Turf-bearing topsoils on the central Tibetan Plateau, China: Pedology, botany, geochronology

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Abstract

Vast areas on the Tibetan Plateau are covered by alpine sedge mats consisting of different species of the genus *Kobresia*. These mats have topsoil horizons rich in rhizogenic organic matter which creates turfs. As the turfs have recently been affected by a complex destruction process, knowledge concerning their soil properties, age and pedogenesis are needed. In the core area of *Kobresia pygmaea* mats around Nagqu (central Tibetan Plateau, c. 4500 m a.s.l.), four profiles were subjected to pedological, paleobotanical and geochronological analyses concentrating on soil properties, phytogenic composition and dating of the turf. The turf of both dry *K. pygmaea* sites and wet *Kobresia schoenoides* sites is characterised by an enrichment of living (dominant portion) and dead root biomass. In terms of humus forms, *K. pygmaea* turfs can be classified as Rhizomulls mainly developed from Cambisols. Wet-site *K. schoenoides* turfs, however, can be classified as Rhizo-Hydromors developed from Histic Gleysols. At the dry sites studied, the turnover of soil organic matter is controlled by a non-permafrost cold thermal regime. Below-ground remains from sedges are the most frequent macroremains in the turf. Only a few pollen types of vascular plants occur, predominantly originating from sedges and grasses. Large amounts of microscopic charcoal (indeterminate) are present. Macroremains and pollen extracted from the turfs predominantly have negative AMS ^{14}C ages, giving evidence of a modern turf genesis. Bulk-soil datings from the lowermost part of the turfs have a Late Holocene age comprising the last c. 2000 years. The development of *K. pygmaea* turfs was most probably caused by an anthropo(zoo)-genetically initiated growth of sedge mats replacing former grass-dominated vegetation ('steppe'). Thus the turfs result from the transformation of pre-existing topsoils comprising a secondary penetration and accumulation of roots. *K. schoenoides* turfs, however, are characterised by a combined process of peat formation and penetration/accumulation of roots probably representing a (quasi) natural wetland vegetation.
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Keywords: Alpine turf; Qinghai-Xizang Plateau; Topsoil properties; Vegetation change

1. Introduction

On the Tibetan Plateau, vegetation belts rich in sedges occur in the subalpine and alpine storey (Atlas of Tibet Plateau, 1990). The north-eastern part is covered in extensive areas (c. 3000–4000 m a.s.l.) by subalpine sedge mats mainly consisting of *Ko-bresia humilis* (C.A. Mey. ex Trautv./Serg.). This vegetation zone includes forest islands of spruce (*Picea*) and juniper (*Juniperus*), and interfingers downwards with dense coniferous forests and steppes. On the other hand, the eastern part of the central Tibetan Plateau around Nagqu and Amdo (c. 4000–5000 m a.s.l.) is covered by alpine mats consisting of the tiny sedge species *Ko-bresia pygmaea* (C.B. Clark), which is 2–3 cm in height. Such mats also occur in the upper altitudes of the southern Tibetan Plateau up to c. 6000 m a.s.l. (Miehe, 1989). Including degra-dation stages, the total area of zonal *Kobresia* mats ('alpine

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meadows') mapped in the Atlas of Tibet Plateau (1990) comprises c. 450,000 km^2 (Fig. 1). It is considered to be the world's largest alpine ecosystem (Miehe et al., in press).

Apart from the sedge mats described above, sedge swamps of *Kobresia schoenoides* (C.A. Mey./Steud.) form an additional azonal vegetation pattern at water surplus sites. The total area of these wetlands on the Tibetan Plateau is given as c. 80,000 km^2 (Atlas of Tibet Plateau, 1990).

A common pedological feature of both (relatively) dry *K. pygmaea* and *K. humilis* sites and wet *K. schoenoides* sites is the presence of topsoil horizons rich in rhizogenic organic matter creating so-called *turfs* (also named sods, mats or swards; Retzer, 1956; Green et al., 1993; Luo et al., 2005). This uppermost soil horizon may have a thickness of a few centimetres to a couple of decimetres and appears to consist mainly of felty remains of living and dead fine roots. Actually, there is an intensive mixture of roots, amorphous humus and minerogenic matter. The turfs are extremely firm and widely used for rural construction purposes as walls and shelters, and sometimes also as fuel. This particularly applies to the turfs covered by *K. pygmaea*. Turfs occur in nearly all relief positions (tops, slopes, depressions) and cover different substrates and soil types.

On a smaller areal scale, further occurrences of turf-producing *Kobresia* ecosystems are known from other Eurasian mountain areas (Himalayas, Wutai Shan, Altai), from North America (Rocky Mountains, Canadian Arctic Archipelago) and Greenland. The turf phenomenon has also been described in connection with other alpine vegetation-types rich in graminoids and perennial herbs (European Alps, Caucasus, Andes, New Zealand Alps) as well as with Arctic and Antarctic vegetation rich in graminoids, bryophytes and lichens (see Kaiser, 2007). In general, the large proportion of below-ground phytomass serves as a carbohydrate reservoir for the plants to grow rapidly after the snowmelt/shrinkage of frost, and facilitates the rapid uptake of water and nutrients under the prevailing harsh climatic conditions in high alpine and non-alpine tundra ecosystems (Wielgolaski, 1997).

The turf-bearing soils from the Tibetan Plateau are variably termed in Chinese pedological references; for example, 'grass-root soils' (Chinese Academic Expedition Group, 1985), 'felty soils' (Atlas of Tibet Plateau, 1990), 'cryo-sod soils' (Bao, 1992), 'alpine meadow soils' (Shi et al., 2004) or 'mattic cryic cambisols' (Wang et al., 2007). However, there has been no pedogenic investigation on the formation of *Kobresia* turfs so far. According to biogeographical and paleoecological records, the *Kobresia* pastures on the Tibetan Plateau partly represent a secondary plant formation adapted to livestock grazing (Miehe et al., in press). Consequently, the *Kobresia* turfs and underlying soil horizons might represent an important archive for the regional Holocene environmental history, possibly reflecting vegetation changes.

As the turfs have recently been affected by a complex destruction process following climatic changes and human use (e.g. Zhang et al., 2006; Wang et al., 2007; Miehe et al., in press) knowledge concerning their properties, circumstances of formation, age and possible re-establishment is needed. Therefore, besides inadequate autecological knowledge on the genus *Ko-bresia*, three problems arise: (1) Soil properties and soil geographical/ecological aspects of turf-bearing soils on the Tibetan Plateau are only rudimentarily known. (2) Exact determinations of plant remains which build up the turf are lacking. Since changes in the Holocene vegetation have been suggested, accordant traces might be expected (e.g. charcoal? stratification of plant macro- and microremains?). (3) Since only few radiocarbon data from turfs have been published so far, *direct* datings on selected plant remains are required to date the establishment of the *Kobresia*-dominated vegetation. Accordingly, the objectives of the study presented here were to shed light on the pedological properties, the phytogenic composition and the dating of turfs using three profiles from 'dry' *K. pygmaea* sites and one profile from a 'wet' *K. schoenoides* site.

2. Materials and methods

2.1. Study area

The area around Nagqu (31°29′N, 92°04′E) represents the core area of *K. pygmaea* mats and, accordingly, of turf-bearing soils on the central Tibetan Plateau (Chinese Academic Expedition Group, 1985; Atlas of Tibet Plateau, 1990; Miehe et al., in press; Fig. 1, Appendices 1, 2). Relatively dry sedge mats cover the whole landscape except eroded sites, water surplus sites with *K. schoenoides* swamps, lakes and high-lying barren areas with screes of the gelifluction belt. In the study area, a hummocky relief prevails, except for a few mountain ranges and river valleys, comprising a total altitude range of c. 1300 m (4000–5300 m a.s.l.). The profiles analysed are located at altitudes between 4450 and 4570 m a.s.l. As upper-slope and crest sites are very often affected by erosional processes, only currently undisturbed sites of footslope, valley and basin position were chosen for analysis. Mean annual precipitation ranges from 589 mm (station Sogxian, 4023 m a.s.l.) to 431 mm (station Nagqu, 4507 m a.s.l.); mean annual air temperature (MAAT) fluctuates around 0 °C (Sogxian=+1.4 °C; Nagqu= −1.5 °C; Miehe et al., 2001). The area represents the headwaters of the Salween River. Several lakes and peatlands occupy the depressions. Nearly the whole area is covered by a thin layer of silty loess (Lehmkuhl et al., 2002) covering metamorphic and igneous rock. Additionally, morainic, fluvial-lacustrine and peaty sediments form the soil substrates. At present the land is mainly used for animal husbandry (yaks, goats and sheep). Field observations of eroded topsoils as well as assessments of grazing capacity and desertification have indicated that the *Kobresia* pastures are severely overgrazed, which has resulted in serious pasture deterioration (e.g. Clarke, 1998; Wei and Chen, 2001; Zhang et al., 2006).

2.2. Pedological analyses

Horizon designations and soil types are given using WRB (IUSS-ISRIC-FAO, 2006). Since the turf horizon had not yet been suitably named, a new designation was created for it: 'Afe'/'Hfe' (suffix *fe* from *fe*lty; Kaiser, 2004, 2007). Afe and Hfe horizons are characterised by a strong enrichment of felty
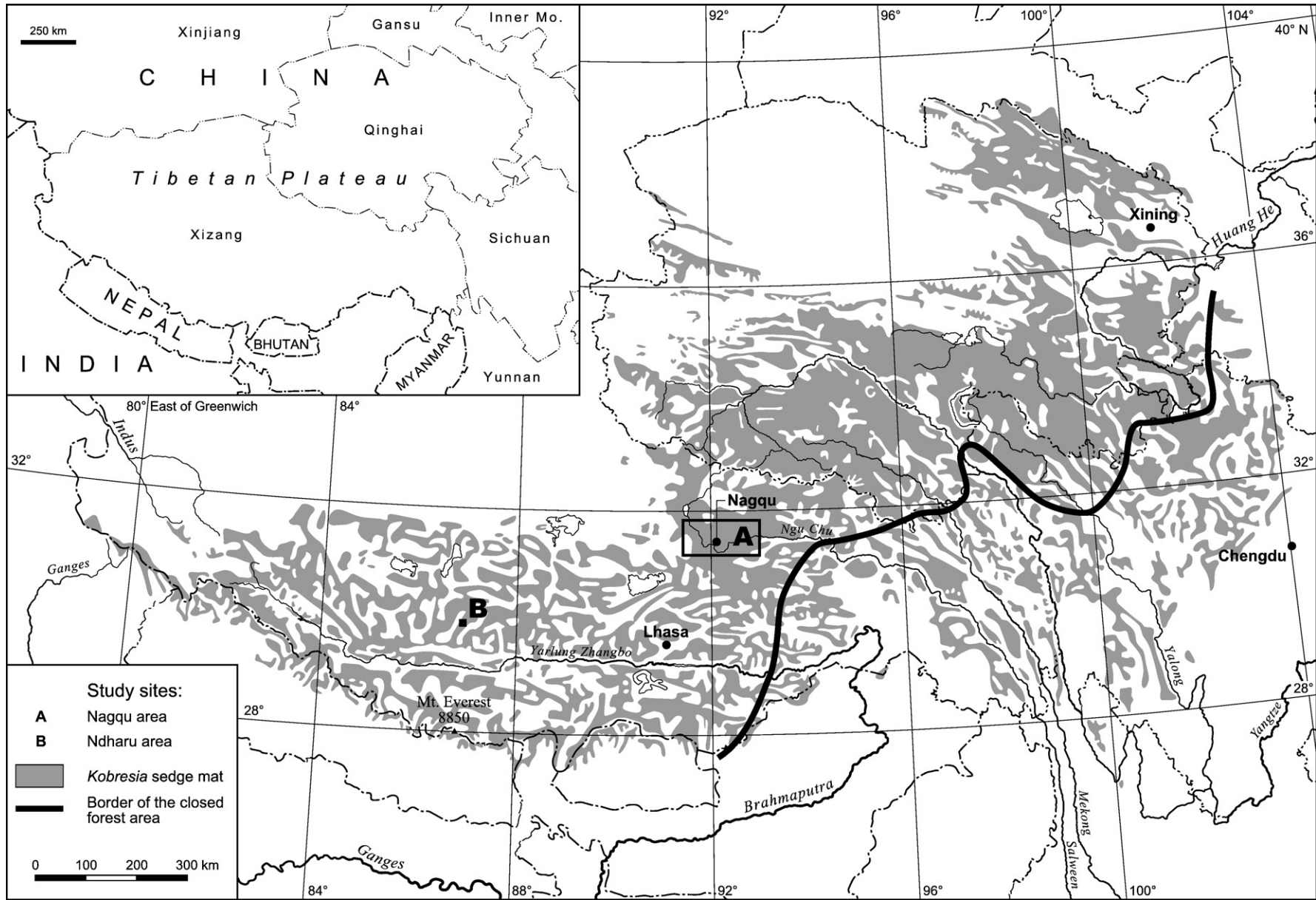
Fig. 1. Occurrence of alpine sedge mats on the Tibetan Plateau (genus *Kobresia*) and location of the study sites (adapted from Atlas of Tibet Plateau, 1990).

root biomass (>50 roots dm^{-2}), and distinguished from mollic A horizons by a 'massive' soil structure and considerable firmness.

A combined pipette and sieving test was used to determine the grain-size distribution. Organic carbon (OC) and total nitrogen (N_{tot}) were measured by dry combustion at 975 °C in duplicates. Samples were treated by burning for 2 h at 550 °C to determine the loss-on-ignition (= LOI). $CaCO_3$ was determined volumetrically. Soil pH was analysed potentiometrically in 0.01 M $CaCl_2$. Electrical conductivity (EC) was measured by means of an electrode. The content of well crystalline pedogenic iron oxides (Fe_d) was determined using the hot dithionite–citrate–bicarbonate method (Mehra and Jackson, 1960), whereas poorly crystalline forms of iron (Fe_o) were determined using the NH_4 oxalate solution method (Schwertmann, 1964). Fe concentration in the extracts was measured by atomic absorption spectroscopy. Total Fe and further main elements were determined by X-ray-fluorescence analysis of powdered samples after ignition of the ground samples at 975 °C. Both root content and LOI of the turf horizons were determined in 1-cm slices using undisturbed tin box samples ($20 \times 8 \times 5$ cm). To test the homogeneity of the solum, different ratios were calculated by means of the grain-size distribution and main/trace element composition (Alaily, 1984).

For micromorphological analysis an undisturbed sample was collected with a modified Kubiëna tin ($8 \times 6 \times 4$ cm). The block was air dried, impregnated with Palatal P80-21 and sliced into a $7.5 \times 5.5 \times 0.03$ cm thin section. The section was described at 12.5–400× magnification under a petrological microscope using principles and methods described by Stoops (2003).

2.3. Macro- and microremain analysis

The volume of the macroremain samples was measured by water displacement. The samples were boiled in KOH (5%) and sieved into three fractions (>1.0 mm, 0.5–1.0 mm, <0.5 mm). Macroremains are given in volume percentages based on the original volume (58.9–139.1 ml), in the categories <1%, 1–3%, 3–5%, and from 5 to 100% in steps of 5% based on the mesh plus. Fruits and seeds were counted and given in absolute numbers. Identification and nomenclature of macroremain types follow e.g. Berggren (1969) and Grosse-Brauckmann (1972).

Samples for microremain analysis, comprising pollen, spores and charred particles, were taken volumetrically (0.5 cm^3). A known quantity of exotic *Lycopodium clavatum* (L.) spores was added in order to calculate pollen concentrations (Stockmarr, 1971). Sample preparation followed Fægri and Iversen (1989). Identification and nomenclature of pollen types follow Punt et al. (1988), Moore et al. (1991) and Beug (2004). Since too few pollen were found that would allow the calculation of a statistically reliable pollen sum, only concentration values (Berglund, 1986) are presented.

2.4. Radiocarbon dating

AMS ^{14}C dating on macroremains was performed to date various sampling levels of turf horizons directly (sampling depth = 2–17 cm). From the same profiles, bulk-soil datings from the turf base should provide further chronological arguments (sampling depth = 13–30 cm). Additionally, from turfs on the southern Tibetan Plateau (Ndharu area; Fig. 1) both macroremains and pollen concentrations were dated. Macroremains were extracted according to the method given above. Due to the very small size of the samples (3.5–19.0 mg of seeds and root remains), they were only pre-treated with acid (HCl). Bulk-soil samples were pre-treated by the removal of roots and mobile humin acids. The soil organic matter fraction dated consists of humins, which are considered to be a reliable material for ^{14}C dating in soils (Pessenda et al., 2001). For the extraction of pollen grains a procedure by Brown et al. (1992) with several steps of cleaning and sieving was used. Further treatment of the samples followed the standard methods of the Erlangen AMS Laboratory (Scharf et al., 2007). The radiocarbon ages discussed in the text are uncalibrated (^{14}C years before present = BP).

3. Results and discussion

3.1. Pedological properties

Profiles NAQ 3 and 7 have well-developed brownish Bw or BwAh horizons showing low pH values (4.6–5.8) and a distinct content of pedogenic Fe compounds (Table 1, Appendices 2, 3, 4). Both aeolian silts/loams and morainic sands form the soil substrates. The total thickness of the main weathering zone (Afe + Ah + Bw horizons) amounts to 40–45 cm. A designation of soil types according to WRB (IUSS-ISRIC-FAO, 2006) is ambiguous. On the one hand, topsoil depth, colour and organic content could firstly qualify a mollic horizon. On the other hand, due to the characterising enrichment of root matter (see below), the Afe horizons show a more 'massive' than a granular or subangular soil structure, which is attributed to mollic properties. Furthermore, a mollic A horizon requires a base saturation (BS) of at least 50%. This most probably is not the case, considering the strong to very strong soil acidity (BS estimation acc. to Broll et al., 2005: <50%; BS estimation acc. to AG Boden, 2005: 20–<80%). Also the totalised thickness of Afe and underlying Ah/AhBw horizons (25–31 cm) is close to the limit for potential mollic horizons at these sites (>25 cm). Considering the conspicuous Bw horizons and the high content of organic matter within the upper 50 cm (up to 9.1% OC), the profiles can be classified more appropriately as Humic Cambisols than alternatively as Phaeozems. The Humi-Gleyic Fluvisol (NAQ 22) consists of fluvial sand showing a remarkably thick humic topsoil horizon (Afe + AhBg = 60 cm; Table 1, Appendices 2, 3, 4). The Histic Gleysol (NAQ 18) is characterised by a 30-cm thick peat layer overlying gyttja (Table 1, Appendices 2, 3, 4). In October 2003, this site was free of surface water. Organic matter content is relatively low (OC = 14.4%, LOI = 32.7%), indicating regular phases of water saturation and desiccation.

The EC of the profiles investigated ranges from 0.02 to 1.66 mS cm^{-1}, indicating non-saline site conditions (Schoeneberger et al., 2002). There are no distinct vertical differences of

Table 1
Basic analytical data of turf-bearing soils from the Nagqu area, central Tibetan Plateau

Profile/ horizon	Depth [cm]	Munsell colour moist	Clay, silt, sand [%]	Particles >2 mm [%]	fS:mS ratio	cSi+fS:mS+cS ratio	LOI [%]	OC [%]	N_{tot} [%]	C:N ratio	pH CaCl$_2$	CaCO$_3$ [%]	EC [mS cm^{-1}]
NAQ 3	Humic Cambisol, (1) aeolian loam/(2) morainic sand/(3) morainic sand, 4572 m a.s.l., 31°45′52.6″N, 92°37′47.6″E, footslope 10°S, *Kobresia pygmaea* mat												
Afe	0–18	10YR2/1	27, 37, 36	0	2.8	6.0	14.0	9.06	0.62	14.6	4.9	0	0.109
2Ah	18–31	10YR2/1	16, 22, 62	1	2.4	1.7	5.3	2.09	0.19	11.0	5.3	0	0.041
2Bw	31–45	10YR5/4	10, 22, 68	20	1.6	1.3	2.2	0.40	0.05	8.0	5.2	0	0.038
3C	45–70+	10YR5/3	5, 5, 90	20	0.6	0.3	1.1	0.08	0.01	8.0	5.3	0	0.020
NAQ 7	Humic Cambisol, (1) aeolian loam/(2) fluvial sand, 4484 m a.s.l., 31°51′46.7″N, 93°05′30.1″E, plain valley bottom, *Kobresia pygmaea* mat												
Afe	0–15	7.5YR3/2	29, 45, 26	1	1.8	4.0	20.6	8.98	0.55	16.3	4.6	0	0.090
AhBw	15–25	10YR4/2	24, 38, 38	3	1.8	1.6	6.5	2.58	0.26	9.9	5.8	0	0.059
BwAh	25–40	10YR5/3	27, 41, 32	5	2.1	2.1	4.3	1.09	0.17	6.4	5.8	0	0.044
2C	40–70+	2.5Y4/2	–	45	–	–	–	–	–	–	–	0	–
NAQ 22	Humi-Gleyic Fluvisol, (1) fluvial sand/(2) gyttja/(3) fluvial sand, 4446 m a.s.l., 31°18′58.4″N, 92°03′20.0″E, river floodplain, *Kobresia pygmaea* mat												
Afe	0–15	10YR4/2	11, 11, 78	0	1.2	1.4	6.3	2.45	0.19	12.9	5.9	0	0.349
AhBg	15–60	2.5Y3/2	10, 12, 78	0	1.4	1.5	5.7	2.44	0.18	14.3	6.2	1.2	0.189
Bg	60–72	2.5Y5/4	6, 7, 87	0	2.0	2.1	1.1	0.20	0.02	10.0	7.1	0	0.380
2Bg	72–76	2.5Y2.5/1	–	0	–	–	–	–	–	–	–	0	–
3Bg	76–90+	2.5Y6/3	–	0	–	–	–	–	–	–	–	0	–
NAQ 18	Histic Gleysol, (1) peat/(2) gyttja, 4568 m a.s.l., 31°35′17.8″N, 91°28′57.5″E, basin, *Kobresia schoenoides* swamp												
Hfe	0–30	2.5Y2.5/1	33, 48, 19	0	5.1	13.5	32.7	14.42	1.14	13.7	7.0	9.7	0.860
2Cr	30–70+	5Y4/2	29, 33, 38	0	2.6	3.0	4.2	1.11	0.07	29.3	7.2	7.8	1.660

The turf horizons are indicated by the designations Afe and Hfe, respectively.

the main element contents regarding the turf horizon and the underlying horizons except NAQ 18 (Appendix 4).

The depth functions of grain-size distribution, grain-size ratios (Table 1) and Ti–Zr ratio (Appendix 4) reveal inhomogenities (NAQ 3, 7, 18) as well as homogenities (NAQ 22) in the top soil horizons.

The uppermost horizons of both *K. pygmaea* sites (Afe) and *K. schoenoides* sites (Hfe) are characterised by an enrichment of root biomass. Fine roots (<2 mm) dominate the former; coarse roots (>2 mm) dominate the latter. According to the dominant bright colour of fine roots, the prevailing portion of root matter originates from living roots (Webber and Ebert May, 1977). This is corroborated by a previous study on *K. humilis* turfs on the north-eastern Tibetan Plateau (c. 3100–4100 m a.s.l.) showing exemplarily a soil organic matter (SOM) proportion in the depth interval 0–10 cm of 68.4% amorphous humus, 23.4% living roots and 8.2% dead roots (Bao, 1992).

The turfs from *K. pygmaea* and *K. schoenoides* sites have different contents of organic matter (*K. pygmaea* sites: OC=2.4–9.1%, *K. schoenoides* site: OC=14.4%; Table 1). Also the thicknesses of turf horizons clearly differ (*K. pygmaea* sites: Afe=15–18 cm, *K. schoenoides* site: Hfe=30 cm; Table 1). The root content is extraordinarily high (mean and standard error of counting in 1-cm slices dissecting the turf horizon: NAQ 3=14.6±0.9 roots cm^{-2}, NAQ 7=11.1±0.8 roots cm^{-2}, NAQ 22=3.0±0.7 roots cm^{-2}, NAQ 18=6.3±0.5 roots cm^{-2}; Fig. 2). Root content and LOI showed both a clear linear correlation (NAQ 3: $r=0.73$, $P=0.001$; NAQ 7: $r=0.93$, $P<0.001$) as well as no clear relationship (NAQ 22: $r=0.45$, $P=0.091$; NAQ 18: $r=0.47$, $P=0.009$). In general, both root content and LOI show clear gradients by depth. The C:N ratios

have values between 12.9 and 16.3 (Table 1), giving evidence of a mull humus form (Green et al., 1993).

The micromorphological thin section of the turf horizon in profile NAQ 3 reveals a large quantity of living and dead organic matter, especially fine roots (Appendix 5A). The volume of roots was measured, yielding a distinctly decreasing gradient by depth (Appendix 6A). There is evidence of an undulating soil density: A relative maximum at a depth of 3 to 6 cm is bordered by a relative minimum above and below (Appendices 5B, C, 6B). The section of higher density is probably caused by compaction by grazing animals. Furthermore, the lower section of the slice is far better aggregated than the upper one (Appendix 5B, C). The aggregates have an average diameter of c. 50 μm and consist of both organic and minerogenic substances, most probably representing droppings of Enchytraeidae (Dawod and FitzPatrick, 1993).

Living roots have an internal filling of cells and an external ring (cortex) of a substance showing birefringence/double refraction (Appendix 5D, E). Living roots are concentrated in the upper section of the slice. In the course of an incomplete decomposition, dead roots lost their internal cells; only the cortex remained (Appendix 5F, G, H). A test was performed to trace their chemical composition by means of a SEM-based microprobe. However, only carbon was detected frequently, but never calcium as an element occurring in calcite or calciumoxalates. Nearly all roots bear mycorrhiza or endophytic fungi (Appendix 5I, J). Hyphae of fungi (mycorrhiza or destruents) frequently occur in plant remains (Appendix 5K). Obviously, fungi play an important role for the uptake of nutrients and destruction of organic matter.

Traces of the soil macro- and meso-fauna, such as earthworms, soil mites and Diptera (flies), are lacking in the thin
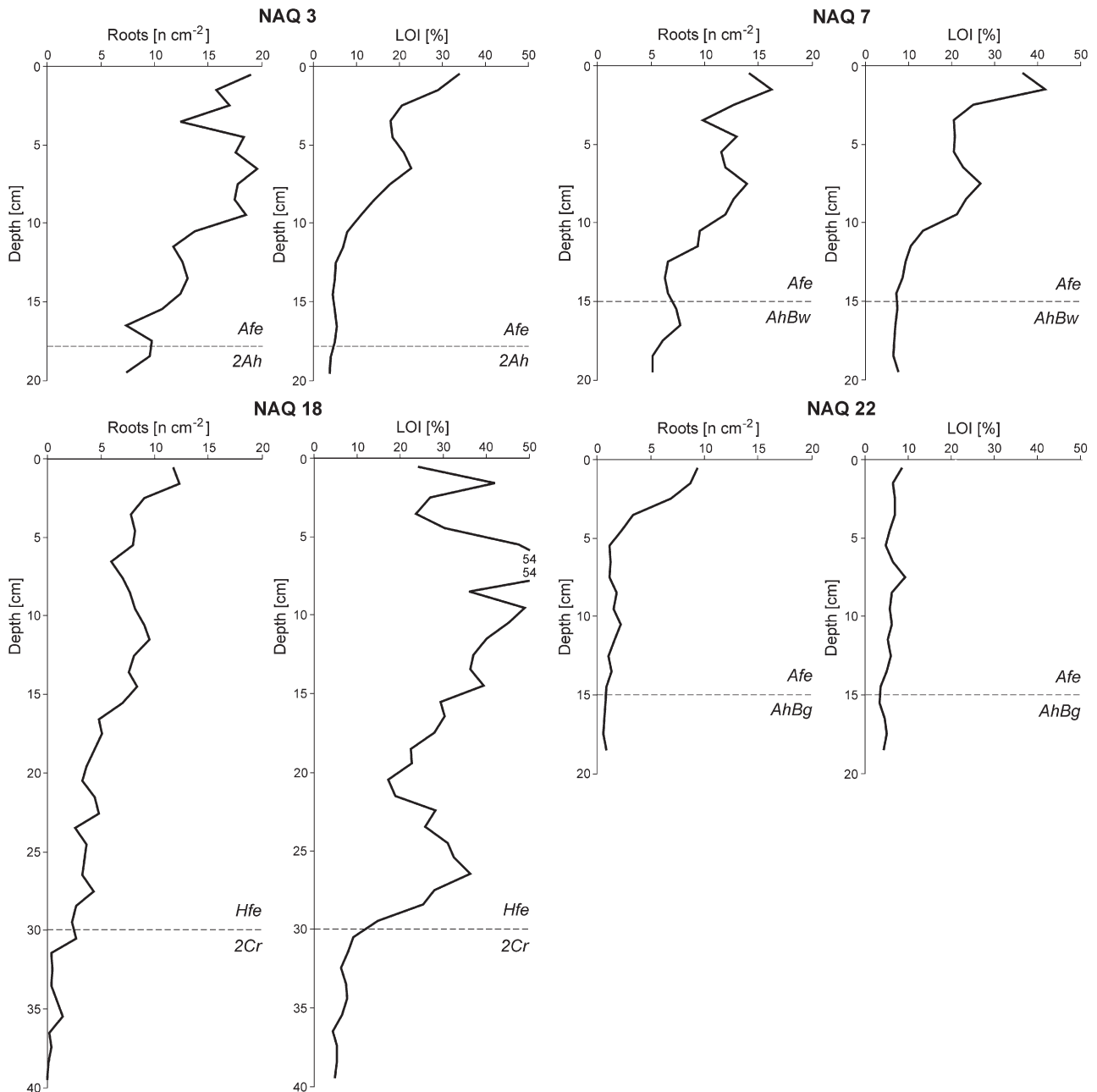
Fig. 2. Root counts and LOI content from turf horizons of the profiles investigated (thickness of the Afe/Hfe horizons according to the field record).

section except small Oligochaeta worms. Protozoa were detected sporadically. There is a distinct increase of Enchytraeidae droppings by depth ranging between 15 and 60% of the soil matter (Appendix 6C). This points at a distinct (but very local) influence of the fauna on the soil structure.

3.2. Macro- and microremain content

Remains of herbaceous roots and radicels were the most frequent 'macrofossils' (Table 2), whose determination on a genus or species level is prevented by the absence of clear anatomic properties. According to the excessively high amount of Cyperaceae (sedges) pollen (Appendix 7), however, these morphotypes can be attributed very probably to Cyperaceae.

Wood from perennials/dwarf-shrubs occurs in all profiles, which remain undetermined due to the lack of botanical data for comparison. Cyperaceae-type leaf sheaths and epidermis were also common, whereas Ericaceae type periderm as well as fruits and seeds from other species were only sporadically found.

In all samples only a few pollen types occurred (Appendix 7). The most frequent types are Cyperaceae, wild grass group, Lactucaceae, *Aster* type, whereas *Artemisia*, Caryophyllaceae undiff., *Stachys sylvatica* type and *Thalictrum* were seldom found. In NAQ 3, 7 and 22, the highest Cyperaceae values and the largest diversity of pollen types occur in the surface-near samples. In NAQ 18 the highest Cyperaceae values and the largest diversity of pollen types occur at lower depths. Very rare are pollen types that can be attributed to trees (*Pinus*, *Alnus*,

Table 2
Results of macroremain analysis

	Profile										
	NAQ 3			NAQ 7			NAQ 22		NAQ 18		
Sampling depth [cm]	2–6	8–12	14–18	2–6	8–12	14–18	2–6	9–12	2–8	13–17	24–28
Original volume [ml]	139.1	118.7	105.1	99.3	125.9	115.1	97.8	100.9	65.8	58.9	63.0
Macrofossil morphotype [%]											
Ericaceae type periderm	–	–	–	–	0.2	0.1	0.2	0.2	–	–	–
Salicaceae type periderm	–	1.0	–	–	–	–	–	–	–	–	–
Wood undiff.	1.6	–	–	–	–	–	–	–	–	–	–
Periderm undiff.	–	–	0.5	–	–	–	0.2	–	0.2	0.2	0.0
Wood root	16.4	1.3	2.0	23.4	16.7	6.8	2.8	4.2	3.3	–	–
Rootstock	–	–	–	0.1	–	–	–	–	–	–	–
Cyperaceae-type leaf sheath	2.2	–	–	13.9	0.1	–	6.1	4.2	15.7	0.8	–
Cyperaceae epidermis	–	–	–	0.1	–	–	–	–	–	–	–
Rosaceae/Ranunculaceae type seed	–	–	–	–	–	–	–	–	7.0	–	–
Cyperaceae nutlet	–	–	–	1.0	–	–	–	–	–	–	–
Large radicel black	2.7	–	–	–	–	–	–	0.7	6.7	2.5	1.4
Radicel diameter <0.4 mm, black	0.6	1.0	0.9	–	0.1	0.2	0.1	–	0.2	0.6	0.1
Radicel diameter <0.8 mm	14.1	5.8	6.2	10.1	11.4	4.8	3.0	4.9	6.8	3.0	0.2
Radicel diameter <0.8 mm, fungified	15.5	5.8	6.2	9.0	2.1	1.1	9.0	1.4	–	–	–
Radicel diameter >0.8 mm	–	–	1.0	–	–	–	1.3	1.4	5.0	2.5	0.8
Radicel with root hairs	–	–	–	–	–	–	–	–	0.8	0.4	2.4

Data of morphotypes are given in volume percentages based on the original volume. Difference to 100% corresponds to the loss-on-conditioning.

Betula), certainly originating from long-distance transport (Schlütz, 1999; Yu et al., 2001; Shen, 2003; Herzschuh et al., 2006).

In the samples of all profiles, large amounts of microscopic charcoal (<100 μm; Whitlock and Larsen, 2001) occur, which is indeterminable due to the lack of anatomic properties (e.g. bordered pits; Appendix 7).

Various fungal spores have been detected in the samples (Appendix 7). In particular Type 172 was found in large amounts. It mainly grows on dung (van Geel et al., 1983). Types 55A and 55B represent coprophilous fungi as well (van Geel et al., 2003). Types 140 and 263 were described from wet and eutrophic sod-sites so far (van Geel et al., 2003). Type 124 occurs in all profiles analysed, indicating mesotrophic to eutrophic site conditions (Pals et al., 1980). Microfossil type 207, representing chlamydospores of *Glomus* (an indicator for soil erosion; van Geel et al., 1989), has high values in the surface-near samples of NAQ 3, 7 and 18, and in the lower sample of NAQ 22.

In all profiles, the highest values of rootlet remains occur in the surface-near samples. The highest amounts of above-ground macroremains and pollen of Cyperaceae were also found near the surface except in NAQ 18. Sedges, therefore, must have been the most important producers of the turf. These might have been *Kobresia*- and/or *Carex*-species: a more precise conclusion cannot be drawn from the pollen or macroremains determined.

3.3. Radiocarbon ages

The extraction of suitable macroremains – pre-eminently fruits and seeds, furthermore branches of mosses as well as leaf sheaths and stems of sedges – yielded only small amounts ranging from 0.1–2.2 mg for seeds, via 0.5–3.4 mg for mosses to 0.5–16.3 mg for leaf sheaths and stems. Thus, only an assorted macroremains sample per sampling level met the requirements for dating forming total sampling weights of 3.5–19.0 mg.

All macroremain samples from the Nagqu area yielded negative radiocarbon ages (Table 3). The atmospheric nuclear weapon tests in the 1950s and early 1960s caused a steep increase of atmospheric ^{14}C production to nearly double the natural value in 1963, leading to 'hyper-modern' ^{14}C contents in naturally produced organic material, thus to highly negative radiocarbon ages (e.g. Scharpenseel and Pfeiffer, 1998; Trumbore, 2000; Six and Jastrow, 2002). Thus the radiocarbon ages of the macroremains analysed can be clearly identified as modern (after 1950).

The four ages from bulk-soil dating range from 1882 ± 50 to 395 ± 53 BP (Table 3). Taking the relatively low (recent) perturbation by the soil fauna as well as a probable top-down penetration of roots into account, these datings could provide humus ages of the (pre-existing) Ah and H horizons. However, measured ^{14}C ages of SOM or its fractions are always younger than the true ages due to continuous input of organic matter into soils (Wang et al., 1996). Furthermore, soil dating research unanimously shows that ^{14}C dating of bulk SOM from different depths below the surface does not give an exact numerical age, because SOM consists of a continuum of organic materials in all stages of decomposition (e.g. Scharpenseel and Becker-Heidmann, 1992). Thus the data available represent only approximations, but indicate a (very) Late Holocene age of the turfs with high probability.

The datings from profiles in the Ndharu area, southern Tibetan Plateau (Table 3, Fig. 1), yielded modern and pre-modern ages. The ages of pollen concentrations of Sod I (34 ± 38 BP, *Kobresia yadongensis* Y.C. Yang) and Sod III (-82 ± 57

Table 3
Results of AMS ^{14}C dating

Profile	Altitude [m a.s.l.]	Sampling depth [cm]	Material dated	Lab No. Erl-...	[14]C content [% Modern]	[14]C content SD [% Modern]	δ^{13}C [‰]	[14]C age [years BP]	[14]C age SD [years BP]	Calendar age [a] [years AD]	Present sedge species [b]
NAQ 3	4572	2–6	Macroremains	8060	107.71	0.67	−25.3	−597	50	>1958	1
NAQ 3	4572	16–18	Humin fraction	8066	79.11	0.49	−26.4	1882	50	21–242	1
NAQ 7	4484	2–6	Macroremains	8061	110.15	0.56	−26.3	−777	41	>1958	1
NAQ 7	4484	13–15	Humin fraction	8067	91.39	0.56	−26.3	723	49	1214–1389	1
NAQ 22	4446	2–6	Macroremains	8064	124.56	0.67	−25.4	−1764	43	>1960	1
NAQ 22	4446	9–12	Macroremains	8065	123.88	0.64	−25.8	−1720	41	>1960	1
NAQ 22	4446	13–15	Humin fraction	8069	95.20	0.63	−26.8	395	53	1431–1634	1
NAQ 18	4568	2–8	Macroremains	8062	125.54	0.64	−28.0	−1827	41	>1962	2
NAQ 18	4568	13–17	Macroremains	8063	119.28	3.61	−26.8	−1416	243	>1958	2
NAQ 18	4568	28–30	Humin fraction	8068	90.55	0.47	−28.1	798	42	1165–1279	2
Sod I	5065	6–8	Pollen	7999	99.58	0.47	−27.7	34	38	1693–1955	3
Sod III	5065	8–11	Pollen	8001	101.03	0.72	−27.4	−82	57	>1955	1
Sod V	5065	16–20	Macroremains	7995	96.08	0.64	−25.5	321	54	1451–1658	2
Sod V	5065	16–20	Humin fraction	8002	98.56	0.72	−26.9	117	59	1668–1944	2

[a] Two sigma calibration according to Hua and Barbetti (2004) and Reimer et al. (2004), respectively. Calibration is only valid for single year samples.
[b] Dominant present-day plant species: 1 = *Kobresia pygmaea*, 2 = *K. schoenoides*, 3 = *K. yadongensis*.

BP, *K. pygmaea*) indicate the presence of pollen in the turf from before the bomb peak and from after it.

4. Final discussion

4.1. Soil classification and turf formation

In the Nagqu area, turfs occur in nearly all relief positions: at dry tops and slopes as well as wet depressions. They cover different substrates and soil types. Most of the turf profiles recorded belong to the dry *K. pygmaea* facies predominantly comprising Cambisols, supplemented by Leptosols, Chernozems and Fluvisols. Wet-site profiles have a *K. schoenoides* vegetation and predominantly represent Histic Gleysols supplemented by Fluvisols. Consequently, at dry *K. pygmaea* sites, a (Humic) Cambisol with an idealised succession of Afe/Ah/Bw/C horizons is the prevailing soil type (Kaiser, 2007).

According to the results presented, turf horizons are not comparable with ordinary O horizons terming organic layers on top of mineral soils (Green et al., 1993; AG Boden, 2005; IUSS-ISRIC-FAO, 2006). The differences consist in the intensive mixture of fine roots, amorphous humus and minerogenic matter as well as the relatively small amount of organic matter and the remarkable firmness of the turfs. Using the Canadian classification of humus forms (Green et al., 1993) and the revised German classification of humus forms (Broll et al., 2006), respectively, dry-site *K. pygmaea* turfs can be classified as Rhizomulls or rhizic Mulls mainly developed from Cambisols. Wet-site *K. schoenoides* turfs, however, can be classified as Rhizo-Hydromors or rhizic 'Moor(e)' developed from Histic Gleysols.

At sites without groundwater influence, the genesis of the turfs was already previously attributed to both a permafrost-dependent slow turnover of organic matter and to a stagnant soil water regime (Chinese Academic Expedition Group, 1985). Also Bao (1992) claimed water saturation during the summer rainy season in the topsoil of a (dry) *K. humilis*-dominated vegetation, which would prolongate decomposition. At our dry

sites (NAQ 3, 7), however, signs of recent permafrost conditions such as gleyic or stagnic properties, mottling of humus or a platy structure were not detected. In contrast, most of the higher-lying sites in the Nagqu area (>4800 m a.s.l.) have clear properties of present-day periglacial processes (patterned ground/sorting, frost-shattering, vertically oriented mineral clasts, gleying; Kaiser, 2007). Thus at dry *K. pygmaea* sites of the altitudes investigated, the decay of SOM seems to be mainly controlled by a non-permafrost cold thermal regime, which is indicated by low MAATs around 0 °C. At wet *K. schoenoides* sites, water saturation forms an additional factor reducing the decomposition of roots. Obviously, at both sites, a further factor prolonging decomposition of rhizogenic organic matter might consist in the impregnation of dead roots by a substance (cortex) showing birefringence.

The development of dry-site *K. pygmaea* turfs is to be considered as a continuous penetration of below-ground matter into the topsoil. In contrast, the growth and deposition of above-ground organic material is marginal. Arguments for this are (1) that an O horizon is always lacking and (2) that hardly any fruits, seeds and other above-ground parts of plants were found in the lower parts of the turfs. Also the fact that the highest Cyperaceae pollen values and the greatest diversity of pollen types occur near the surface are an indication of this mechanism. An argument against the possibility that the smaller amount and lower diversity of plant remains in the lower layers are the result of oxidation is that in general pollen corrosion in the lower parts is not higher than in the upper parts. A further argument for the 'root penetration mechanism' forming the turfs is the distinct gradient of both roots and organic matter within the turf horizon.

4.2. Soil–vegetation relationships

Generally, in comparison to other topsoil horizons from alpine sites (unburied, dry: e.g. Beug and Miehe, 1999; Gavin and Brubaker, 1999; Blinnikov, 2004), the paleobotanical (especially palynological) archive potential of *K. pygmaea* turfs from the Nagqu area seems to be very

restricted, according to our results. They are characterised by a low variability of pollen taxa from mainly locally growing vascular plants and by an obviously young age. Moreover, the variability and long-term preservation of macroremains also appears to be low. Neither macro- nor microremains – except charcoal particles – reflect a probable Late Holocene vegetation succession. This is most probably caused by the long-term corrosion of plant remains in the well-aerated topsoil zone (Havinga, 1984).

However, the wide range of fungal spores recorded gives additional information about the site (e.g. input of dung, trophic level, moisture). High values of *Glomus* can be connected with soil erosion (van Geel et al., 1989). The occurrence of this type in our samples, therefore, might point to a treeless landscape around both dry and wet sites influenced by (former?) redistribution of soils.

The microscopic charcoal recorded could be evidence of a flammable local vegetation in the past. However, as the charred particles might originate at least partially from long-distance aeolian transport (e.g. Whitlock and Larsen, 2001; Benedict, 2002), the following assumptions should be regarded most carefully and need further research. On a larger areal scale, a burned *K. pygmaea* vegetation has never been observed or reported from the Tibetan Plateau so far except at tree-line sites (Winkler, 2000). In general, both *K. pygmaea* and *K. schoenoides* sods are flammable provided that they are extracted from the soil and dried. This is proven by their use as fuel on a local scale (Clarke, 1998). Thus, at least for the *K. pygmaea* sites, we may exclude with high probability that the charred particles originate from a sedge-dominated vegetation. According to experimental vegetation studies at pasture exclosures on the north-eastern and southern Tibetan Plateau (Miehe et al., 2003, in press), even the recent *K. pygmaea* mats in the Nagqu area may have been preceded by a grass-dominated (= steppe-like) vegetation.

Directly from the Nagqu area, a long-term record of the Holocene vegetation history is available only in the form of a both botanically and temporally low-resolution pollen diagram from Lake Ahung Co (4600 m a.s.l., c. 10 km north of Nagqu; Shen, 2003; Appendix 1). During the Early and Mid-Holocene, steppe/grassland elements (*Artemisia*, Gramineae) have rather high pollen percentages, whereas in the Late Holocene the pollen percentages of Cyperaceae markedly increase. However, this is interpreted as an effect of local wetland expansion coming from a drop in the lake level. In contrast, a further pollen diagram from Lake Co Ngion (4515 m a.s.l., c. 50 km west of Nagqu) reflects regional vegetation changes, revealing a detailed history of 'meadow' (= alpine sedge mats) and steppe ecotonal shifts finally resulting in 'meadow' vegetation since c. 1500 BP (Appendix 1; Shen, 2003). Pollen diagrams from Lake Nam Co (4740 m a.s.l., c. 120 km southwest of Nagqu, Appendices 1, 8; S. Adamczyk, unpubl.) and from the vicinity of Damxung (4250 m a.s.l., c. 140 km southwest of Nagqu, Appendices 1, 9; Schlütz et al., 2007) show an increase of Cyperaceae in the beginning Late Holocene (c. 3000–4000 BP), which might represent an expansion of sedge mats. The parallel share of synanthropic taxa (Frenzel, 2002) points to a strong

anthropo-zoogenic influence. Biome reconstruction from a further pollen diagram c. 130 km northwest of Nagqu (Appendix 1; Lake Zigetang, 4560 m a.s.l.) suggests a dominance of temperate steppe vegetation during the first half of the Holocene, while alpine steppes with desert elements tend to dominate the second half (Herzschuh et al., 2006).

4.3. Turf dating

Taking all radiocarbon data yielded into account, the questions arise (1) 'are they reliable' and, closely connected therewith, (2) which aspect of turf dating – comprising a time span from the (first) establishment to the latest presence/growth of the *Kobresia* vegetation – do they reflect? Even relatively deep-lying macroremain samples from the Nagqu profiles gave highly negative radiocarbon ages. In general, a mixture of 'old' carbon coming from fossil *Kobresia* remains and 'new' carbon coming from subrecent or recent *Kobresia* remains cannot be ruled out. However, even the datings on pollen concentrations from turfs of the Ndharu area (southern Tibetan Plateau) gave recent and negative ages, respectively. Thus different sampling methods have produced similar results, leading to the conclusion that at least parts of the turfs are modern. The bulk-soil datings from the turf base reveal at least a (very) Late Holocene age. Against the background of a 'high turf age hypothesis' based on one (!) ^{14}C age from the Nepalese Himalayas (Beug and Miehe, 1999; Miehe and Miehe, 2000; Appendix 10C), our data give evidence of a present-day or continuing turf formation. In this sense the radiocarbon data can be regarded as 'reliable'. The local establishment of a *Kobresia* species dominated vegetation and the accordant *onset* of turf formation, however, cannot be determined.

The *Kobresia* turf datings from Tibet and the adjacent Nepalese area can be differentiated with respect to their mode and reliability (Appendix 10). Most of the radiocarbon datings available suggest a (very) Late Holocene to recent age of *Kobresia* turfs, refuting previous ideas on their possibly greater age (Beug and Miehe, 1999; Miehe and Miehe, 2000). Another interpretation assuming a greater age of the turf but actually yielding younger ages due to the turnover/constant renewing of sedge plant matter cannot be ruled out. In the area under study, turf formation is definitely a process which continues today.

4.4. Rates of turf formation and model on soil genesis

For the Tibetan Plateau, studies focussing on soil genesis and soil geography including their ecological and (paleo-) environmental implications are rare (e.g. Chinese Academic Expedition Group, 1985; Iwatsubo et al., 1989; Smith et al., 1999; Zhang et al., 2006; Kaiser et al., 2007; Wang et al., 2007). Moreover, systematised data on rates of regional soil forming processes – comprising the profile development from the initial to the mature stage (e.g. Huggett, 1998) – are completely lacking so far. In contrast, there exist numerous studies from alpine areas in various parts of the world dealing with soil genesis, rates of soil forming processes and soil–vegetation relationships as well as

weathering aspects and carbon storage (e.g. Bockheim and Koerner, 1997; Wielgolaski, 1997; Scharpenseel and Pfeiffer, 1998; Bäumler, 2001; Hitz et al., 2001; Baillie et al., 2004; Darmody et al., 2004; Egli et al., 2006).

On the Tibetan Plateau, two studies have dealt with the turnover time of SOM at dry *Kobresia*-covered sites. However, roots were removed before analysis, so that the total SOM was in each case certainly underestimated. The turnover time of SOM in a topsoil horizon from a subalpine *Kobresia cuneata* mat on the south-eastern Tibetan Plateau (3900 m a.s.l., MAAT = −1.4 °C) amounts to c. 30 years (Wang et al., 2005). Furthermore, the turnover time in the topsoil horizon of a *K. humilis* mat on the north-eastern Tibetan Plateau (3200 m a.s.l., MAAT = −1.7 °C) has a range from c. 45 years (2–4 cm) to 900 years (8– 10 cm; Tao et al., 2007). Consequently, these studies argue that turf horizons from sites at higher altitudes with *K. pygmaea* vegetation might also comprise SOM turnover times ranging from a few decades to some centuries.

Some data are available to outline the deposition rates of organic matter at permanently wet sites on the Tibetan Plateau. According to dated peat sections/Histosols (50–380 cm thick) from the eastern part of the Plateau, Holocene deposition rates amount to c. 0.1 to 1.0 mm a^{-1} (Schlütz, 1999; Yan et al., 1999; Frenzel, 2002). However, these quasi-continuously accumulating sites with greater peat thicknesses are hardly comparable with the *K. schoenoides* sites found in the Nagqu area, which have thin peat layers only (10–30 cm; Histic Gleysols; Kaiser, 2007) representing periodically wet sites with discontinuous peat formation.

Our results and further material allow soil profile genesis to be modelled both for dry *K. pygmaea* sites and wet *K. schoenoides* sites on the central Tibetan Plateau lying at c. 4500 m a.s.l. (Appendix 11). A till–loess sequence was used for an exemplary *K. pygmaea* site, whereas a till–gyttja–peat sequence was taken for an exemplary *K. schoenoides* site. The chronology of the first three stages in each case is a raw approximation and thus hypothetical. Since accordant data for the Nagqu area are widely lacking, information on timing of depositional and pedogenic processes from neighbouring areas as well as large-scale overviews have been integrated (see Kaiser, 2007).

5. Conclusions

(1) The uppermost horizon of both dry *K. pygmaea* sites and wet *K. schoenoides* sites is characterised by an enrichment of mainly living root biomass.

(2) In terms of humus forms (Green et al., 1993), *K. pygmaea* turfs can be classified as Rhizomulls mainly developed from Cambisols, whereas *K. schoenoides* turfs can be classified as Rhizo-Hydromors developed from Histic Gleysols.

(3) Below-ground remains of Cyperaceae are the most frequent macroremains. Sedges must therefore have been the most important producers of the turf both at *K. pygmaea* and *K. schoenoides* sites. Only a few pollen (microremain) types of vascular plants occur, which predominantly originate from sedges and grasses. Very rare are pollen types that can be attributed to trees, originating from long-distance transport. Large amounts of microscopic charcoal (indeterminate) occur. All in all, however, the paleobotanical archive potential of *K. pygmaea* turfs from the Nagqu area seems to be very restricted.

(4) Macroremains and pollen extracted from the turfs predominantly have negative AMS ^{14}C ages, giving evidence of a subrecent to modern turf genesis. Bulk-soil samples from the lowermost part of the turfs have a (very) Late Holocene age.

(5) At the altitude studied, the development of *K. pygmaea* turfs is most probably caused by an anthropo(zoo)-genetically initiated growth of sedge mats replacing former grass-dominated vegetation ('steppe'). Thus the turfs result from the transformation of pre-existing soils. *K. schoenoides* turfs, however, are characterised by a combined process of peat formation and penetration/ accumulation of roots probably representing a (quasi) natural wetland vegetation.

Acknowledgements

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.catena.2007.12.001.

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