Journal of Nepal Geological Society, 2013, Vol. 46, pp. 19-24

Soils as proxies of the history of landscape and climate: Eexamples from eastern Bhutan

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ABSTRACT

The reconstruction of the landscape history and past environmental fluctuations is a major task with respect to forecasting man or naturally-induced changes. In this context the extent of soil development in fluvial deposits of the Chamkhar Chhu river system in Eastern Bhutan were studied for relative age dating. The deposits represent 25 fluvial terraces up to more than 260 m above the recent river level. We used a set of methods covering physical (soil texture, specific surface area) and chemical (pedogenic oxides, soil development indices) processes, and we calculated solum-weighted means of individual soil parameters to compare different sites, and to minimize problems caused by heterogeneity of the parent materials. The results were maintained by numerical age dating of fossil A horizons. Pedogenic oxides and soil development indices as well as soil texture indicate that soils can be used as proxies of the history of landscape and climate. Local as well as global climate fluctuations are well preserved in the soils despite slope processes inducing reverse-tended soil formation in fluvial deposits of Late Pleistocene origin and older, while soils on fluvial deposits of Holocene age indicate distinct chronosequences (Dorji et al. 2009).

Key words: Soil development, landscape history, climate fluctuations, Bhutan

Received: 29 October, 2013 **Revision accepted**: 14 June, 2013

INTRODUCTION

Soil formation is strongly influenced by its surrounding environment. Sediments are playing a major role as parent materials in this context as they cover about 80% of the earth's terrestrial surface. Soils on the other hand represent the interface of any kind of processes induced by terrestrial eco-subsystems, again affecting the parent materials before or after (re-)distribution. In this context time is an important factor of soil development, and soils might therefore preserve information about landscape and environmental fluctuations especially since the late Quaternary.

Soil development is a process, and soils change with time. The speed, and the extent of soil development is controlled by biotic and abiotic factors, as for example climate, or the parent material (different resistance towards weathering), topography (erosion for example keeps a soil young), organic matter, or soil fauna. And time is the main reason that soils looked different in the past, and will look different in the future. A soil profile as we see it today is not more but a snapshot during the period of its development. Moreover, a given period of time may induce significant changes to the one soil, and little effects on another soil due to variable influences of different soil forming factors (Bäumler 2001).

Soils take time to develop. Parent materials break down, i.e., by the influence of climatic forces, and soils start to develop - first characterized by a dominance of primary minerals. Soil formation proceeds, and pedogenic minerals are formed. The processes continue until we have an overall dominance of pedogenic oxides (Fig. 1).

Horizons develop, the soil color more and more intensifies by the accumulation of iron oxides, clay minerals are formed from the weathering products, acidification proceeds, and the soils get more and more infertile by leaching of nutrient cations under wet climates, or by the accumulation of weathering products under dry climates which may lead to cementation or salinization. The addition of organic matter, and processes of melanisation and pedoturbation are proceeding in parallel and interacting with the mineralogical changes during soil development.

Why and where to study soils with a focus on soil development and the history of landscape and climate?

During the process of soil formation time-dependent

Paper presented in 27th HKT Workshop, Kathmandu, Nepal, 28-30 Nov., 2012

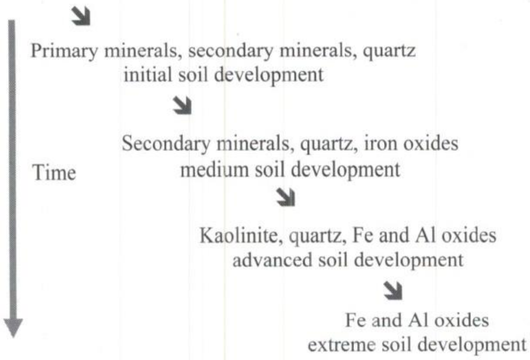

Fig. 1: Schematic process of soil formation.

or environmental information are built up which might be long-term preserved or even irreversible. Soils have a memory of their history of pedogenesis, that can be used to reconstruct the landscape history and past environmental fluctuations to get further or new information with respect to the discussions on global warming and prediction models of future changes, or future land-use planning.

One of the best ways to study soils with regard to time-dependent processes are chronosequences or at least sequences of soils or horizons which may have the same soil forming factors except for the period of development. Even considering that non-time soil forming factors have not remained constant during the Pleistocene and Holocene, chronosequence studies enable general time trends and anomalies due to palaeo-environmental fluctuations to be distinguished. Those studies may include buried or relict properties or different stages of weathering, and it may well be applied for river-, lake-, or marine terraces, coastal dunes, glacial deposits of different age or loess-palaeosol-sequences, and regions with minor or even without any information on soils and landscape history at all.

The present study focus on relative age dating of soils developed in fluvial deposits in Eastern Bhutan. The area is sparsely populated which means that an anthropogenic factor on soil formation is of minor importance. More than 70 % of the total area is forested. This means that erosion or mass movement are kept at minimum with regard to the preservation of information about the history of landscape and climate.

STUDY SITE

The working area is located in the District Bumthang, a wide valley, which is characterized by a sequence of fluvial terraces. The terrace system is located between 2600 and 3000 m asl. Monsoonal climate predominates with annual temperatures of 7.6 °C and around 1100 mm precipitation. The native vegetation is conifer forests with rhododendron and bamboo in the understory. The parent materials are metamorphic rocks of the Thimphu gneiss group and some Tertiary leucogranites in the north close to the Tibetan border.

The terrace system is separated into two major parts, and the terrace names are assigned on the height above the current river level: a series of 7 lower terraces under agriculture including the 41 m terrace which is the most prominent terrace of the valley (Dorji et al. 2009). And a series of 21 higher terraces which are under pasture or forest (Caspari et al. 2004). The lower terraces are characterized by distinct shape, and the gravels are non-cemented and well-rounded which points towards long-distance transport.

The higher terraces are covered by aeolian deposits, they include palaeosoils, the gravels are consolidated and cemented, there are signs of periglacial processes with solifluction, eroded edges, and fossil ice wedges in and above the 160 m terrace. The gravels are again well-rounded. However, they are completely disintegrated except for the quartzite gravels.

METHODS

Studies on time-related soil formation in most cases go ahead with various problems. The one is the natural heterogeneity of soils, especially when different sites have to be compared. It holds especially for soils developed in sediments of mixed parent materials. Periglacial processes and aeolian covers may severely influence time-related processes of soil formation. Aeolian sediments may be pre-weathered to an unknown extent before deposition. Changes of the catchment areas cannot be excluded. It may influence soil formation by changes in the parent materials. Extension to older landforms may also cause problems by multiple or overlapping polygenic pathways of soil formation. Therefore different methods are combined recording processes which predominantly proceed in one direction over long periods and which cover chemical and physical processes (leaching or accumulation of minerals/weathering products). It further requires the study of the total solum, as most soils in high mountain areas have a polygenic history.

In this study we used particle size analysis, surface area measurements after the BET method, pedogenic oxides, and soil development indices, which calculate the release and subsequent leaching of alkali and alkaline earth cations by weathering. All pedogenic Fe compounds (Fed) were extracted by dithionite-citrate-bicarbonate (DCB) solution

(Mehra & Jackson 1960). Poorly crystallized Fe-oxides, hydroxides and associated gels (Feo) were extraced by acid ammonium oxalate solution (Schwertmann 1964). Well-crystallized iron oxides were calculated from the difference of Fed and Feo (Fed-o). Soil development indices after Parker (1970) and Kronberg and Nesbitt (1981) were calculated based on total element contents..

For particle size distribution the samples were pre-treated with H_2O_2 to destroy organic matter. The sand fractions were determined by wet sieving after dispersion. Silt and clay fractions were analysed with the Sedigraph 5100 (Fa. Micromeritics).

The surface area was determined by N2-adsorption after Brunauer et al. (1938), using an Quantachrome Autosorb 1 surface area analyser. Weighted means over the total solum or over mono-genetic parts of the solum were calculated to compare soils from different sites, and to minimize heterogeneity.

$$x_m = \frac{\sum (x_i * d_i)}{\sum d_i} \quad \text{.......................} \quad (1)$$

xm = weighted mean

xi = parameter x of horizon i

di = depth of horizon i

RESULTS AND DISCUSSION

In theory the amount of fine particles should increase with time of soil development both under physical and chemical weathering. Fig. 2 gives the results of the particle size analysis from the Chamkhar terrace system at Thangbi. An increasing amount of silt and clay with the height of the terraces above the recent river could be found indicating an increasing extent of soil development or relative soil age in the same direction (Caspari et al. 2004).

The 74 m terrace does not fit to the overall tendency having higher silt contents. The reason is the aeolian covers of various thicknesses. And this may lead to misinterpretations, if calculating solum-weighted means over the total soil depth. In addition, local or regional redistribution of aeolian sediments, which may again be pre-weathered to some extent before deposition, may complicate the interpretation of soil development indicators (Caspari et al. 2009). It will be referred to using the example of the 74 m terrace in the following.

Fig. 3 shows the weighted means of the surface area measurements at the Thangbi terraces. There is again the clear tendency of increasing values with increasing terrace height. There is a distinct step between the lower and the higher terraces indicating a higher extent of soil development. And again the results fit to the theory of a continuous clay mineral formation with the process of soil formation (Caspari et al. 2004).

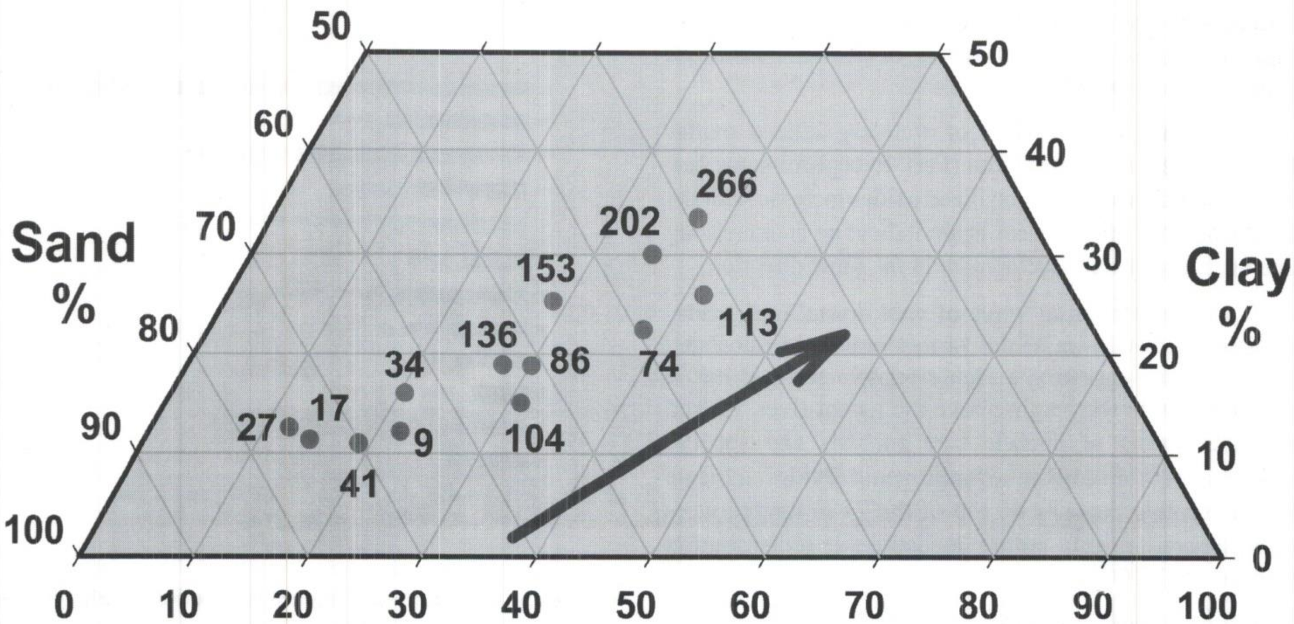

Fig. 2: Solum-weighted means of particle sizes of the soils from the Chamkhar terrace system at Thangbi. The numbers give the height of the terrace levels above the recent river.

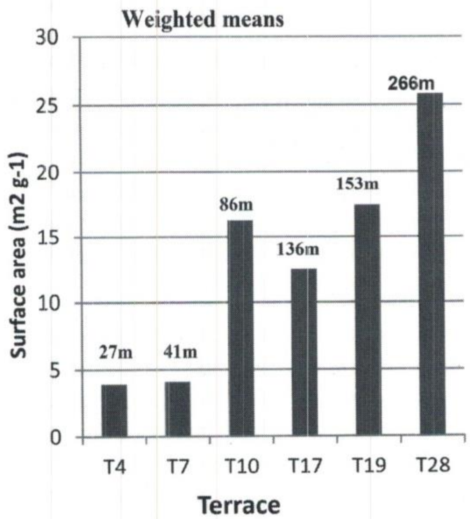

Fig. 3: Solum-weighted means of the surface area of the soils from the Chamkhar terrace system at Thangbi. The red numbers give the height of the terrace levels above the recent river.

Consistent with the results of the high silt contents the 74 m terrace has a mean surface area of 18.1 m² indicating a comparable extent of soil development as the 153 m terrace.

One of the most important indicators with regard to the extent of soil formation are the different iron fractions, which is the release of silicate-bond iron by chemical weathering and the subsequent formation of pedogenic iron oxides, especially of well crystallized ones, which is in many cases a time-controlled process of ageing of poorly crystallized oxidic iron compounds.

Fig. 4 shows the amount of well crystallized oxides (Fed-o), in relation to total iron (Fet). Except for some few highly eroded sites well crystallized oxides increase with the relative height of the terraces again indicating an increasing time or extent of soil development in the same direction.

In contrast the mean value of well crystallized oxides in relation to total iron of the 74 m terrace was calculated to 0.26, again suggesting a higher relative soil age not in accordance with the height above the recent river. Linked with the results of particle size analysis and specific surface area, the amount of pedogenic oxides indicate that the aeolian deposits on top of the 74 m terrace were pre-weathered already before deposition or redistribution (Caspari et al. 2009).

Soil development indices, i.e. the Parker index (Parker 1970) record the release and subsequent leaching of alkali and alkaline earth cations during the time-dependent process of soil formation, and the index should decrease with increasing soil age.

Fig. 5 shows the weighted means of the soils from the Chamkhar terrace system at Thangbi. The values decrease with increasing height of the terraces above the present river from the lowest 9 m terrace to the 266 m terrace. It indicates an increasing extent of soil development with time or relative soil age in the same direction (Caspari et al. 2004). The mean Parker-index of 36 at the 74 m terrace again suggests an extent of soil development comparable to the 153 m terrace. It might be in accordance with recently dated aeolian deposits at Bondey in western Bhutan by IRSL (GI-32) to a minimum age of 46 ± 5 ka.

Fig. 6 shows the results of time-dependent soil formation, i.e. the relative age dating of soils with numerical ages to get information how soil development proceeds with time especially in High Asia. The figure gives another soil development index which was published in 1986 by Kronberg & Nesbitt, and results of numerical dating of different sites from the Khumbu Himal, Central Nepal, Tian Shan, Southern Kamchatka, and the soils from the study site in Bhutan (Bäumler 2001, Bäumler 2004). At the study site, the 41 m terrace could be dated to 27000 years BP by wood fragments within the body of the terrace. The most important result is a clear trend of soil formation with time beyond regional differences and despite a variable influence of other factors indicating that soils are well suited as proxies of the history of landscape and climate.

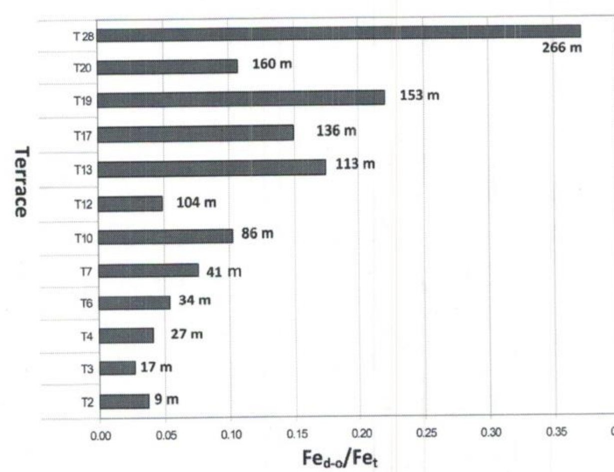

Fig. 4: Solum-weighted means of well-crystallized iron oxides (Fed-o) in relation to total iron (Fet) of the soils from the Chamkhar terrace system at Thangbi. The red numbers give the height of the terrace levels above the recent river.

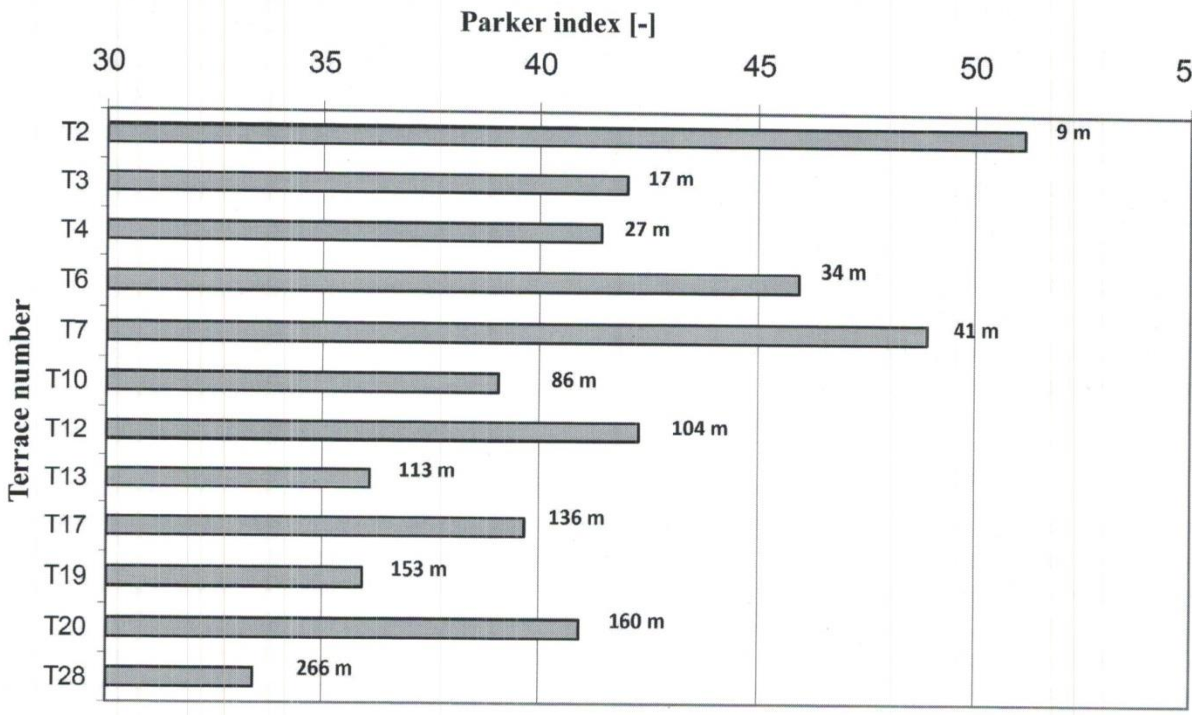

Fig. 5: Solum-weighted means of the Parker-index of the soils from the Chamkhar terrace system at Thangbi. The red numbers give the height of the terrace levels above the recent river.

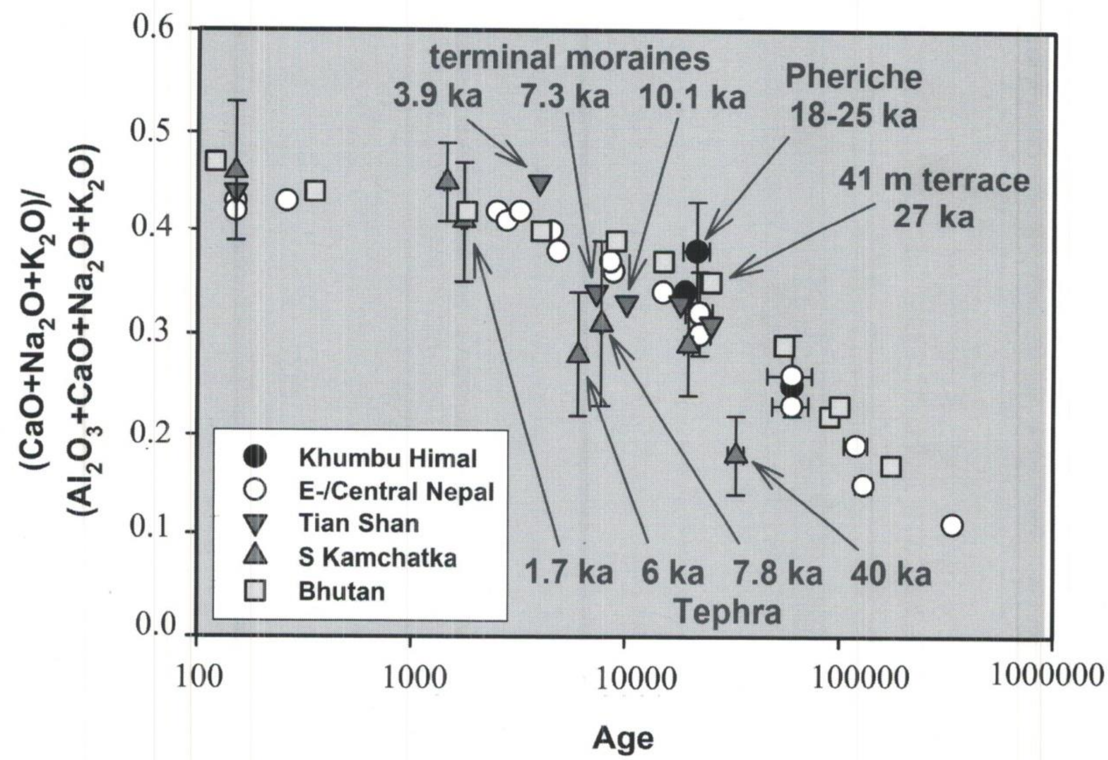

Fig. 6: Solum-weighted means of a soil development index after Kronberg and Nesbitt (1981) in combination with numerical datings. Examples are from this study, Eastern and Central Nepal, Tian Shan, and the Southern Kamchatka peninsula (Bäumler 2001; Bäumler 2004).

CONCLUSIONS

Time appears to be one of the major factors of soil formation. This holds especially for studies of soils which have been developed during the Quaternary period. However, a combination of methods are suggested to be applied which take into account physical and chemical weathering processes, and which may also display the various problems which may arise during soil formation. Including numerical dating, time-related soil studies provide information on the pedogenic history of the soils themselves, the landscape history of the study areas, and in the case of chronosequences information about past environmental fluctuations.

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