji \( \text{lhakang} \)). The mist of history only clears in the 15th century, when \( \text{drukpa} \) lams like Ngawang Chhoegyay (1465-1540), the cousin of \( \text{Drukpa Kuenley} \), visit the western part, whereas Lams of the \( \text{nyingma}\text{mapa} \) tradition, especially the famous saint \( \text{Pema Lingpa} \) (1450-1521), a busy traveller and teacher, visited central Bhutan. \( \text{Pema Lingpa} \) predicted that a monastery would be built where Gangtey Goempa now stands (see “Gangtey Monastery – then and now”, page 19). From this time, with more and more people entering the valley, grazing (and most probably also agriculture & deforestation) will have been practised significantly more intensive than before. From observations during our field work there can be no doubt that in former times the agricultural use of the valley was even more intense than today. Terracing can be seen on steep slopes, which are now only used for grazing. This indicates higher pressure on the land, resulting from a higher population density at that time or a “tax” scheme under which farmers were forced to deliver a certain percentage of the harvest to their landlords. The latter may not sound unrealistic, as until 1963, the people of Phobji were required to supply 120 butter containers to the store officer of Wangdiphodrang Dzong annually. It was then resolved that instead of the above practice, the people of La-Wogma would make a permanent box for keeping butter at Wangdiphodrang Dzong (RSPN 2003).

The “cultural chronology” above, even if it is only tentative, is of importance because of its influence on the local soils. It can be observed that in places, where forest has been cleared at some stage during or after the Holocene climate optimum (i.e. in most areas of the main and side valley bottoms and nearly all lower slopes), higher plants or even trees have not been able to re-develop. So, in some way, grassland has been the climax vegetation for more than 2000 years. This fact was and still is due to two main reasons: a) grazing and b) aeolian input.
Gantey Monastery – then and now

High on a hill in the center of Phobjikha Valley is Gantey Goempa (von gang = “hill”, teng = “on”), the largest private Buddhist monastery in Bhutan. The site was recognized by Pema Lingpa, who predicted that one day a great temple would rise on the spot where then was a cave used by cow herders. Initially constructed in 1613 by the first Gantey Tulku, Gyalse Pema Thinley, Pema Lingpa’s grandson and first incarnation, Gantey Goempa was enlarged to its present size during the late 16th century. One of many miraculous stories which surround the Goempa relates that the huge, flat stones covering the entrance to the central temple - exquisitely fitted and matched, an engineering marvel even by today’s standards - were placed by the dakinis as their offering to the Goempa.

For nearly four centuries Gantey Goempa has remained an isolated, secret repository of the innermost teachings and traditions of Pema Lingpa (1450-1521). Even today its ancient spiritual rhythms remain uninterrupted. Among its traditional activities is the oldest annual tsechu in Bhutan. In this religious festival the entrancing sacred dances of Pema Lingpa’s terma revelations are performed by costumed and masked monks, who leap, whirl and beat drums as they depict the inner dramas of our spiritual nature.

As the 21st century begins, outwardly the Phobjikha Valley has changed very little: electricity is still unknown; the narrow mountain road leading to it remains impassable several months of the year; and the elegant Black-Necked Cranes still grace the valley floor for several months each year, performing, in exquisite privacy, the leaps, whirls, and whoops of their own magical natures.

With the presence of the current incarnation of the Gantey Tulku—which incarnation had been absent from the monastery for over 75 years—new shoots of dharma activity abound at Gantey Goempa. During the past ten years the Gantey Tulku has constructed a three-year retreat facility adjacent to the Goempa (the three-year retreat is a rigorous traditional meditation and study program which is vital to the preservation of the inner and secret levels of Vajrayana Buddhism), and has established a shedra there as well, a university-level Buddhist studies program for advanced monks. Several other major undertakings have been realized, and new projects are being planned, both at the main Goempa and at more than 20 satellite monasteries and hermitages throughout Bhutan, all of which together comprise the extended spiritual household of the Gantey Tulku.

While it does provide basic support to Gantey Goempa, the Royal Government of Bhutan is unable to subsidize this burgeoning of spiritual activities. During the past twelve years the Gantey Tulku has had to rely on the generosity and financial participation of his expanding base of foreign students and friends to fund his spiritual vision for Gantey Goempa.

At the dawn of the 21st century, in the midst of the current flowering of spiritual growth and activity, Gantey Monastery - a magnificent physical focus of Guru Rinpoche’s legacy and the Pema Lingpa Lineage, which houses not only a dozen spiritually significant, actively attended shrines, but a vast collection of sacred art, statues and thangkas - is threatened by imminent physical collapse. In August, 1995, a team of four government representatives and engineers conducted a cursory, one-day inspection of the Goempa, at Rinpoche’s request. They reported, “Despite the short time available, the team could find that there are some serious problems which have to be investigated further... to allow the drawing up of a list of actions to be taken.” Since then, a complete engineering inspection of the Goempa has been undertaken and completed. Construction costs in Bhutan, in general shockingly high, are even more so in the Phobjikha Valley. Many materials must be trucked in, laboriously, from India. The engineers estimated that renovation costs will run approximately 3 million US-$, but until a detailed engineering study is conducted, a precise figure will not be known.

source: http://www.yeshekhorlo.org/gangtey-restoration.html (modified)
As mentioned before, the quantity of aeolian input can be regarded as considerable and even a soil-forming factor. What this means for the process itself, can be best understood by imagining the fluxes of soil material in the Phobji-Gangtey valley and surrounding areas to be a simple dynamic system:

During the whole year, there is an influx of inorganic material being transported from the South by winds passing the valley. This material is sedimented around fixed objects (like vegetation) and partly redistributed by saltation on the lower slopes and less swampy areas of the valley floor – literally spoken – creeping up-valley (from south to north). Fine silt might even be transported beyond the valley and thus partly get lost from the system we look at. The opposite force is active (especially) during summer monsoon, when soil material is again flushed out by the rivers, only to be (partly) re-blown into the valley in the time thereafter. What we therefore look at, could be described as an intensive cycle of silt- and fine sand-sized particles, which already existed during late Pleistocene/early Holocene times and which is now – after deforestation started with the first settlers within the valley - active again.

Chapter 5.2 will show which implications this process has on the properties of the present soils.
5.2 Soils and the Present

After having understood the development of Phobji-Gangtey’s soils under conditions of varying climate and increasing human land use within the valley, it does not come as a surprise that most soil profiles we established in 2001 do not look homogeneous. They are “polygenetic”, meaning that various phases of soil formation have taken place under varying climatic conditions, thereby leaving different kinds of material which now constitutes the soil profile as a whole. In the following, three soil profiles will be presented and discussed, which are thought to be representative for the grasslands on the valley bottom (PK 143), grasslands on the lower slopes (PK 138) and the forested areas (PK 155).

5.2.1 Grassland soils on valley floor (example: PK 143)

As can be seen from Fig. 9, PK 143 (incl. PK 143A) is an impressive, nearly 5 m deep profile situated at 2885 m a.s.l. on an alluvial terrace right below Gangtey Goempa. The fossil A horizon in 1.1 m depth, having formed during the Holocene climate optimum, can clearly be identified. PK 143/1-3 represent aeolian sediments deposited since that time. The older generation of aeolian deposits (123 cm – 375 cm depth) is still more pronounced.

<table>
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<tr>
<th>horizon</th>
<th>pH [KCl]</th>
<th>C [%]</th>
<th>CEC [cmol c kg⁻¹]</th>
<th>clay [%]</th>
<th>bulk d [g cm⁻³]</th>
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<td>53</td>
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</tr>
</tbody>
</table>

Fig. 9: PK 143 (incl. PK 143A) and selected chemical properties
Apart from its darker colour, the fossil A horizon is analytically proven by a second peak in the organic carbon gradient in about 1 m depth. Whereas the boundary between 2A2 and 2B2 is clear, the beginning of the recent topsoil can hardly be identified. It is suggested that the continuous sedimentation of aeolian material has prevented the formation of a “proper” topsoil horizon. In the course of several thousand years, organic and inorganic material have been added and thoroughly mixed at more or less constant rates, thus leading to the phenomenon of an “extended” or “straightened” A horizon. This concept also explains the fairly high $C_{org}$ contents throughout the first ca. 1 m of PK 143, and may contribute to the understanding of the extraordinary low bulk densities. The forest topsoil horizon PK 155/1 with a carbon content of 8.6% gives us a feeling for the potential $C_{org}$ contents in places sheltered from sediment accumulation and spared from deforestation. Another explanation for the above soil properties involves a land use practice called pangshing (grass fallow), a labour-intensive procedure of burning heaped dry topsoil, using plant biomass or manure and soil organic matter as “fuel”. This would suggest that the mighty AB horizons are rather man-made. However, during our presence, pangshing was not practiced any more within Phobij-Gantey valley, and unfortunately we have no information yet if it was used in former times at all.

Throughout the profile, pH values are low, indicating the acid nature of the underlying granitic and phyllitic schists of the low-grade metamorphosed Chekha formation. Correspondingly low are the CEC results, showing a first, mainly organic matter-induced maximum in the topsoil and a second peak in approx. 2 m depth, which is rather explained by the high clay contents. According to the clay contents, the profile can be separated into three main units: 1) the first meter, showing contents around 40%, 2) the middle part down to 375 cm with contents of around 50% and 3) the bottom of the profile with clay constituting below 25% of the <2 mm matrix.

The difference between units 1) and 2) shows that pedogenic clay formation and dislocation only occurs below the fossil A horizon. If we suggest a similar mode of formation, i.e. aeolian accumulation, it indicates the higher age of the lower sedimentary unit. Within the whole Phobij-Gangtey valley system, clay skins were only found in the horizons below the fossil A corresponding to the Holocene climate optimum. The differences in clay content also find their expression in the BET results: the specific surface areas of the older generation were found to be above 40 m$^2$/g in all horizons, whereas values for the recent sediments were found to be below this figure.

Besides clay cutans, organic coatings have been observed in some rare cases (e.g. in the topsoil of PK 140A), indicating transport of organic material between horizon boundaries. This has also been proven by column experiments (unpublished data).

**Fig. 10: Particle size distribution of top- and subsoil of PK 143**

Regarding the recent aeolian sediments, a clay content of 40 % seems unusually high and has not been found in any other recent aeolian sediments around the world. (Prof. Arndt Bronger, personal communication).
communication). This could indicate that the process of clay formation is favoured by particular local conditions, as e.g. the daily freeze-thawing cycles which frequently occur during spring and autumn. The higher degree of weathering in the subsoil also finds its expression in the “step-wise” increasing gradient of the bulk density values (Fig. 9). Fig. 10 shows the similarity of the top- and subsoil aeolian material of PK 143. Whereas the silt fractions are nearly identical, the subsoil is clearly increased in clay content. The same development is observed for all soil profiles within Phobji-Gangtey valley.

Even though the PSD significantly varies within the profile, the XRD analyses have shown that the composition of the clay minerals remains comparatively constant. Pedogenic chlorite, illite and kaolinite are the main clay minerals. Vermiculite and smectite could not be found. There are some minor trends within the profile, e.g. kaolinite seems to increase with increasing depth. The existence of gibbsite (AlOH$_3$) was proven, starting with low relative amounts from PK 143/4 (3A horizon) and reaching a maximum in the subsoil (horizons PK 143/7-9). Gibbsite only occurs in landscapes which have been stable for long time periods, often several millions of years (Huang et al. 2002). The subsoil of the profile – in particular the obviously coarse, fluvial sediments of PK 143/7 and 8 – is therefore of clearly pre-Holocene age. This can be taken as another evidence against a potential glaciation of Phobjikha valley during the LGM, as a glacier would have eroded these and all neighbouring sediments below Gangtey Goempa.

The lowest horizon, PK 143/9, has a markedly grey (5Y 5/2) appearance and consists of homogenous fine sand. The same material can be found in PK 150/7 and 8. It might represent the sediments of a lake which filled the valley bottom during late Tertiary or Pleistocene. After its disappearance, the rivers will have removed most of the lake sediments, except the ones in protected locations like below Gangtey Goempa.

It is interesting to compare the particle size distributions not only within but also between the profiles in the valley. In Fig. 11, the results for the recent aeolian generation have been selected (the subsoil characteristics thought to be too much over-printed by pedogenic development). At first glance, no distinct maximum can be found within the silt-sized fraction. This may not seem noteworthy, but is in contrast to the findings of Pye (1987), that aeolian dust sampled at continental sites commonly exhibit a markedly bi-modal and sometimes poly-modal grain-size distribution. The multi-modal distribution in the examination area could be another hint that the aeolian material is only “locally” transported and redistributed within the aeolian cycle described in 5.1, and not blown in from distant sources like the Tibetan loess plateau or the Indian floodplain.

![Fig. 11: Comparison of particle size distributions (PSD) in recent aeolian sediments (PK 136, PK 143 and PK 151)](image-url)
It has to be pointed out that during the determination of the PSD, the soil sample is sonicated and connecting agents like Fe and organic material are being removed. The “real” PSD in the field might therefore be different, most probably coarser. Within the silt fraction (63 µm – 2 µm), the compared samples all show a similar pattern with the most common grain size being approx. 5 µm. The only clearly contradictory pattern between the curves occurs in the coarse silt fraction. Whereas particles of approx. 33 µm in size are low at the valley bottom (PK 136) and virtually non-existent in PK 151, they are favourably sedimented on the fluvial terrace below Gangtey Goempa (PK 143). These particles are probably transported through the valley by saltation and finally deposited in the area around PK 143 (they cannot “creep up the hills to reach PK 151). This finding also contradicts a possible aeolian sediment transport from northern directions into the valley, in which case the coarsest transportable particles would have been sedimented in lee sides like PK 151.

The most striking differences between the profiles are found within the clay fraction. The sediments on PK 143 are already finer compared to PK 136, and particularly high amounts of fine clay are found in profiles PK 151 on a slope northeast of Gangtey Goempa, and also in the basin-like situation at the upper end of Taphu lateral valley (PK 141/2, not included in Fig. 11). Even though it is highly speculative, these differences in PSD could be an indication for the continuous wind-induced “sorting” and redistribution of deposited air-borne particles within the valley system.

5.2.2 Grassland soils on lower slopes (example: PK 138)

This profile is situated on the southern slope of the Taphu side valley, southeast of Pilam at 3185 m a.s.l. (Fig. 12). The parent material constituting the Cv horizon are the strongly weathered quartzitic and phyllitic schists of the Chekha formation.

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<th>clay [%]</th>
<th>bulk d [g cm⁻³]</th>
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<td>23</td>
<td>-</td>
<td>4.2</td>
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</table>

Fig. 12: PK 138 and selected chemical properties
In comparison to PK 143, three apparent differences exist:

- The depth is only half, owing to the significant losses from water erosion and gravitational downslope transport of soil material.
- The fossil A horizon is disrupted without clear horizon boundaries to either side. A possible explanation are landslides following the deforestation upslope of PK 138 and disturbance by subsequent agricultural activities.
- The colour of the younger aeolian deposit is bright orange (7.5 YR 5/6); whereas most profiles within Phobji-Gangtey area exhibit a uniform distribution of iron (Fe\textsubscript{2+}) throughout the profile, PK 138 shows an increasing content of this parameter from sub- to topsoil. As a result from partly hydromorphic conditions during monsoon time Fe\textsuperscript{2+} is set free in anaerobic areas, and migrates upwards along the Q gradient. There, it forms colour-intensive, low-crystalline Fe-compounds like ferrihydrite. The formation of lepidocrocite (\textdelta-FeOOH) seems also possible, however has not yet been proven by XRD analyses.

While digging the profile, another striking characteristic of the soil became visible: it is thixotropic, meaning that the material becomes less viscous, "smeary" when subjected to pressure (e.g. between the fingertips). This property was found in many profiles within the examination area, mainly in connection with the recent aeolian sediments (PK 138, 143, 144, 148, 151, 152), but also in the ones dating back to the Pleistocene (PK 142, 150, 151, 152, 155). In case of the former group, the thixotropic features usually already start within the fossil A horizon.

Soils with orange-coloured horizons displaying thixotropic features, high C\textsubscript{org} contents, high clay contents and low bulk densities (crumb structures) at the same time, have been described from various sites in the Himalayas and the rest of the world (see section 3) and mostly referred to as "non-volcanic Andosols", "Pseudo-Andosols" or "Cryptopodzols". Unfortunately, their formation is not yet well-understood. In Phobji-Gangtey valley, these properties can only be interpreted as a result of "cycling" of aeolian material as described above. In-situ weathered soils are not likely to have developed similar features. The thixotropic character particularly evolves where clay contents reach a critical threshold (either by weathering or in basin-like sites where air-borne sediments have been originally clay-rich) and therefore suggests thixotropic stabilisation of the clay fabric. Blake & Gilman (1970) described thixotropic changes of artificially prepared soil aggregates and conclude that the observed increased aggregate stability results from "orientation of water molecules and associated cation equilibrium" and "spontaneous shifting of clay particles to positions of lowered potential energy". Accordingly, Molope et al. (1985) showed that thixotropic changes contributed to aggregate stabilisation ("age hardening process") after simulated cultivation. They also pointed out that this physical component in aggregate stability – significant as it might be – does not compensate for lack of organic matter as the main stabilizing agent.

In one sentence: the main key for understanding the local soils is their aeolian nature, which in the course of aging – in combination with high organic contents – leads to the development of highly porous, clay-rich horizons. Which processes are responsible on a molecular scale, will have to be examined in the future.

Another focal point of discussion will be the placement of these soils within the international soil classification schemes. In connection to the current system of the WRB (1998), most soils within the valley system would qualify for Andosols. Reflecting upon their particular genetic mechanism and their (possibly) global distribution, it may not seem audacious to suggest an additional reference soil subgroup, plausibly named "Aeolic Andosols" (or similar). Generally, classification schemes do not take into account polygenetic structures, which further complicates the assignment of the Phobji-Gangtey soils.
5.2.3 Forest soils (example: PK 155)

Besides PK 151, this profile is the only one established under forest (Fig. 13). It is situated at 3010 m a.s.l. south of Gophu lhakang on the outer stretch of the ridge bordering the Thang/Hal lateral valley to the south. Blue pine (Pinus wallichiana) is the main tree species, whereas Rhododendron and Yushania (bamboo) species can be found in the understorey.

![Image of PK 155 and selected chemical properties](image)

The parent material of the profile came as a surprise: it consisted of blocky conglomerates, which – according to the chronology illustrated in chapter 5.1 – were deposited as river sediments during Tertiary or early Pleistocene, and subsequently consolidated by silicic acid. More than 2 million years are displayed here in only 2 m of soil profile! Although it is commonly known that the leaf litter of Pinus wallichiana has a strong acidifying effect on the soil below (Miehe & Miehe 1998), no podzolisation features could be found within this profile. The existence of an eluvial horizon could be obscured by the leaching of organic matter from the topsoil, as mentioned by Baillie et al. (2004). However, illuvial horizons also seem to be absent, and the base saturation is between 40 and 50% throughout. It is likely that a change to cooler and drier climate in combination with human activities (grazing) resulted in the replacement of the original forest stands (probably spruce or Hemlock) and the establishment of the present vegetation. With time, this soil will possibly develop into a podsol as described by Baillie et al. (2004) from Lame Goempa (3640 m a.s.l.).

The slope gradient is as high as 38°, rendering the area unsuitable for agricultural use and making even wood harvesting (litter use) an unpleasant business. Deforestation is therefore not likely to have occurred to a greater extent so that whatever kind of forest has been continuously growing since the Holocene climate optimum. The structure of the profile itself is the best evidence: just one organic horizon can be found, meaning that the fossil A horizon coincides (is identical with) the recent one. In no other profile of 2001, we have found a comparably deep topsoil. Its C$_{org}$ content of 8.6% is the highest within the valley system.

Following this assumption, horizons PK 155/2-4 would have developed mainly before the climate optimum (assigned to the older aeolian generation). Their clay content does not give clear indication, nevertheless light thixotropic features have been found. Especially the high figures for specific surface area justify the assignment to late Pleistocene rather than late Holocene.
5.3 Soils and the Future

The livelihood of almost all people in Phobji-Gangtey valley is based on agricultural activities. The sustainable use of the local soils is therefore of high importance. Apart from climatic limitations (high altitude and connected temperatures), the initial situation is advantageous: the soils are well-developed and moderately weathered and leached. Their partly aeolian origin results in low bulk density values and a favourable particle size distribution with the maxima in the silt-sized fraction.

In the past, indigenous farming practices involved successful strategies like tseri (shifting cultivation) and maybe also pangshing (grass fallow), crop rotation, intercropping, contour ploughing, regular application of organic matter and low plant population densities. The regular organic inputs are reflected by the current moderate to high levels of organic C and N up to 1 m depth. Amounts of phosphorus have not been analysed, but are assumed to be sufficient as well.

As a result, most soils in the study area seem to be in a good state. Natural settings and man-made treatments lead to stable aggregates, guaranteeing good air supply and high water holding capacity. Furthermore, the local cycle of aeolian sediments as described in section 5.2.1 might partly make up for erosion losses caused by agricultural activities.

The current low cation exchange capacity (CEC) of mostly below 5 cmol$_c$ kg$^{-1}$ counts among the unfavourable chemical properties. It results from low variable charge properties (low pH) and might be aggravated by low permanent charge properties due to dominance of low activity clays. XRD analyses have shown that pedogenic chlorite is the main clay mineral within the valley system. It is characterised by a fixed layer distance and therefore - with increasing degree of chloritisation - exchanges less positively charged ions within the spacings.

Another restriction for agricultural activities may lie in pH-induced micronutrient deficiencies as described from other parts of Bhutan (Norbu 1997). However amounts of plant available micronutrients have not been determined in the course of this study.

With the production of potatoes as cash crops and accelerated population growth due to enhanced medicinal facilities, pressure on the local soils is increasing as in most other parts of the country. Until today, increased agricultural production as well as productivity have been implemented mainly by enhanced fertiliser input, new crops (like potato), new and/or improved seeds, farm mechanisation, use of pesticides and shortened fallow periods. Currently, the main development issues within the agriculture programs of the Phobji and Gangtey Ninth Plans (2002-2007) comprise:

- improvement of existing crops
- introduction of new crops (e.g. walnut, asparagus), medicinal and aromatic plants
- farm mechanisation (e.g. 1 new tractor, 18 power tillers, 8 potato diggers for Phobji geog)
- establishment of a potato chip manufacturing unit
- reduction of insect pest and diseases
- farmers’ education (training in crop management, post-harvest and marketing; demonstration of new varieties and technologies during on-farm trials)

Besides the positive effects like increased harvests and additional incomes, intensified land use may create a range of soil-related problems, e.g.

- reduction of organic (C and N) contents
  → increase in soil organisms and their biodiversity
  → reduced stability of soil aggregates
- excessive fertiliser use
  → acidification: the most common fertilisers, urea and suphala, have an acidifying effect
  → nutrient imbalances: e.g. urea only adds N → natural soil K and P are depleted, “mined”
  → suphala adds P → danger of eutrophication in neighbouring water bodies
use of pesticides;
→ negative effects on soil organisms
→ accumulation within the food chain → danger of poisoning humans and animals
→ possible contamination of water bodies

soil compaction;
→ decreased water permeability and aeration
→ impeded root growth, especially when soil organic matter content is already low

In the worst case, soil degradation results in the complete loss of soil by erosion. It has to be taken in mind that the potential for both wind (up-valley winds!) and water (monsoon!) erosion is high within Phobji-Gangtey valley. Another particularly local aspect refers to the Black-necked Crane (*Grus nigricollis*) and connected conservation efforts: due to the only gentle inclination of the valley bottom in combination with the generally high hydraulic conductivity of the soils, it has to be pointed out that any soluble amendments are likely to end up in the marshy areas, which are the feeding grounds of the BNCs.

To avoid conflicts between agricultural production and nature conservation, the emphasis should be on sustainable development with a preferably holistic view of the valley system. Caspari et al. (2004b) have suggested that the concept of Gross National Happiness (GNH) provides a suitable development philosophy, and they indicated what can be done on national, district and geog level to achieve this overall aim.

At farm level, “good farming practices” will involve maintaining or even increasing the organic matter input in the first place. Regular organic amendments will be essential, including direct forms of application, e.g. farmyard manure (FYM), harvest residues, composted weeds and kitchen waste (if not fed to animals), and indirect forms like the nutrient transfer from forest to fields by cattle. It is therefore of high importance, to keep the existing integrated crop and livestock systems.

Enhanced input of N can be obtained by temporarily sowing plants capable of biological N fixation (e.g. intercropping of peas).

Careful liming of the arable land might improve the availability of micronutrients. The most important ones in the context of potato farming (B, Ca, Fe, Mg, Mn, Zn) show optimum plant availability under slightly acid conditions (pH 5.0 - 7.0). A rise in pH would further stimulate soil microbial activity, counteract toxic $\text{Al}^{3+}$ concentrations and further chloritisation of the present clay minerals.

Proper measures against wind and water erosion will be essential, involving

- Careful (or no) tillage; tillage breaks down the clumps of soil into smaller particles which are more easily carried away by the wind.
- Keeping plant residue (straw, dead plants except weeds) on the soil surface after harvest; then seed the new crop generationen directly into the stubble without tilling the soil first; thus, arable land is kept covered during most of the year; harvest residues also contribute to $C_{\text{org}}$ input.
- Planting shelterbelts; arrangement of rows of bushes or trees (prefer food instead of fodder trees) to prevent the wind from blowing across open fields; in winter, snow is trapped by the trees, thus providing more moisture for crops in spring; shelterbelts not only help to stop wind erosion but also provide a home for wildlife such as deer, rabbits and birds.
- "strip cropping"; planting crops in narrow strips makes it more difficult for the wind to pick up soil particles.
Beyond these suggestions, RSPN (2003) has proposed to

- Examine the relationship between cropping patterns of the valley and the feeding requirements of the cranes; the aim is to find out if any harm is caused to the BNCs while planting and/or harvesting different crops (effects of farm mechanisation like noise, fast movements etc.).
- Enhance food security at family level; this shall be reached by educating women, studying the feasibility of introducing high economic value crops like fruits, vegetables and/or nuts, and research on upland, frost-resistant maize seeds; the dependence on potatoes as only cash crop is regarded as “risky”.
- Improve the dairy industry; will the attempt be worthwhile to develop a marketing structure for milk products comparable to Gogona?
- Create alternative incomes, e.g. through sheep wool and honey production.
- Educate farmers on soil and water conservation, erosion control and environmental protection.

From this short summary it has become clear that many challenges lie ahead. However, many development initiatives have already been started and the conditions for implementing sustainable development are favourable: naturally well-developed soils in combination with fertility-conserving indigenous land use techniques helped to make Phobji-Gantey valley the main potato cropping area in Bhutan. The occurrence of the Black-necked Cranes has lead to the development of eco-tourism as reliable long-term source of income.

With this framework, the area might even become a “model region”, showing how human interests (agricultural production) and nature conservation can be combined and result in the survival of an overall fragile mountain ecosystem.
6 Appendix

6.1 Sketch map of the study area, scale $\approx 1 : 85,000$ (1 cm $\approx 850$ m)
6.2 Locations of the established soil pits
### Table of Analytical Results

**BET** = Specific Surface Area

**Fe\(_{\text{ox}}\)/Al\(_{\text{ox}}\)** = Oxalate-extractable Iron/aluminium

**Fe\(_{\text{dith}}\)/Al\(_{\text{dith}}\)** = Dithionite-extractable iron/aluminium

Colours determined by the MUNSELL soil colour charts

#### Table 1

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<th>Ca [cmol kg(^{-1})]</th>
<th>Mg [cmol kg(^{-1})]</th>
<th>Fe(<em>{\text{ox}})/Al(</em>{\text{ox}})</th>
<th>Fe(<em>{\text{dith}})/Al(</em>{\text{dith}})</th>
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[Image 85x314 to 524x771]
References


KUHLE, M. (2002): A relief-specific model of the ice age on the basis of uplift-controlled glacier areas in Tibet and the corresponding albedo increase as well as their positive climatological feedback by means of the global radiation geometry. – Climate Research 20: 1-7.


