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Holocene glacier fluctuations and migration of Neolithic yak pastoralists into the high valleys of northwest Bhutan

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ABSTRACT

Here we present geomorphologic, palaeoenvironmental and archaeo-botanical data which elucidate the Late Pleistocene and Holocene glacial history of the high, mountain-locked Himalayan valleys in northwest Bhutan and provide one of the earliest proofs of human activity yet known for the High Himalaya range. In this area, difficult to access, close linkage between climatic change, glacier fluctuations and human migration patterns has been discovered. Glacier systems in the studied area are characterized by avalanching and debris mantled glacier snouts, with the significant local influence of the Indian summer monsoon causing decoupling of glacier responses from temperature changes but supporting the idea of monsoonal forcing. Geomorphologic mapping, together with Optically Stimulated Luminescence (OSL) and radiocarbon dating of ice-proximal sediments, has been used to construct a local glacial chronology. Local ice-stream networks developed during the Early Holocene (ca 10,000–9000 a ago) and during the early part of the Mid Holocene (6710 $\pm$ 90–4680 $\pm$ 155 cal a BP) at which times there were ice advances of about 5 km from the modern glacier termini. At such times, the intensity of pro- and periglacial processes would have intensified and ice-dammed lakes were probably common as well, rendering human colonization of the high valleys in northwest Bhutan impossible. An abrupt shift to dry climatic conditions on the Tibetan Plateau between 5000 and 4500 a BP coincided with glacial decay and the onset of morphodynamically stable conditions on the broad valley floors of the high valleys in this part of the Himalaya. Palynological data suggest that the sudden disappearance of juniper and rhododendron pollen, the immediate onset of pollen input from cereals (confirmed by detailed SEM analysis) and a clear pattern of over-grazing, trampling and peat deterioration can be linked to human arrival in the valleys at ca 4280 $\pm$ 130 cal a BP. Extensive charcoal horizons dating to 4745 $\pm$ 250 and 4680 $\pm$ 155 cal a BP are interpreted as evidence for human use of fire and forest clearances and agree spatially and temporally with the pollen-based picture. Charcoal occurrences as old as 6710 $\pm$ 90 cal a BP might be linked to yet earlier exploration of these Himalayan valleys during phases of low glacial activity. We provide an account of the colonization of these high valleys in response to glacial and monsoonal change and argue that the most likely founder societies come from the Tibetan Plateau, where yak and barley based pastoralism and Neolithic settlements are known to have existed since the Mid Holocene.

1. Introduction

The High Himalaya and the Tibetan Plateau rank among the most extreme environments on earth and were thus one of the last terrestrial ecosystems colonized by human foraging groups (e.g. Alt et al., 2003; Madsen et al., 2006; Brantingham et al., 2007; Rhode et al., 2007a). The Tibetan Plateau has a mean elevation of 5000 m with little internal topography and forms the vast high-altitude core of central Asia, while the Greater Himalaya serves as the prominent topographic boundary in the south and, by contrast, displays considerable relative relief. Deep, unpassable gorges have been cut into the rapidly uplifting Himalayan crystalline rocks via fluvial

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incision. However, the upper reaches of many valleys are glacially overprinted (U-shaped) and thus comparatively broad and flat and some catchments are directly connected to the Tibetan Plateau by high-altitude passes (Gansser, 1983; Duncan et al., 1998, 2003).

Both the Himalaya and the Tibetan Plateau are profoundly affected by the Indian and the South Asian summer monsoon, deriving substantial amounts of precipitation from these atmospheric circulation systems. On millennial to centennial time scales variations in the monsoon intensity caused significant glacier fluctuations and landslides in several drainage basins of the Greater Himalaya, leaving strong imprints on landscape evolution and sedimentation (e.g. Barnard et al., 2004a,b, 2006; Bookhagen et al., 2005a,b; Owen et al., 2005; Gayer et al., 2006). On the Tibetan Plateau lake levels altered following shifts in the monsoonal precipitation patterns and resultant changes in the precipitation-evaporation balance, or else expanded in response to warming, which induced melting of previously accumulated ice (e.g. Gasse et al., 1991; Fang, 1991; Brown et al., 2003; Morrill et al., 2006; Yanhong et al., 2006). Glacier fluctuations *per se* had only a limited impact on the landscape evolution of the interior of the Tibetan Plateau and ice-cover was generally restricted in extent during most of the Late Quaternary (e.g. Schäfer et al., 2002; Owen et al., 2005).

Human colonization of such high altitude environments is constrained by a series of geomorphologic and ecological parameters: (i) the landscape has to be largely ice-free and morphodynamically stable to allow human groups to enter and sustain themselves (although seasonal exploitation of glaciers and smaller ice-fields of hunter-gatherers is documented); (ii) the availability of liquid water as well as fuel material has to be guaranteed (iii) the exploited territory must provide high biological productivity, which is sufficiently diverse to nurture and sustain human populations. Additionally, life at extreme altitudes is characterized by greater food and nutritional demands (Marriot and Carlson-Newberrry, 1996), greater capture costs and reduced physiological capacity (Brutsaert et al., 2000; Moore et al., 2000) as well as reduced fertility rates and high infant mortality (Brutsaert et al., 2000; Moore et al., 2004). In concert, these environmental and physiological parameters place severe constraints on any full-scale occupation of Central High Asia.

Some geneticists suggest that a substantial period of residence at high elevation—perhaps as long as 30 Ka—might be necessary to explain the unique physiological adaptations seen among contemporary Tibetan populations (Moore et al., 2000, 2004; Beall, 2001; Beall et al., 2004). Several archaeological sites at the northern rim as well as in the interior of the plateau have been discussed as representing possible occupation phases predating the last glacial maximum (i.e. are older than ca 20 Ka; An, 1982; Huang, 1994; Zhang and Li, 2002; Yuan et al., 2007). However, reliable absolute age control for these sites is missing. There is strong evidence for an initial colonization phase dating to 13–15 ka, which was restricted to the north eastern fringes of the Tibetan Plateau, namely the Qinghai lake, the Qaidam Basins and the surrounding mountain ranges (altitude range: 3000–4000 m asl; e.g. Madsen et al., 2006; Rhode et al., 2007a). The emerging archaeological view is that sustained occupation of the plateau interior (altitudes >4000 m asl) probably occurred during the early Holocene by human populations with Epipalaeolithic or Neolithic economic and social adaptations (e.g. Brantingham et al., 2007; Madsen et al., 2007 and references therein), a view supported by DNA analysis from Qian et al. (2000), Su et al. (2000) and Gayden et al. (2007). Furthermore, preliminary palaeoenvironmental data indicate that the human impact on these high altitude ecosystems (as well as adjacent areas in NW China) during the Holocene was potentially huge and may have resulted in widespread deforestation and intensification of soil erosion eventually as early as 4700 a ago (Ren, 2000; Kaiser et al., 2006; Miehe et al., 2006, 2007).

In most colonization models it is generally assumed that occupation of the northern and central Tibetan Plateau was initiated from low-elevation source regions situated in North and North West China and little attention has been paid to the role of the Greater Himalaya in the peopling of Asia's high-altitude core. One might assume that much of the main Himalaya range formed a barrier blocking human migration from the north to the south and vice versa (but see Gayden et al., 2007). Indeed, the available archaeological and palaeoenvironmental evidence for prehistoric human activity in the High Himalayas is extremely sparse (Agrawal and Kharakwal, 1998; Knörzer, 2000; Alt et al., 2003; Schlütz and Zech, 2004) partly due to the number and intensity of erosional processes, which are capable of destroying traces of former human occupancy within a short time.

Here we present evidence for one of the earliest phases of prehistoric human activity in the Eastern Higher Himalaya and provide a chronological framework for both the glacial history in NW Bhutan and for human migration into these high-altitude valleys. Our palaeoenvironmental and archaeo-botanical data indicate that Neolithic groups (most likely Tibetan tribes) established settlements in the course of an occupation phase at 4500 cal a BP. Their subsistence was based on barley and (most probably) yak pastoralism. We speculate that the high valleys of NW Bhutan may have been subject to a yet earlier immigration wave from the north dating back to 6700 cal a BP. Glacier fluctuations in the Bhutan Himalaya and shifting precipitation patterns on the Tibetan Plateau, both of which are responses to monsoonal forcing, exerted a strong influence on the migration routes used by these early Himalayan inhabitants.

2. The study area

The study area comprises the upper reaches of the Pho River and its tributaries above ~3300 m asl (known as Lunana among the Bhutanese, Fig. 1b). Down-valley the Pho River enters an impassable gorge and Lunana can thus only be accessed by crossing one of four 5000 m high passes (Fig. 2). Several passes connect NW Bhutan to the Tibetan Plateau but the 5500 m high Gonto La (La = pass) is the only direct entry into Lunana from the north.

With peaks rising to ~7000 m, the main Himalaya range forms the natural boundary between Lunana and the Tibetan Plateau. Steep south-facing cliffs and interconnected cirques dominate the local scenery. Glaciers up to 23 km in length originate in these cirques and extend down-valley to altitudes of about 4100 m asl. Above ~3500 m all valleys display a U-shaped cross-profile, with a valley floor infilling of Quaternary and Holocene sediments up to 1 km wide providing abundant living space.

The vegetation in Lunana displays clear altitudinal zoning. Today open conifer and *Juniperus* forests exist up to 4300 m asl, whereas *Juniperus*–*Rhododendron* scrub and alpine Cyperaceae mats occur above. Vegetation becomes much denser down-valley, the percentage of angiosperms increases and at about 3800 m asl closed canopy forests are encountered (Fig. 3d).

Lunana encompasses seven permanently-occupied small villages, the highest of which is situated at 4200 m asl (Thanza village, Figs. 2 and 3b). Several hundred people live in these high valleys today and linguistically belong to the Tibeto-Burman language family (Matisoff, 1991). Barley and vegetables (radish) are grown up to 4200 m asl and each household possesses yaks and sometimes sheep (Fig. 3). Families adopt an intra-household division of labour: they divide into those who are based in the village (as sedentary farmers) and those who move with herds of yaks (as semi-nomadic pastoralists; Karma, 1993; Gyamtsho, 2000).

The prehistory of the high valleys in NW Bhutan is virtually unknown (Wangchuk, 2000; Ardussi, 2006) whereas aspects of the

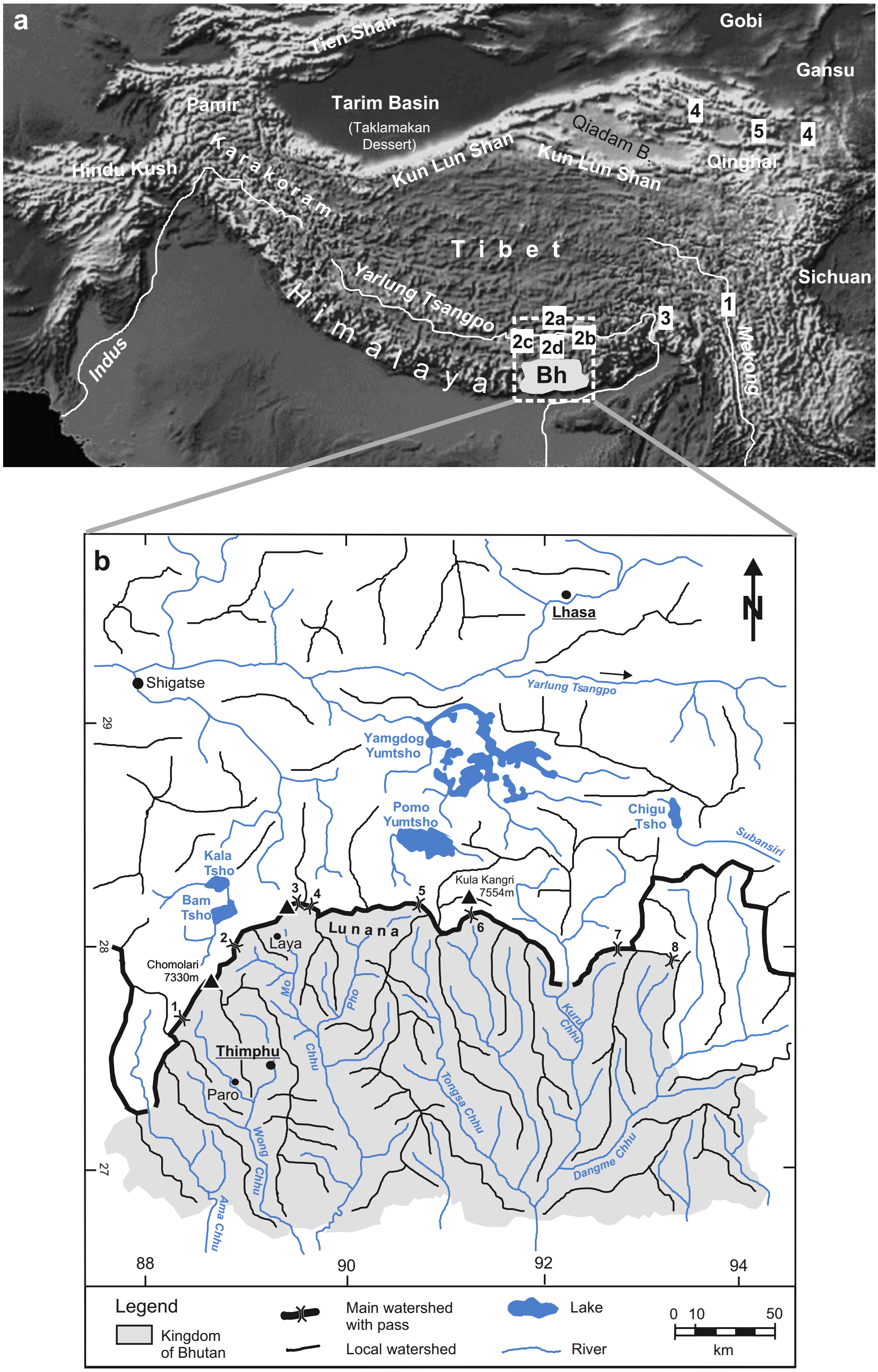

Fig. 1. Overview of central high Asia and the Bhutan Himalaya. (a) Digital elevation model of the Tibetan Plateau with surrounding mountain ranges and low elevation areas. Numbers indicate location of archaeological sites mentioned in the text. 1, Kha rub; 2, Sites around Lhasa and in the middle reaches of the Yarlung Tsangpo river (a, Qugong; b, Qinba; c, Changguogou; d, Bangga); 3, Sites at the great bend of the Yarlung Tsangpo (i.e. Jumu, Beibeng and Maniweng); 4, Qinghai Neolithic sites. (b) Overview of the Bhutan Himalaya and the adjacent sector of the Tibetan Plateau. Indicated are a.o. Lunana and Laya village (both in NW Bhutan) and the passes, which connect the Himalaya valleys with the Tibetan Plateau. 1, Phari and Peme La; 2, Jam La; 3, Toma La; 4, Waghye La; 5, Gonto La; 6, Melakarchung La; 7, Bon La; 8, Me La.

Quaternary geology of Lunana have previously been described by Gansser (1983) and Iwata et al. (2002). These authors established relative moraine stratigraphies but used differing nomenclatures for the observed glacial stages.

3. Methods

Detailed glacial geological mapping was conducted in the course of three field seasons and aided by topographic maps (scale 1:50,000,

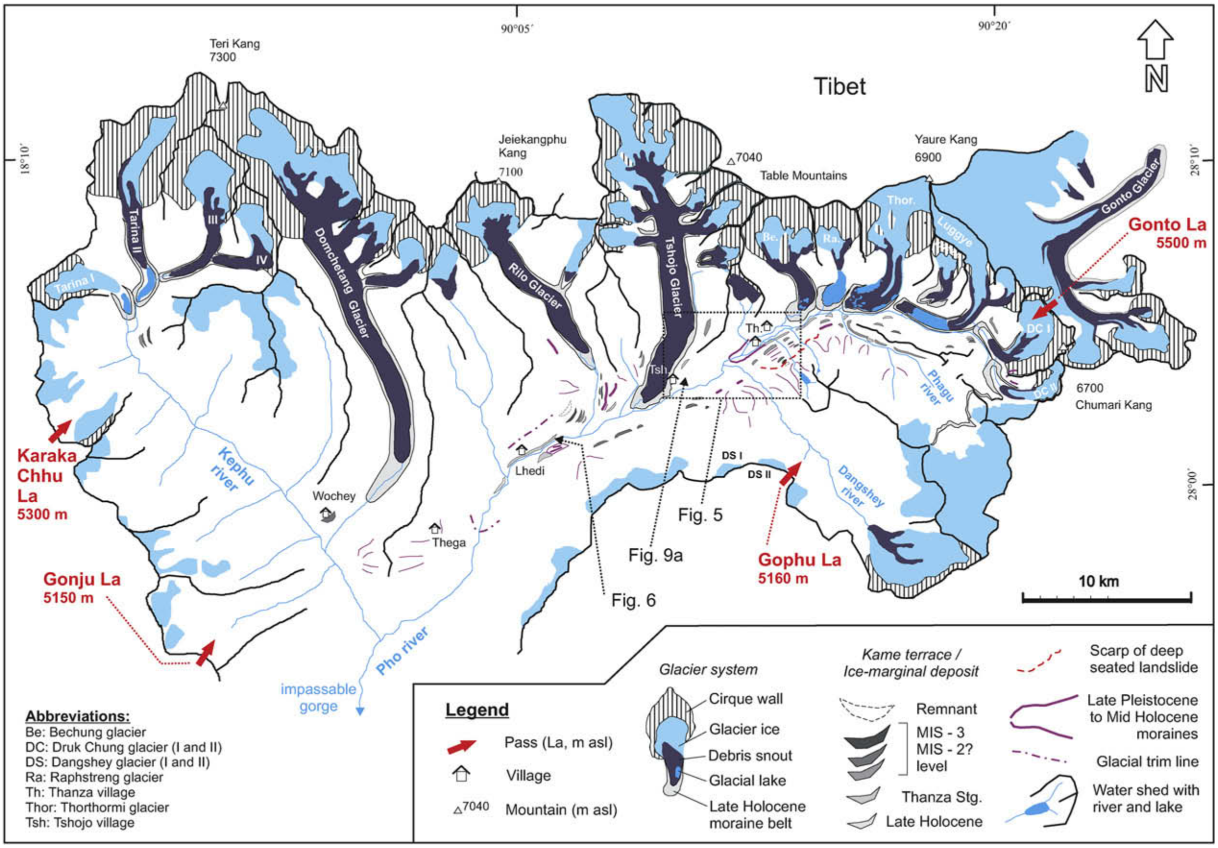

Fig. 2. Glacial-geological overview map of eastern Lunana. The areas covered by Figs. 5, 6 and 8 are indicated. The altitude of Lunana's main villages are: Thanza village (4200 m asl), Tshojo village (4000 m asl) and Lhedi village (3700 m asl). Refer to legend for further details and abbreviations of glacier and village names.

compiled by the Indian survey) and the interpretation of satellite imagery (IRS-1D Pan and Spot-Pan).

For sedimentological logging the lithofacies codes of Miall (1977) and Eyles et al. (1983) have been adapted. For a detailed sediment description see also supplementary online material S1.

To estimate the modern and former equilibrium line altitudes (ELA) the maximum elevation of lateral moraines (MELM) and the toe to summit altitude method (TSAM) were applied to selected modern glaciers with limited or no avalanche activity in the catchment area and little or no debris cover on the glacier snouts and to reconstructed palaeoglaciers (Gross et al., 1976; Meierding, 1982; Benn and Lehmkuhl, 2000).

Radiocarbon ages were measured using conventional as well as AMS dating techniques. The ^{14}C ages are calibrated and reported with 2 sigma errors relative to anno 1950 (i.e. cal a BP; Table 1).

Optically stimulated luminescence (OSL) dating was conducted on multi-grain aliquots of quartz and using a modified single aliquot regenerative (SAR) protocol (Murray and Wintle, 2000). The OSL and dosimetry data are described in detail in the OSL supplementary material S2.

The clay mineralogy of selected sediment and palaeosol samples were determined using standard X-ray diffraction (XRD) techniques (Wilson, 1987; Moore and Reynolds, 1997).

A total of 42 sub-samples were recovered for palynological investigations from a 74 cm long drill core taken from a peat deposit (the lowermost 2.5 cm of which were sampled quasi continuously with 5 sub-samples). Details concerning palynological sample preparation and pollen counts, as well as a list of the encountered taxa and statistics are provided as supplementary online material S3.

The peat deposit is still accumulating and the three radiocarbon ages (from 19, 35 and 74 cm depth) were fitted using a polynomial function to construct an age model for peat growth.

A hierarchical cluster analysis was performed (SPSS, Ward dendrogram using Euclidian squared statistics) to aid separation of the pollen contents of the samples into similar groups (Table 2).

Pollen size and pollen surface patterns of selected Poaceae grains (i.e. pollen diameter, pore diameter, annulus width and spinae) were examined using scanning electron microscopy (SEM) and light microscopy (LM) in order to distinguish cereal grains from pollen of wild grasses following procedures given in Beug (2004) and Halbritter (2000) (Table 3).

For total organic carbon (TOC) measurement 12–36 mg of dried sediment was weighed into special sample holders and analysed (at 980 °C) in the solid sample module of a Shimadzu 5000 TOC analyser.

4. Glaciation

4.1. The glacial system today

Lunana's major glaciers originate from huge south facing cirques, which are cut into the main Himalayan chain and are characterised by avalanche nourishment and heavily debris-mantled glacier snouts (Fig. 2). The adjacent mountain crests to the south (i.e. south of the Pho and Kephu River) are significantly lower in elevation (~5500–6000 m asl) and support small, often clean-ice glaciers or ice-caps.

The main rivers in NW Bhutan (e.g. Mo and Pho River) are N–S oriented and the Indian summer monsoon thus penetrates into the high-valleys of NW Bhutan unimpeded (Fig. 1b) delivering

Table 1
Radiocarbon ages reported in the text.

Lab. code	Dated material	Location (*related Figures*)	Sedimentary context	^{14}C Age (a BP)	Calibrated age (a BP)	Error (2 Sigma)	Calibration curve
Vera-2647	Charcoal	Thanza lateral moraine (*Fig. 5*)	Caly on top of buried palaeosol	5858	6710	±90	OxCal v.3.5
Poz-9911	Charcoal	NE of Tshojo village (*Fig. 9*)	Charcoal horizon in soil profile	4230	4745	±250	OxCal v.3.10
Poz-9930	Charcoal	SE of Laya village (*Fig. 9*)	Charcoal horizon in soil profile	4125	4680	±155	OxCal v.3.10
Vera-2650	Charcoal	SW of Tshojo village	Lenses on top of buried palaeosol	2705	2810	±60	OxCal v.3.5
Poz-9912	Charcoal	SW Lhedi village	Charcoal in river overbank deposits	1235	1220	±50	OxCal v.3.10
Ki-4931	Charcoal	Luggy lateral moraine	Organic rich layer on top of moraine	280	355	±70	Intcal. 98
Vera-2646	Wood	NE Lhedi village (*Fig. 6*)	Clay on top of kame terrace	4145	4700	±130	OxCal v.3.5
Poz-9974	Wood	S of Tshojo village	Lacustrine bottom sets	1590	1470	±70	OxCal v.3.10
Vera-2649	Peat	Behind Thanza lateral moraine (*Figs. 5, 8*)	Base of drill core	3850	4280	±130	OxCal v.3.5
Poz-9909	Peat	s.a.	36 cm Depth of drill core	3040	3255	±105	OxCal v.3.10
Poz-11584	Peat	s.a.	18 cm Depth of drill core	2030	1980	±90	OxCal v.3.10
Extrapolated age	Microscopic charcoal	Sample 31 of drill core	13 cm Depth of drill core		1400		
Extrapolated age	Microscopic charcoal	Sample 33 of drill core	11 cm Depth of drill core		1200		

Conventional radiocarbon dating was performed at the Leibniz Laboratory for Radiometric Dating, Kiel; AMS dating was conducted at the Vienna Accelerator Mass Spectrometry Laboratory and at the Poznan Radiocarbon Laboratory, respectively.

substantial amounts of precipitation during the summer months. Meteorological data, gathered by an automatic weather station in Thanza village from 2000 to 2001, indicate that about 80% of the mean annual precipitation (i.e. 500 mm) falls between June and August at a mean annual temperature of about 8 °C (Leber et al., 2002). We expect precipitation to be much greater in the steep south facing cirques due to the advection of moist air masses into the frigid high-altitude zone. Glaciers in NW Bhutan can thus be classified as summer accumulation type glaciers, i.e. the maxima in accumulation and ablation both occur during the summer months (e.g. Ageta and Higuchi, 1982; Thompson et al., 1997; Phillips et al., 2000; Owen et al., 2002). This glacier type is widely recognized in those parts of the Himalaya where the monsoon influence is strong.

The MELM and TSAM methods for calculation of the Equilibrium Line Altitude (ELA) gave comparable results for a set of eight selected glaciers, and showed that the ELA in NW Bhutan lies at about 5280 ± 125 m asl or even slightly higher (5320 ± 60 m asl) on the clean-ice glaciers Dangshey I and II (Fig. 2).

4.2. The glacial geologic record

4.2.1. Oldest remnants of glaciation

The uppermost glacial trim line in the area indicates the former presence of an extensive ice-stream network. This trim line lies between 500–800 m above the modern valley floor and dips down-valley at ~3° (Fig. 4).

Fig. 3. The study area and its inhabitants. (a) View from Tshojo village towards northeast across the Tshojo plain. The plain is a valuable yak pasture for the village-based pastoralists. Numbers indicate glacial moraines discussed in the text: 1, Thanza stage; 2, Late glacial moraine belts in front of modern glacier snouts; 3, segment of a lateral moraine attributed to the Lunana stage (MIS 3). (b) View southeast across part of Thanza village. About two dozen houses are visible in the middle of the image, surrounded by barley fields, which are bounded by small stone walls. Note staircase of palaeo-kame terraces south of the village, which serve as yak pastures today. (c) Bhutanese women harvesting barley at the beginning of October, Thanza village, 4150 m asl. (d) View up-valley (towards northeast) from near Lhedi village at ~3800 m asl. A barley field is visible in the foreground. 1, Late Holocene terminal moraines of the Tshojo glacier. Note dense vegetation on the Tshojo moraines and open forests on the valley slopes and the valley floor (middle-ground of image). Intense monsoon rain blurs horizon.

Table 2
Pollen assemblages for the Thanza peat core established via a hierarchical cluster analysis.

	Assemblage 1	Assemblage 2	Assemblage 3	Assemblage 4a	Assemblage 4b
	Green	Yellow	Orange	Grey	Brown
Sample number (1 = base, 42 = top)	1	2–5, 8	6, 7, 9–14, 17, 20, 22, 24, 26, 28, 32	15, 19, 29, 31, 40, 41	18, 23, 25, 27, 33–39, 42
Taxa diversity	33 taxa	13–21 taxa	16–29 taxa	26–53 taxa	17–47 taxa
TOC %	40%	43–58%	23–47%	13–26%	4–22%
Important local shrubby taxa (mainly Ericaceae & *Juniperus* representing rhododendron–juniper scrub and few *Spiraea*, *Salix* &*Lonicera*)	Very high 35%	Low 1–4%	Low 2–8%	Low 3–6%	Low 2–7%
Important sedges (*Kobresia* & *Carex*); high abundance indicates Cyperaceae swamps and mats	Very low 5%	Very high 60–81%	Medium to high 31–61%	Medium 28–41%	Medium 25–52%
Increasers: Herbs increasing under grazing pressure, invaders, rural followers & pioneers on disturbed turf	Medium 7% (Apiaceae and accessories)	Very low 3–5% (*Rhodiola*, *Koeningia* & *Primula)*	Medium to high 7–26% (*Senecio*, *Koeningia*, *Rhodiola* & *Primula*)	Very high 22–34% (*Koeningia*, *Senecio*, *Thalictrum* & Apiaceae)	Low to high 3–23% (Apiaceae, Lamiaceae, Liliaceae, *Senecio*, *Koeningia*, *Thalictrum*)
Non-cultivated grasses (increasers: *Agrostis*, *Poa*)	Very low <1%	Low <1–5%	Low to very high 2–27%	Low to high 3–17%	Low to medium 1–13%
Spores (Bryophytes & Ferns); pioneering species on new substrate e.g. disturbed turf	Medium 12%	Low 1–2%	Low to medium 1–14%	Low to medium 1–12%	Medium to high 4–24%

Each assemblage is colour coded and refers to the column "pollen assemblages" in Fig. 8, where the identical colour codes are used in order to visualize their stratigraphic succession. The six clustering parameters used included the TOC content in percent, the taxa diversity (reflecting mainly the abundance of 36 identified taxa of herbaceous plants, often the increasers), the percentages of locally occurring shrubs, percentages of sedges (Cyperaceae mires and mats in water surplus areas), percentages herbs and grasses that increase under grazing (grazing weeds, such as poisonous plants, high alpine invaders), under cultivation (rural weeds), and exposure of bare substrate (pioneers after fire, degradation of turf or flooding) and percentages of fern and bryophyte spores that are pioneers on exposed substrate (after fire, degradation of turf or flooding).

Below the trim line there is a characteristic succession of ice marginal deposits, particularly well-preserved in the middle and upper Pho valley (Figs. 2 and 4). The succession starts with prominent lateral moraines at about 4700 m asl (i.e. 400 m above the modern valley floor, e.g. south of the Raphstreng glacier) which can be traced down-valley along the topographically left (southern) side of the Pho valley for approximately 8 km. Lateral and medial moraines in morpho-stratigraphically similar positions were mapped at the confluence of the former Rilo and Tshojo glaciers as well. Based on their altitudinal position in the valley long profile, on their morphological preservation and the degree of weathering (all moraine ridges reveal a ~50 cm deep weathering soil), we group these lateral and medial moraines into one glacial stage (Fig. 4a). We use the term *Lunana stage* for this moraine group as suggested by Iwata et al. (2002).

A staircase of kame terraces follows ~120–200 m below the Lunana moraine sequence and is well-preserved e.g. along the left (southern) valley side of the Pho River, at the entrance of the Rilo

Table 3
Scanning electron microscopy (SEM) analysis for 87 acetolysed pollen grains from the Thanza peat core.

Sample	Size (μm)	Annulus diam. (μm)	Pore diam. (μm)	Affiliation
1 ($n = 2$)	20–21	3	1.5	Wild grass
2 ($n = 2$)	29–30	4.5–5.5	2	Wild grass
2 ($n = 2$)	40–45	8.5–9	3.5–4	*Hordeum*-type
6 ($n = 4$)	26–29	4–4.5	2–2.5	Wild grass
6 ($n = 3$)	40–42	7–8	4–5	*Hordeum*-type
14 ($n = 7$)	20–26	3–4.5	1–2	Wild grass
14 ($n = 3$)	41–44	7–8	4–5	*Hordeum*- type
19 ($n = 9$)	19–30	2.5–4.5	1–2	Wild grass
19 ($n = 1$)	45	9	4.5	?*Hordeum*-type
22 ($n = 5$)	26–31	4–5.5	1.5–2	Wild grass
22 ($n = 1$)	40	8.5	3	?*Hordeum*-type
24 ($n = 11$)	22–33	3–4.5	0.7–2.5	Wild grass
24 ($n = 4$)	34–40	5–7	2.5–4	*Hordeum*-type & unknown cereal
28 ($n = 1$)	30	5	1.5	Wild grass
28 ($n = 4$)	38–43	8.5–9	3–4	?*Hordeum*-type & unknown cereal
29 ($n = 4$)	22–29	3–4.5	1–1.5	Wild grass
29 ($n = 5$)	37–43	5–8	2–4	Unknown cereal
38 ($n = 2$)	22–24	3.5–5	1–1.5	Wild grass
38 ($n = 7$)	38–43	7– 9	3–4	*Hordeum*-type & unknown cereal
40 ($n = 6$)	20–22	3–4.5	1–1.5	Wild grass
40 ($n = 4$)	40–43	6–8	4	*Hordeum*-type & unknown cereal

Wild grass pollen grains from Thanza usually have diameters between 20 and 33 μm and very faint dotty surface sculptures under LM whilst the cereal grains are generally bigger than 37 μm and display grouped dots.

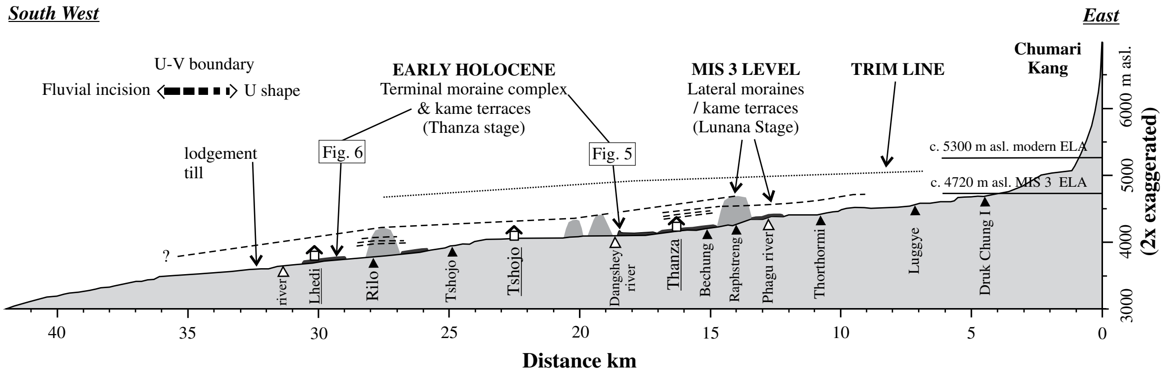

Fig. 4. Glacial-geological section through eastern Lunana. The sequence of lateral moraines of the Lunana stage (in light grey) is projected onto the section. The Early and Mid-Holocene moraine sequences (Thanza stages) are shown in dark grey. White triangles indicate river mouths; black triangles denote main glaciers from tributary valleys or cirques. ELA, estimation of the equilibrium line altitude.

valley, southeast of the Tarina lakes and around Wochey village (Figs. 2 and 4). The kame terraces are laterally extensive ($\leq$1 km), several tens to 100 m broad, dip at $\sim$5–8° towards the central valley axis and, in most instances, are arranged in three levels ($\sim$180 m, $\sim$125 m and $\sim$90 m above the modern valley floor, Fig. 2).

Immediately south of Thanza village these ice-marginal deposits have been affected by a deep-seated landslide and now dip up-valley at an angle of 8° (presumably in response to strong seismic shaking, Meyer et al., 2006) and have therefore not been used for morpho-stratigraphic correlations or for ice-stream network reconstructions.

4.2.2. The Thanza moraine complex

A well-preserved moraine complex (the Thanza stage of Gansser, 1983 or the Tenchey stage of Iwata et al., 2002) is found on the present valley floor 2.5 km southwest of Thanza village (Fig. 5, see supplementary section S1 for sedimentary details). The complex comprises (i) an ice-contact fan (Fig. 5b), (ii) lateral moraines, which merge into the ice contact fan via latero-frontal moraine segments (Fig. 5c and d) and (iii) hummocky moraine, which covers the terrain within these ice-marginal deposits (Fig. 5a).

We sampled three well sorted sand-silt horizons, intercalated into the otherwise coarse grained ice contact fan for OSL dating (Fig. 5b). The OSL ages for these samples are 9148 ± 848 a (ABU 226), 9788 ± 719 a (ABU 228) and 51,096 ± 3683 a (ABU 229), respectively (consult supplementary section S2 for OSL details).

The Thanza lateral moraine consists of a clast supported diamict overlain by 1.6 m of matrix supported diamict. The diamict units are separated by a palaeosol (Thanza palaeosol), which itself is overlain by a greyish clay, several cm in thickness (Fig. 5d). XRD analysis for the Thanza palaeosol indicate poorly crystallized clay minerals, a predominance of secondary chlorite and a range of additional mixed layer minerals. Centimetre sized charcoal pieces were recovered from the greyish clay horizon and yielded a calibrated ^{14}C age of 6710 ± 90 cal a BP (Vera-2647, Table 1).

The hummocky moraine is composed of unconsolidated diamictic sediments more than ten metres in thick in places and shows an irregular surface morphology as well as several kettle holes and kame mounds (Fig. 5a). Kame mounds are particularly common on top of the left (southern) part of the Thanza ice-contact fan and also immediately in front of it, but have not been observed further down valley (Fig. 5a).

4.2.3. Terraces and moraines near Lhedi village

About 15 km downstream from the Thanza moraine complex and 2 km northeast of Lhedi village (Fig. 2), remnant terraces and moraines again occur on the modern valley floor but are more intensively dissected by fluvial erosion and morphologically less well-preserved than the Thanza moraine complex.

A sediment succession is exposed in the right-hand (northern) river bank, including a clast supported, crudely stratified diamict in the basal part of the exposure (from 0 to 8 m, Fig. 6, see also supplementary section S1). Individual clasts vary from metre to decimetre in size and clast morphologies range from angular to well-rounded, but sub-rounded clasts are predominant. The clasts lack any preferred orientation and reveal no stoss and lee forms or striations. Fine gravels, sand and silt infill the spaces between these coarse components and sometimes reveal undulated bedding as well as crude trough and cross bedding (Fig. 6).

This diamict is overlain by a $\sim$0.8 m thick horizon of well-sorted, fine-grained sediments, which coarsens upwards from clay to sands and gravels. A calibrated radiocarbon age of 4700 ± 130 a BP (Vera-2646, Table 1) was obtained for organic lenses, which are intercalated into the clay deposit at 8.2 m above the base of the section (Fig. 6).

On the opposite river bank a sediment body, with hummocky surface morphology and remnant ridges resembling latero-frontal moraines (Fig. 2) is preserved on the valley floor.

4.2.4. Moraine complexes in front of the modern glacier snouts

The youngest moraine complexes are located within 1 km of the modern glacier snouts, where they form belts of stacked moraines (Fig. 2). At least four distinct moraine groups (numbered 1–4) can be recognized. The outer most group (number 4) is the lowest one and rises about 30–40 m above the modern valley floor, while the inner moraine groups become progressively higher and reveal clear signs of stacking (i.e. the innermost moraine is sometimes nearly overriding the moraines of the next group).

We sampled living *Juniperus* trees and in-situ trunks from the outer slopes of the moraines of group 1. Dendro-chronological analysis for two living *Juniperus* trees on the left lateral moraine of the Luggye I glacier indicate ages of 285 a and 213 a, respectively. In addition, an in-situ trunk from the left lateral moraine of the Thorthormi glacier yielded an age of 281 a. Furthermore, an exposure in the Luggye I left lateral moraine reveals a thick charcoal horizon with a ^{14}C age of 280 ± 25 cal a BP (Ki-3941; Table 1). This horizon directly overlies a morainic deposit, but has not been overridden by any subsequent glacier advance.

5. The palynological record

A 74 cm long drill core has been recovered from a water-saturated organic rich turf/minerotrophic peat, which is situated at 4100 m asl behind the left Thanza lateral moraine and directly

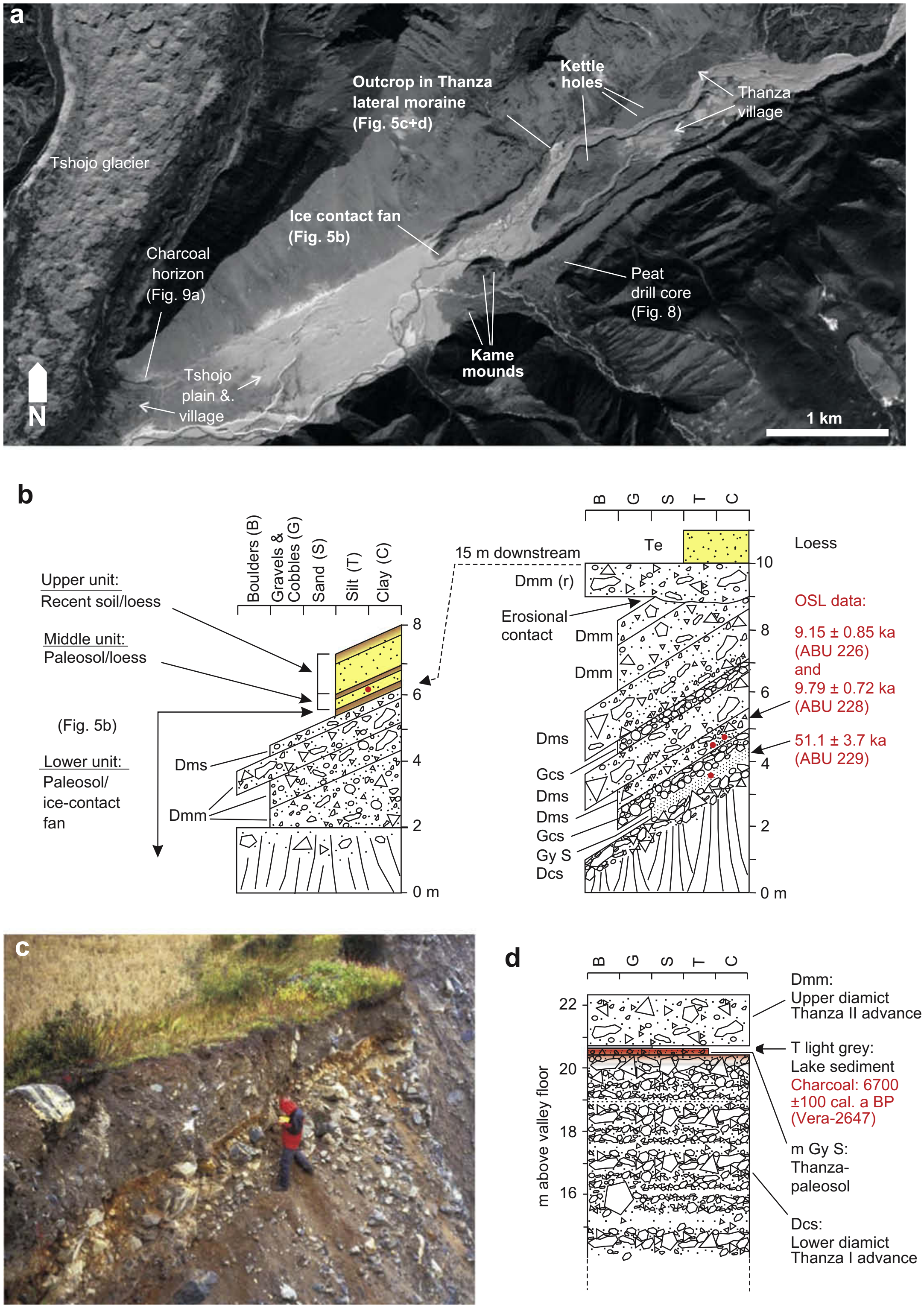

Fig. 5. The Thanza moraine complex. (a) Overview of the Thanza moraine complex and the adjacent Tshojo plain (IRS-1D satellite image). The moraine complex consists of a sharp crested lateral moraine, an associated kame terrace, an ice contact fan and a hummocky moraine (containing kettle holes and kame mounds). The areas covered by Figs. 8 and 9a, as well as the position of the Tshojo village and the Tshojo plain, are also indicated in this overview. (b) Sedimentology of the Thanza ice contact fan and the OSL sampling points and ages. The lithofacies codes of Miall (1977) and Eyles et al. (1983) have been adapted for this and all other sedimentary logs. (c) The palaeosol within the Thanza lateral moraine (view towards northeast). (d) Sedimentary log of the Thanza lateral moraine.

overlies coarse (morainic) material (Fig. 2 and 5a). No signs for disturbance or mixing (with e.g. pre-bog deposits) were found after close examination of the fresh core. The vegetation at the drill site and surrounding valley flanks mainly consists of Cyperaceae (*Kobresia* spp.), mosses and accessorial herbs but patches of woody vegetation (rhododendrons, junipers, spireas) occur occasionally.

The base of the peat deposit has been dated to 4280 ± 130 cal - a BP (Vera-2649; Table 1) and our age model suggests high

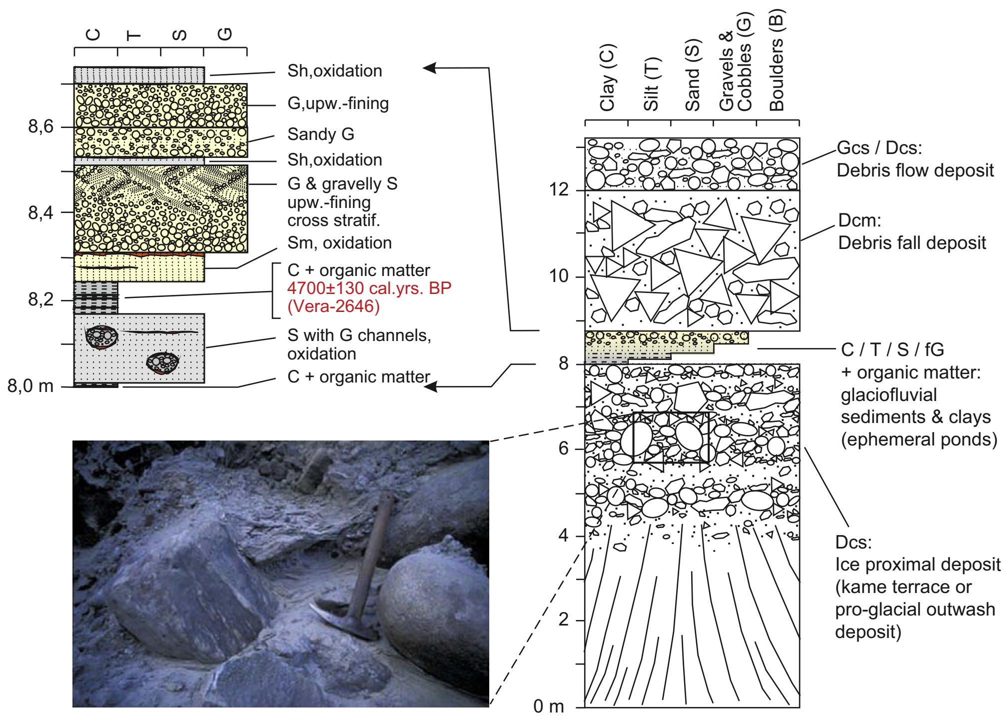

Fig. 6. The ice-proximal sediments northeast of Lhedi village. Position of radiocarbon sample and age indicated in left sediment log. Note crude trough and cross bedding of fine gravel and coarse sand in between sub-rounded boulders in zoomed image (hammer for scale).

accumulation rates in the lower half of the core (~370 μm/a), which are clearly decreasing up-section (~110 μm/a; Fig. 8). With a constant sampling distance of 2 cm we thus achieve a decadal and centennial resolution in the lower and the upper part of the core, respectively.

The TOC decreases towards the top of the core as well, reflecting deterioration of a basal minerotrophic peat (40–60% TOC near base) into an organic rich soil (10–20% TOC near top, Fig. 8). The decrease of organic growth is also reflected in the growth rate, which declines throughout the core by a factor of three. A last pronounced decline in TOC is observed at ca 2000 BP (19 cm depth).

The pollen data are characterized by varying amounts of local grass-, herbaceous-, spore plant-, and shrub (junipers and Ericaceae) taxa. The input of extra-local tree pollen (e.g., *Quercus, Castanopsis, Alnus Symplocos*) throughout the core is highly variable (8– 36% of the pollen sum curve, Fig. 8). A clear trend occurs in the local taxa diversity, which is increasing up-section.

The herbaceous pollen consist mainly of taxa which increase under grazing pressure, because yak, sheep and goats remove the most nutritious and palatable taxa first. The remaining taxa are either unpalatable (poisonous: e.g., Ranunculaceae such as *Thalictrum* and *Anemone, Senecio*, Gentianaceae such as *Swertia* and *Lomatogonium*) or produce tiny rosettes and cushions (e.g., *Primula, Draba, Saxifraga, Rhodiola*), creepers (e.g., *Potentilla, Koeningia*) or spiny plants (e.g., *Acanthocalyx*), unattainable for grazing livestock and in consequence survive and reproduce (thus termed "increasers" in the rangeland literature, e.g. Fernandez-Gimenez and Allen-Diaz, 2000; Miller, 2000; Holzner et al., 2002; Roder, 2002). Some grasses tend to increase under grazing pressure as well (Holzner et al., 2002; *Agrostis* sp., *Poa* sp.; Gyaltsen and Dorji, 2002).

While the changes in the quantity and quality of local pollen and spores in the core imply severe changes in the vegetation cover of the swamp through time, their palaeoenvironmental interpretation is not straight forward. In order to specify these changes, the pollen and TOC data were combined into a matrix and treated via a hierarchical cluster analysis to separate samples into groups with similar pollen content, a procedure commonly used in palaeontology (Bruch and Mosbrugger, 2002; Hofmann and Zetter, 2005). We first separated the local palynomorph taxa into five groups or variants (column 1 in Table 2). These variants are: (i) important local woody taxa (Ericaceae, *Spiarea, Salix* and *Juniperus* spp.), (ii) important sedges (Cyperaceae: mainly *Kobresia* spp., *Carex* sp.), (iii) unpalatable herbs (increaser: e.g. *Senecio, Thalictrum, Koeningia*, Gentianaceae), (iv) wild grasses, rarely grazed on Poaceae (increaser: e.g., *Agrostis, Poa*), (v) spores (bryophytes and ferns).

The hierarchical cluster analysis resulted in four crude pollen/spore assemblages (for details and the stratigraphic context see Table 2 and Fig. 8: note colour coding of the respective pollen assemblages). The most important characteristics of each assemblage are summarized below.

Assemblage 1 (basal sample only) consists of the highest woody contents (Ericaceae: 27% and *Juniperus* spp.: 6.6%), the lowest sedge percentages (5.2%), possesses a TOC content of 40% and is relatively rich in local taxa (33 taxa).

Assemblage 2 overlies assemblage 1, has a very high TOC content and the pollen spectrum is dominated by sedges, while increasers attain 2– 5% of the local pollen spectrum. The local taxa diversity is low (13– 21 taxa).

Assemblage 3 shows TOC contents ranging from 23% to 47%, medium to high contents of sedge and herbaceous increasers (31–61% and 7– 26%, respectively) and medium to high non palatable grass contents (2–27%),taxa diversity ranges between 16 and 29 taxa.

Assemblage 4 reveals low TOC contents (13–26%), medium sedge contents (25– 52%) and displays a very variable taxa diversity (17– 53 taxa). A further subdivision of assemblage 4 into 4a and 4b is based on the very high contents of increasers in 4a (22–34%) and very high spore contents in 4b (ferns and mosses forming pioneering vegetation).

In all pollen assemblages a more or less continuous water saturation even in the uppermost samples of the substrate is evidenced by the occurrences of different fresh water algae (e.g., *Botryococcus* and bilateral symmetric diatoms), and various algal cysts and sporadic appearances of pollen from water plants (*Myriophyllum, Potamogeton*) indicating that there have been at least periods of standing water.

We also encountered putative cereal-type pollen in the core (from sample 2, i.e. 73 cm depth, onward), which slightly increase in abundance towards the top of the core. In order to distinguish cultivated cereal pollen from pollen of undomesticated wild grasses, we analysed 87 Poaceae grains along the entire core under LM and SEM. Traditionally, cultivated grasses are separated from their wild relatives by their size (acetolysed cereal pollen grains are >37 μm in diameter, Beug, 2004) and by their pore and annulus diameter (pore >2.7 μm; annulus diameter >8.1 μm; i.e. the annulus of cereal pollen is larger and thickened compared to that of wild grasses; Beug, 2004; Halbritter, 2000). Surface sculpturing, best visualised via SEM, additionally allows further distinction, for example between different types of cultivated cereals through the identification of columnar structures of the exine (regularly spaced single dots: *Hordeum* type; irregularly spaced or groupings of dots: *Triticum* type, and fused dot groups: *Avena* type; Beug, 2004, see also Tinner et al., 2007). Our SEM investigations reveal clear differences within the Poaceae pollen grain populations with respect to pollen size, pore and annulus diameter as well as surface sculpturing (Table 3). A clear distinction can be made between small-grained populations (sizes: 20–33 μm) and large pollen grains (sizes: 37–45 μm). The large grains are always associated with very large pore and annulus diameters and their exine shows either regularly spaced single dots (~52% of the grains) or reveals an insular surface pattern (i.e. a clear grouping of dots, ~48% of the pollen grains).

6. Sedimentary charcoal

We identified several places where thick charcoal horizons have been preserved in soil or sediment profiles. Table 1 presents the ^{14}C ages obtained from these and further sites at which sedimentary charcoal has been retrieved.

A laterally extensive charcoal horizon occurs in a 70 cm thick sandy to silty soil 200 m north-east of Tshojo village. The charcoal is exposed in a series of small outcrops at the base of a south facing slope at 4120 m asl (Figs. 5a and 9a). The 5 cm thick horizon contains millimetre to centimetre-sized pieces of charred wood for which we obtained a calibrated ^{14}C age of 4745 ± 250 a BP (Poz-9911).

Between Lunana and the neighbouring Mo valley a soil profile is exposed ~12 km south-east of Laya village at the edge of a kame terrace at 3650 m asl, which is used as a pasture by yak pastoralists today (Fig. 1b). In the profile moraine deposits are overlain by a 20–30 cm thick palaeosol, followed by a ~8 cm thick horizon of charred wood and topped by rock fall and slope deposits, which are deeply weathered and pedogenetically altered (Fig. 9b). The calibrated ^{14}C age for the charcoal layer is 4680 ± 155 a BP (Poz-9930).

The oldest ^{14}C age for macroscopic charcoal in Lunana comes from the clay horizon deposited on top of a palaeosol preserved within the right Thanza lateral moraine (6710 ± 90 cal a BP, Vera-2647, see Section 4.2, Fig. 5c and d).

Centimetre-sized pieces of charred wood were found in numerous other exposures and sedimentary settings in the upper and lower Pho valley and their calibrated ^{14}C ages all fall into the Late Holocene (Table 1).

Microscopic charcoal analyses for the palynological drill core samples were carried out semi-quantitatively. From a total of 42 samples small amounts of fine-grained charcoal (~10 to 35 μm) were encountered in >50% of these samples but were particularly abundant in samples 31 (13 cm depth) and 33 (11 cm depth). Based on the age model derived from the ^{14}C age control points, we obtain ages of 1400 a BP and 1200 a BP for samples 31 and 33, respectively (Table 1; Fig. 8).

7. Discussion

7.1. Style and timing of glacial sedimentation

7.1.1. Late Pleistocene

We have no absolute age control for the oldest remnants of glaciation in Lunana, i.e. the glacial trim-line and the *Lunana stage* moraines. Any sedimentary evidence associated with the glacial trim-line (e.g. terminal or lateral moraines) has been eroded, but glaciers probably expanded far below 3500 m asl, i.e. extended beyond the current transition from an U-shaped valley cross-profile into a fluvially incised and thus V-shaped valley cross-profile (termed the U-V boundary, Fig. 4).

In contrast, the lateral and medial moraines of the *Lunana stage* are morphologically well-preserved and define a glacial advance during which the valleys were filled with up to 500 m of ice. These moraines and the associated staircase of kame terraces might indicate the advance and stepwise reduction of a major ice-stream net during the Late Pleistocene. As detailed in Section 8.3, we correlate the Lunana stage with morpho-stratigraphically similar deposits in the western Himalaya, where surface exposure dating suggests significant glacial advances during the marine isotope stage (MIS) 3 (Fig. 7a; e.g. Owen et al., 2002, 2005; Finkel et al., 2003; Gayer et al., 2006).

We have used the TSAM method (assuming that Lunana stage was reaching but not significantly exceeding the current U-V boundary) and the MELM method (applied to the huge sequence of lateral moraines of the Lunana stage in the upper Pho valley) to estimate the corresponding ELA values. In both instances we obtain an approximate ELA depression of about 600 m compared with the present day. This agrees well with results obtained by Duncan et al. (1998) for Central Nepal where, for full-glacial conditions, the modal value of computed ELA depressions lies at about 650 m. An ELA lowering of ≥400 m would cause extensive areas within high-level valleys (e.g. the upper reaches of the Phagu river, Fig. 2) to become part of the accumulation area. Such a hypsometric effect (i.e. a sudden increase of the accumulation area) would thus trigger a significant glacier response potentially capable of filling the Pho catchment with several hundred metres of ice.

7.1.2. Early and Mid Holocene

The sedimentological and morphological data from the Thanza moraine complex and the Lhedi kame terrace, in conjunction with OSL and radiocarbon dating, suggest repeated advance and decay of a debris covered glacier system in this area during the Early and the Mid Holocene.

OSL samples ABU 226 and ABU 228 both come from the same sand layer of the Thanza ice-contact fan and the OSL ages of 9148 ± 848 a and 9788 ± 719 a overlap within errors, suggestive of an early Holocene glacier advance of about 5 km relative to the modern glacier termini. Sample ABU 229 (OSL age of 51096 ± 3683 a) most probably suffers from incomplete bleaching (e.g. Rhodes and Pownall, 1994; Gemmell, 1999) and has thus been rejected (see also supplementary section S2).

The ice-contact fan is directly connected with the Thanza lateral moraines and corresponds to the lower diamict unit visible in the right-hand moraine (Thanza I advance, Fig. 5). The well-developed palaeosol on top of this diamict suggests geomorphologically stable conditions existed for a prolonged period of time (i.e. no

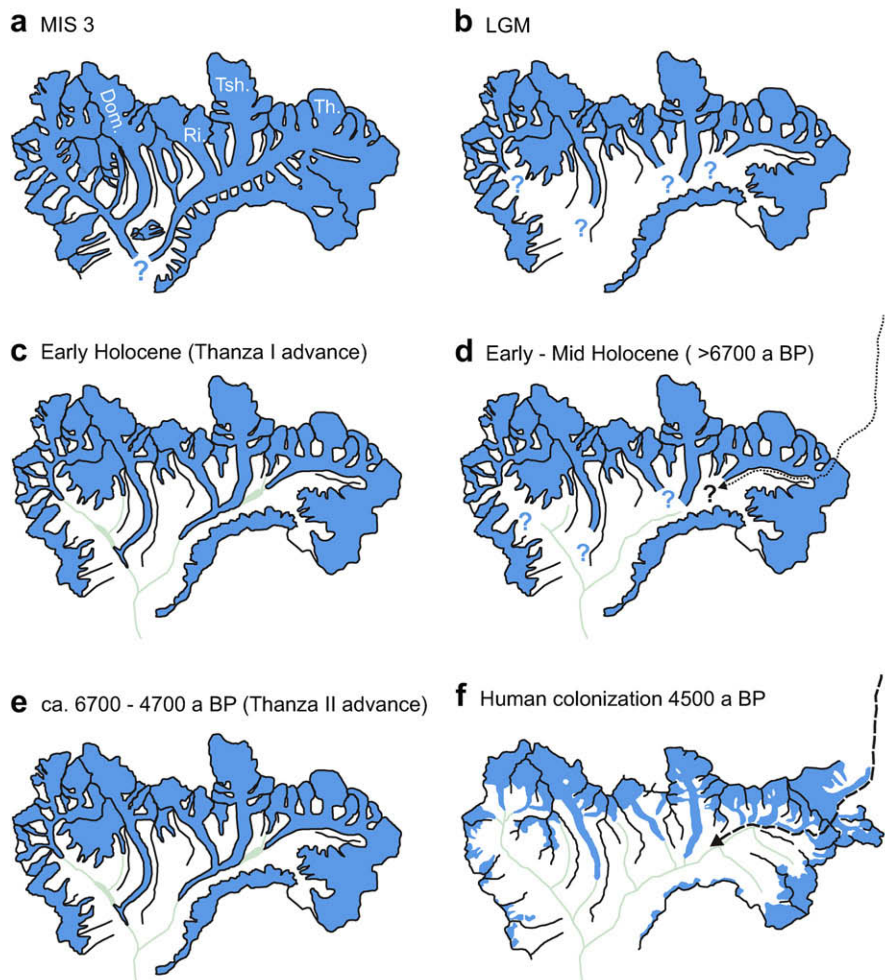

Fig. 7. Glaciation and human colonization of eastern Lunana—a schematic model. Dom., Domchetang glacier; Tsh., Tshojo glacier; Ri., Rilo glacier; Th., Thorthormi glacier. For more topographic information compare Fig. 2. (a) Inferred extent of MIS 3 glaciers. (b): The expansion of the LGM glaciers is unknown (blue question marks) but glacier termini are assumed to be in restricted positions. (c, d) Holocene glacier fluctuations as reconstructed via OSL and radiocarbon dating as well as mapping. Thanza advance II (e) was slightly more extensive than Thanza advance I (c). Note formation of ice-dammed lakes (light blue) in both instances. The degree of retreat between the glacier advances (d) is unclear. Since ca 4500 a BP the glacier termini have been restricted to positions within ±1 km of their modern positions (f). The broken line in (f) represents migration from the Tibetan Plateau into the Bhutan Himalaya at 4500 a BP. The dotted lines in (d) and (f) indicate an alternative but speculative peopling scenario (black question marks): an initial occupation phase at 6700 a BP (d) and re-occupation of Lunana subsequent to Thanza advance II (i.e. at 4500 a BP; f). See text for details. Note: Instead of crossing the Gonto La (a 5500 m high glacier pass), as indicated in these occupation scenarios, Lunana can also be entered from Tibet via a series of lower passes from the neighbouring catchments.

overtopping of the existing moraine and thus no glacier advance, Fig. 5c and d). We estimate that up to 3000 or 4000 a of soil formation (but not much more) might be required for a clay mineralogical composition like that observed in the Thanza palaeosol to develop (Section 4.2). This estimate is based on a comparison with pedological data obtained from alpine soils (developed on granitic glacial deposits as in the case of the Thanza palaeosol) where the main clay mineral transformations typically take place within the first couple of millennia (Egli et al., 2001, 2003). A second glacier advance (Thanza II advance, upper diamict unit, Fig. 5d) has overtopped this moraine-palaeosol sequence. The $\sim$3 cm thick greyish clay horizon which drapes the entire palaeosol is interpreted as the bottomset of a proglacial or ice-marginal lake, which would already have been forming during this second glacier advance. The ^{14}C dated charcoal pieces retrieved from this clay layer (6710 $\pm$ 90 cal a BP, see above) thus give a maximum age for the Thanza II advance. Furthermore, a peat deposit started to accumulate immediately outside, i.e. south of the left Thanza lateral moraine, at 4280 $\pm$ 130 cal a BP (Vera-2649, Table 1, Fig. 5a). This strongly suggests that the second phase of glacier expansion ended well before ca 4300 a BP (as morphologically and hydrologically stable conditions are required for peat formation).

The sedimentological and morphological features of the hummocky moraine, blanketing the terrain between the lateral moraines and the ice-contact fan are consistent with down-wasting of a former debris-mantled glacier snout (i.e. coarse-clast till hummocks and topographic inversion; Eyles, 1979; Iwata et al., 1980; Benn and Evans, 1998, p. 483). We attribute this moraine deposit to glacial decay subsequent to the Thanza II advance. The fact that the left (south) branch of the Thanza ice-contact fan is dotted with kame mounds (Fig. 5a) and that a degree of overtopping occurred within the Thanza lateral moraine suggests that the Thanza II advance was slightly more extensive than the earlier advance, and therefore able to breach the pre-existing Thanza I moraine belt.

The sediment sequence northeast of Lhedi village is interpreted as an ice-proximal sediment deposited by meltwater streams which were flowing either (i) between the glacier margin and the adjacent valley wall, or (ii) directly in front of the former glacier snout. This interpretation is based on the following observations.

The sedimentary fabric in the lower part of the Lhedi sediment sequence (i.e. from 0 to 8 m, Fig. 6, see also supplementary section S1) suggests a two-fold depositional mechanism common in ice-proximal aquatic environments (Miall, 1977). Peak-discharge events (e.g. during the melting season) were probably capable of transporting metre sized components, while fine gravels, sand and silt infiltrated into the space between these boulders during the falling limb of such high-discharge events themselves, and display trough and cross bedding. The angular nature of the clasts indicates ice-proximity, suggesting that the material is supraglacial debris, dumped from the glacier margin and probably transported no more than a few tens to a few hundred metres.

The greyish clay units which conformably overlie these coarse deposits indicate the former presence of standing water and are interpreted as bottom sets of ephemeral lakes, formed during the retreat of the adjacent glacier. We note that clay deposits from modern supra- and pro-glacial ponds and lakes are macroscopically indistinguishable from these clay units (as well as from the greyish clay horizon within the Thanza lateral moraine). We attribute this to their common origin (i.e. suspension settling from glacial melt-water). This interpretation is in agreement with the XRD results (indicating fresh and unweathered clay minerals), the observation of desiccation cracks (formed during periods when the water bodies were drying up) and the presence of overlying gravel and sand units, which suggest that these ponds and lakes were silting up rapidly. This sediment sequence is situated about 5 km in front of the modern termini of the Rilo and Tshojo glaciers (Fig. 2). The radio-carbon age from the clay unit constrains this ice-decay scenario to immediately prior to 4700 cal a BP.

We expect that these ice-proximal deposits and the moraine-like ridges, situated on the opposite valley side and resembling a debris covered glacier tongue with latero-frontal moraine ridges, genetically belong together, i.e. were both deposited during one glacial event (advance and decay of the Tshojo-Rilo glacier). This glacial event occurred $\geq$4700 a BP and thus may well be part of the Thanza II advance in the upper Pho valley (constrained to 6700–$\geq$ 4300 a BP).

In summary we interpret Lunana's glacial geologic record for the Lateglacial to Mid Holocene as follows (Fig. 7c–e). (1) Based on OSL dating of the Thanza ice-contact fan we conclude that glaciers reached positions about 5 km in front of the modern glacier snouts during the early Holocene (ca 10, 000–9 000 a BP, the Thanza I advance) as indicated by formation of the ice-contact fan and the lower diamict unit in the Thanza lateral moraine. We assume a similar glacier response to climate forcing elsewhere within the catchment and therefore expect that the Tshojo and Rilo glaciers in the middle part of the catchment advanced in a broadly similar way (Fig. 7c). (2) Formation of the Thanza palaeosol suggests a geo-morphologically stable period with glaciers in more restricted positions. Based on the degree of weathering of the palaeosol we estimate this period lasted until ca 3000–4000 a (Fig. 7d). (3) Glaciers re-advanced during the Mid Holocene (Thanza II advance), and over-riding of the existing Thanza lateral moraine occurred immediately subsequent to 6710 $\pm$ 90 cal a BP (clay horizon capping the Thanza palaeosol containing charcoal). This glacier advance ended well before 4280 $\pm$ 130 cal a BP (the basal age of the swamp deposit behind the Thanza moraine) but more likely just prior to 4680 $\pm$ 155 cal a BP as constrained by the radiocarbon dated ice-proximal deposits NE of Lhedi village. During the Thanza I and II advances, two local and independent ice-stream networks formed in the catchment (i.e. the combined Rilo and Tshojo glacier in the middle part of the catchment and a network incorporating the Bechung, Raphstreng, Thorthormi, Luggye and Druk Chung glaciers in the upper catchment; Fig. 7c and e).

We estimate an ELA depression of about 300 m during each Thanza advance and expect that pro- and periglacial process activity intensified accordingly. Waxing and waning of these glacier systems almost certainly resulted in the formation of numerous ice-proximal lakes and ponds (in particular ice- and moraine dammed lakes) and enhanced glacio-fluvial activity (Fig. 7c and e). However, the rather small size of the Thanza moraine complex indicates an intermittent glacier advance rather than a stable terminus thickening in situ over a considerable period of time.

7.1.3. Late Holocene

Subsequent to ca 4700 BP the glaciers in Lunana were restricted to positions within one kilometre of their modern termini where they developed moraine belts (Figs. 2 and 7f). Older moraine systems formed insurmountable obstacles for younger glacier advances, thus causing stacking and in-situ thickening of glacier termini e.g. the innermost moraine complex almost overrides the next youngest moraine system and reaches a height of up to 140 m above the valley floor, while the outermost group of moraines only attains a height of approximately 30–40 m. These observations are in agreement with a radiocarbon dates from a palaeosol buried in between moraine groups 2 and 3 of the Raphstreng glacier (Iwata et al., 2002), and which brackets glacier fluctuations to $>$2080 $\pm$ 40 cal a BP (moraine group 3) and $<$1690 $\pm$ 40 cal a BP (moraine group 2). Our dendro-chronological analyses and the ^{14}C dated charcoal layer on top of the lateral moraine of the Luggye I glacier (Ki-4931; Table 1) suggest that no significant over-riding of the innermost moraines has taken place within at least the last 300 years.

7.2. Palaeoenvironmental evidence for prehistoric human colonization

Untangling human–environmental linkages in the palaeo-record is a non-trivial task but proxy records may provide direct or indirect evidence for anthropogenic disturbance of natural ecosystems on various spatial and temporal scales. Recent studies have demonstrated that combining sedimentological and palyno-logical records with charcoal analysis is a powerful tool for the evaluation of local and regional anthropogenic impacts on sensitive (high) alpine environments (e.g. Miehe et al., 2006; Tinner et al., 2007). Human arrival in many of these instances is associated with an increase in fire activity, possibly due to forest clearances, pasture maintenance or slash–burn practices of early settlers or pastoral groups (mirrored in the sedimentological record) and the intro-duction of cultivated cereal crops (detectable via detailed pollen analysis). However, differentiating anthropogenic fires from natural (and thus climatically controlled) fire activity and distinguishing cereal pollen from that of their wild relatives (the undomesticated Poaceae species) remains a challenging task (e.g. Tweddle et al., 2005; Carrión et al., 2007).

7.2.1. Anthropogenic versus natural fire activity

A striking feature of the valleys in NW Bhutan is the relatively high mean annual precipitation, mainly delivered during the summer months. This favourably influences the potential timber-line (which lies at 4300 and 4700 m on north and south facing slopes, respectively) and allows a dense vegetation cover to grow (e.g. dense *Juniperus/Rhododendron* scrub occurs as high as 4400 m asl). The debris-covered glacier tongues, on the other hand, reach down to 4000–4400 m asl and thus directly penetrate into wood-land and scrub-covered terrain. Hence, glacial and pro-glacial processes and dense vegetation (at least in its undisturbed, natural state) dominate valley floor development. Indeed human occupa-tion of this high alpine terrain seems only to have been possible during periods of low glacial activity and after clearance of parts of the otherwise impenetrable scrub. For highly mobile and altitude-adapted foraging groups from the Tibetan Plateau, these green valleys in the south might have become attractive living places during some time in the past (as we will explore in more detail below) and burning the scrub appears to have been the only way to reclaim land for living, pastures and agricultural purposes. The occurrence of sedimentary charcoal, in particular the thick charcoal horizons in Lunana and the neighbouring catchment area (both dating to ca 4500 a BP), is thus best interpreted as the result of anthropogenic fire activity and forest clearance.

Alternatively and in addition to anthropogenic fires, the charcoal occurrences in NW Bhutan might be the result of natural fires started by lightning strikes during exceptional warm and dry seasons (see Clark, 1989 or Johnson, 1992 for a general discussion of natural fire causes). While winters in the Bhutan Himalaya are cold and dry with only occasional snowfall, the summer season is mild and characterized by precipitation maxima brought by the Indian monsoon. These summer rains are orographic in origin (slow and continuous advection of moist air masses) and thunderstorms with lightning activity (preferentially dry electrical storms) are thus extremely rare or have never been reported for the Central and Eastern Himalaya (Dittmann, 1970; Flohn, 1970). Furthermore, the valleys in NW Bhutan reveal ubiquitous periglacial and permafrost features such as earth hummocks, solifluction lobes and rock glaciers (Iwata et al., 2003) above ~4000 m asl, revealing the presence of subsurface ice and frequent thawing and freezing of water saturated soil (i.e. the soil moisture is high throughout the year). Because lightning and moisture (as precipitation and in the soil) are thought to control alpine fire regimes (Carcaillet, 1998; Luterbacher et al., 2004; Tinner et al., 2005) we conclude that natural fire probably never played a dominant ecological role in the ice-proximal, high-elevation setting of NW Bhutan.

7.2.2. The palynological record

The pollen record functions as the principal source of palaeoenvironmental information and reveals a number of features, which require careful examination. In the following sub-sections, we analyse each of these features separately before synthesizing our palynomorph information together with the TOC and the charcoal data.

7.2.2.1. Abrupt vegetation change at the base of the core. Pollen assemblage 1 (the core base) is characterized by very high percentages of Ericaceae (particularly *Gaultheria trichophylla*) and *Juniperus* spp., which is in stark contrast to the palynomorph data obtained from the rest of the core, where sedges (e.g. *Kobresia sp*., assemblage 2, directly overlying assemblage 1), herbaceous weeds (e.g. *Koeningia*, *Thalictrum* or *Senecio*, assemblage 3) and various amounts of spore taxa (i.e. ferns and mosses, assemblage 4) are prevalent (Fig. 9). Assemblage 1 reflects a "juniper–rhododendron" scrub, which dominated during the early stage of the peat swamp but then disappeared abruptly. Today juniper–rhododendron scrubs are only preserved on steep flanks and mountain slopes, which are inaccessible for grazing yaks, but otherwise would form the original vegetation of that altitude zone in NW Bhutan (Grierson and Long, 1983; Ohsawa, 1987).

The succeeding pollen assemblage 2 is comparable with the relatively species-poor "Cyperaceae swamp" or "Giant Kobresia bog" (*Kobresia schoenoides* and few other taxa) as described by Miehe and Miehe (2000) and Holzner et al. (2002) from Tibet. Such swamps exist in areas of excess water (Miehe, 1996; Miehe and Miehe, 2000) and represent an extrazonal plant association which is most valued by the pastoralists because of its productive and qualitative pastures (Holzner et al., 2002).

Deposition of the peat swamp started after glacial retreat following the Thanza II advance, probably as soon as the area behind the Thanza lateral moraine became geomorphologically and hydrologically stable. The sudden disappearance of the juniper–rhododendron scrub (which was probably dominating the surrounding valley slopes) immediately subsequent to 4300 a BP, and the rise of the sedge swamp, can not be reconciled with climate change but might be the direct result of fire, either natural or anthropogenic in origin (i.e. early settlers might have cleared the scrub cover away to make space for pastures). Although the charcoal evidence for this burning event is not captured in our core, it might be preserved in other parts of the swamp and would thus require further investigations.

7.2.2.2. Peat deterioration due to grazing and trampling. Assemblage 3 (overlies assemblage 2) displays the first changes in the sedge swamp. The percentages of sedge decreases because the swamp area is invaded by herbaceous weeds from the surrounding alpine vegetation and by unpalatable grasses (i.e. increasers as outlined in Section 5, leading to more taxa).

In assemblage 4a (intercalated into assemblage 3 and 4b), the sedges are even less abundant and more weed taxa (particularly high percentages of the increasers *Koeningia*, *Thalictrum*, *Senecio*, Apiaceae, Liliaceae, and Gentianaceae) and more grasses enter the swamp.

Assemblage 4b differs from 4a because of the presence of additional spore taxa (ferns and mosses), which are generally pioneering plants (Miehe and Miehe, 2000; Kiss et al., 2004; Table 2). Mosses might invade when the turf surface/vegetation cover is destroyed (e.g. by yaks, see Miehe and Miehe, 2000, p. 291), or covered by clastic sediments (e.g. input of sediment laden meltwater or floods), and inhabit the barren plots as pioneers. A similar behaviour is assumed for the ferns (Byers, 2005) which invade when the vegetation cover becomes inconsistent, heterogeneous and patchy.

We exclude meltwater or flood events as possible agents for clastic sediment input because the peat swamp is located in a sheltered position behind a lateral moraine at a considerable horizontal and vertical distance from the central valley axis where the main drainage system is situated. The vegetation development as revealed by the pollen assemblages of the middle and upper core section is therefore interpreted as the result of grazing pressure and trampling (e.g. from yak, sheep or goats; Holzner et al., 2002), which was slight to moderate at the beginning (assemblage 3), became more severe over time (assemblage 4a) and ultimately resulted in the mechanical break up and erosion of the vegetation cover due to overgrazing and trampling (assemblage 4b).

7.2.2.3. SEM analysis of Cerealia-type pollen. The presence or absence of putative cereal pollen in a palynomorph data set is a key feature if anthropogenic land use and farming in prehistory are under discussion.

The use of pollen size and surface sculpturing to separate cultivated grasses from their wild relatives and to distinguish between different types of cultivated cereals was put forward by Beug (2004) and Tweddle et al. (2005) and has been established for mid European cereal pollen grains (see also Tinner et al., 2007). Using LM and SEM analysis we can clearly isolate a population of large pollen grains (sizes: 37–45 μm) which are always associated with very large pore and annulus diameters—a characteristic feature for cereal pollen (Table 3). More than 50% of these grains reveal an exine, which shows regularly spaced single dots, again resembling the *Hordeum*-type,(the rest show an insular surface pattern). Exine surface patterns in cereal pollen can be very similar to those observed in different tribes of grasses (Albers, 1975; Liu et al., 2004) and surface sculpturing alone is thus not an unequivocal diagnostic tool. Taken to extreme, cereals that have been domesticated for a long time and evolved into different races (e.g., *Oryza sativa* races, *Sorghum*

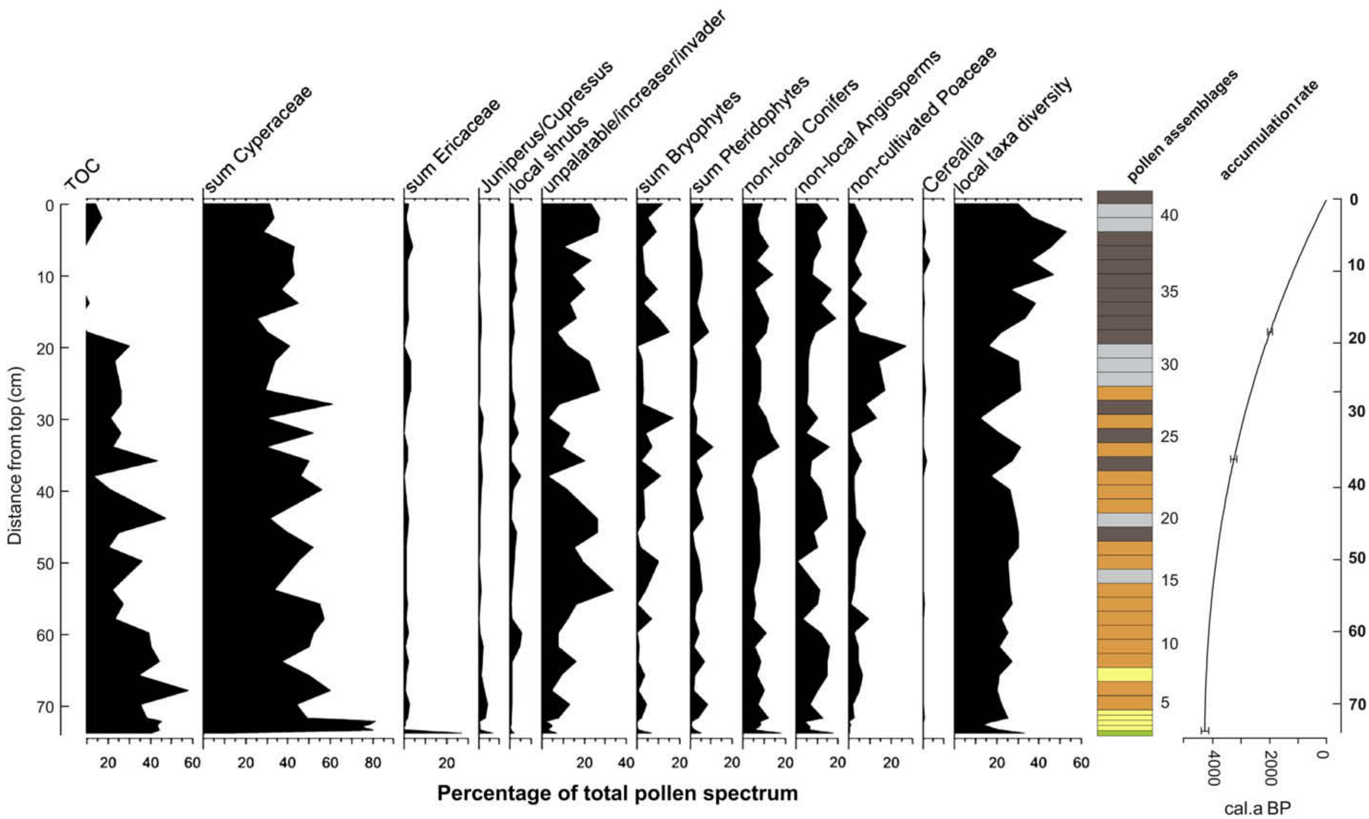

Fig. 8. Pollen diagram showing pollen assemblages and accumulation rate for the drill core retrieved from the peat deposit behind the left Thanza lateral moraine (see Figs. 2 and 5a for exact drill core location). The accumulation rate was calculated from 3 radiocarbon ages fitted via a polynomial function. The pollen assemblages are colour coded (compare Table 2): 1, green; 2, yellow; 3, orange; 4a, grey; 4b, wine-red. See text for details. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

variants and *Zea*) themselves display different exine surface patterns (varying from isolated spines and granules to grouped and fused granules/insular and mixed types; Grant, 1972; Chatuvedi et al., 1994, 1998; Datta and Chatuvedi, 2004). Furthermore, ancient Central Asian domesticated barley or millet plants might reveal different exine surface pattern as extant ones under SEM. Nevertheless, one of our two pollen types affiliated to cereals resembles the *Hordeum*-type by its size, pore and annulus diameter and the exine surface pattern under SEM (Table 3 and Fig. 10) and is closely comparable to *Hordeum vulgare* (i.e. barley; compare e.g. SEM images of Andersen and Bertelsen, 1972; Köhler and Lange, 1979). To date, the insular surface pattern of other cereal type encountered has also been found on species of *Sorghum*, *Eleusine*, *Dactylis*, *Setaria*, and *Agrostis* (i.e. on wild Poaceae species) and therefore no affiliation is proposed at the present stage.

7.2.2.4. TOC content and microscopic charcoal. The strongly decreasing TOC throughout the core cannot be attributed to desiccation with subsequent oxidation and removal of organic matter (which can be an important reason for successional sequence in a drying bog-to-meadow), because fresh water algae, algal cysts and pollen from water plants occur throughout the core and indicate a more or less continuous water saturation of the substrate.

Instead, the decrease in TOC can be linked to the reduction of peat building plants (e.g., *Kobresia spp.*) due to a combination of (i) heavy grazing and trampling by animals corroborated by the succession of pollen assemblages outlined above; (ii) occurrence of periodical fires as revealed by microscopic charcoal throughout the core (from sample 2 onwards); (iii) periodical input of clastic material into the peat swamp due to an increased surface runoff from the surrounding valley flanks.

Again these factors can be readily explained in the context of anthropogenic land use rather than being solely natural environmental changes. We suggest that early settlers practised some form of pastoralism which involved barley cultivation. Occasional fires would have been used to maintain and expand pastures. Long-term trends such as population increase, expansion of agricultural and pastoral activities and degradation of the natural vegetation cover on the surrounding valley flanks may ultimately have caused an increase in clastic material and thus significantly contributed to the deterioration of the peat swamp.

In summary we thus conclude that the variability and changes observed in the palynomorph data set are difficult to reconcile solely with climate or natural environmental changes but instead, if considered in concert, strongly suggest anthropogenic disturbance of a high alpine ecosystem with clear fingerprints of early farming and pastoralism. We argue that Neolithic people entered the high valleys of NW Bhutan and used fire as a tool for clearing the dense juniper-rhododendron scrub for pastoral and agricultural purposes as revealed by (i) extensive charcoal horizons found at the valley flanks close to Tshojo village and south east of Laya village (dating to 4745 ± 250 and 4680 ± 155 cal a BP, respectively); (ii) abrupt pollen changes near the base of the core (suggesting further scrub and forest clearances immediately subsequent to 4280 ± 130 cal a BP—almost overlapping with the above- mentioned charcoal horizons); and (iii) the onset of cereal pollen input into the peat swamp (coinciding with scrub and forest clearances). The presence of cereal pollen suggests that people have been at least seasonally resident in these valleys at altitudes around 4000 m, i.e. close to the

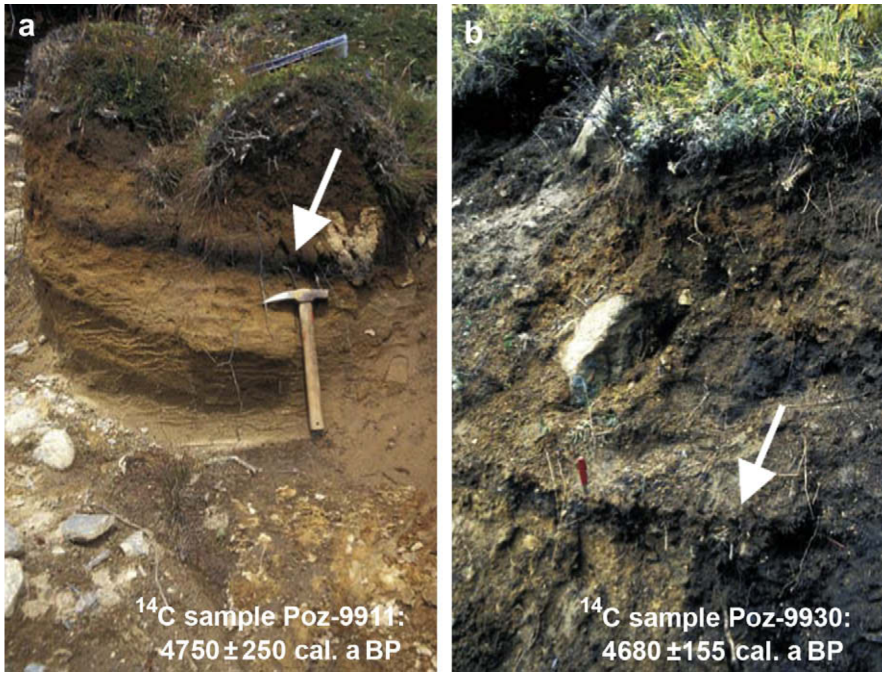

Fig. 9. The charcoal horizons near Tshojo (a) and Laya (b) village. The calibrated radiocarbon years from cm-sized charcoal samples are indicated (see Table 2 for details). (a) The exact outcrop position for sample Poz-9933 is given in Figs. 2 and 5a, respectively; hammer for scale. (b): Sample Poz-9911 comes from a sediment profile at the edge of a kame terrace situated at 3650 m asl ∼12 km southeast of Laya (see Fig. 1 for location of Laya village); knife for scale.

timber line, since at least 4500 cal a BP (using the minimum ages suggested by the two charcoal horizons). Several lines of evidence reveal that the grazing pressure increased dramatically thereafter and throughout the Late Holocene and we link peat deterioration and associated vegetation changes to the impact of domesticated yaks, goats and (or) sheep, which have been kept by these early Bhutanese inhabitants as part of their (presumably) semi-nomadic life style.

8. Palaeoenvironmental change and migration of Neolithic yak pastoralists

If the above scenario (i.e. yak and barley based pastoralism in NW Bhutan since ca 4500 BP) is even partially correct then a number of interesting questions arise. Where did these people come from? How did they enter these Himalayan valleys? Which palaeoenvironmental constraints, if any, influenced the migration routes of these Neolithic pastoral farmers? In this section we will explore further dimensions and implications of our data and evaluate our findings in the context of current thinking on archaeological and palaeoclimatic events in central High Asia.

8.1. The genetic picture

Genetic data (Qian et al., 2000; Su et al., 2000; Gayden et al., 2007) suggest that Tibet as well as the Himalaya (at least the central and northern part of the range) were peopled by proto- Tibeto-Burman populations which originated from a source area beyond (i.e. north and northeast of) the Tibetan Plateau (e.g. the Yellow river area and some admixtures from central Asia; Qian et al., 2000; Su et al., 2000; Gayden et al., 2007). Using the genetic clock as a (rough) chronometer some studies propose that people migrated onto the Tibetan Plateau as early as 30, 000 a ago (Moore et al., 2000; Beall, 2001; Beall et al., 2004; Moore et al., 2004) while other geneticists suggest a migration onto the plateau during Neolithic times (i.e. ca 10 000–5000 a ago; Qian et al., 2000; Su et al., 2000) with subsequent expansion into the Himalaya range (Gayden et al., 2007).

As a first approximation we infer that the groups who entered the high valleys of NW Bhutan ca 4500 years ago (as proposed by our palaeoenvironmental reconstruction) came from the Tibetan Plateau, an interpretation which is also supported by the fact that (i) Tibetans would posses all the physiological adaptations necessary to survive in high elevation hypoxic environments (as opposed to migrants from the Indian sub-continent; Gayden et al., 2007); (ii) the dialects spoken in Tibet as well as in northern and central Bhutan belong to the Tibeto-Burman language family (Matisoff, 1991); and (iii) that the Kingdom of Bhutan has been inhabited by Tibetan descendents throughout historic times (Chakravarti, 1999; Wangchuk, 2000).

8.2. The archaeological record of the Tibetan Plateau

While the general patterns of the human colonization of Tibet are broadly revealed by the genetic data (i.e. peopling from north and northeastern source areas during the Late Pleistocene and/or the Holocene), the detailed timing and sequence of these events are very much under debate. The archaeological record of high Asia is currently too scanty to decide which sub-scenario derived from DNA analysis is likely to be the correct one (Aldenderfer and Zhang, 2004). This is particularly true for possible pre-LGM (Last Glacial Maximum) Palaeolithic occupation scenarios for the interior of the Tibetan Plateau above 4000 m asl, mainly due to a lack of sound chronological control. Evidence for a post-LGM (Late glacial) presence of humans on the plateau exists. However, these were probably limited forays into mid-elevation areas of Qinghai, most likely seasonal in nature, and the earliest secure dates range from 15,800 to 12,400 cal a BP (Madsen et al., 2006; Brantingham et al., 2007). In contrast, the Neolithic is comparatively well-constrained and ages from a number of radiometrically dated archaeological sites, spread across the plateau, can be used to evaluate our Himalaya scenario.

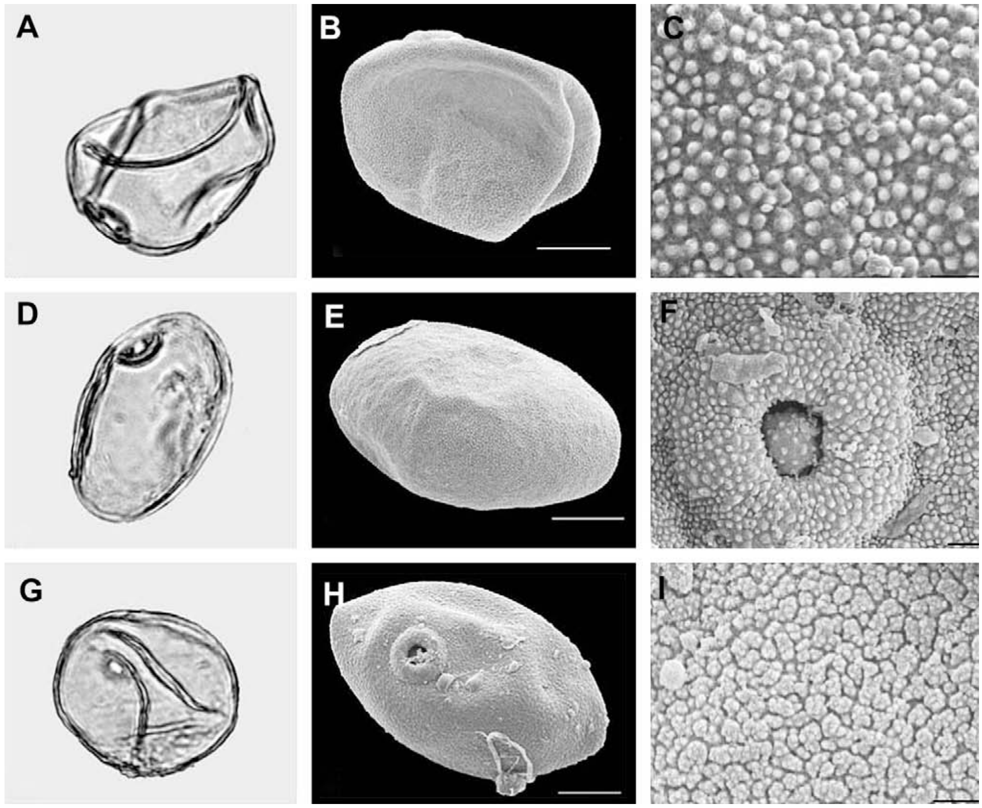

Fig. 10. Light microscope and SEM images of selected cereal pollen grains. (A) shows the LM image of a *Hordeum*-type grain (magnification ×900) (B) is the SEM overview of the same grain (bar = 10 μm) and (C) displays the surface micro-sculptures of individual micro.verrucae ("dots"bar = 1 μm). (D) LM image of a *Hordeum*-type grain (magnification ×900) from sample 14 with (E) a SEM overview (bar = 10 μm) and (F) a detail of the annulus and pore of another *Hordeum*-type grain (bar = 1 μm) from sample 14. (G) LM picture (magnification × 900) of unknown cereal pollen grain from sample 39 with (H) a SEM overview (bar = 10 μm) and (I) a detail (bar = 1 μm) of the surface micro-sculptures displaying insular features with tiny dots.

The earliest known Neolithic site on the Tibetan Plateau is Kha rub, situated at 3100 m on a terrace above the Mekong river (Fig. 1a). Residential structures and a wide range of artefacts were recovered by Chinese archaeologists and associated radiocarbon ages indicate that the site was occupied from ca 6000 to 4000 cal a BP (Aldenderfer and Zhang, 2004). The subsistence at Kha rub is inferred to have been a mixture of hunting, gathering and plant cultivation (e.g. millet). A range of neighbouring sites are related to Kha rub (at least ten; Chayet, 1994), links based on their similar cultural contents and preliminary radiocarbon ages. One striking feature about these sites is that they show a largely unmodified low-elevation adaptive pattern based on permanent architecture, storage features and the use of low-elevation domesticated plants and animals but the Neolithic package seems clearly not to originate from mid-and low-elevation areas in NW China (i.e. Qinghai, Gansu and the Yellow river area; Aldenderfer and Zhang, 2004; Brantingham and Gao, 2006).

Several Neolithic sites have been found in the wider area around Lhasa and in the middle reaches of the Yarlung Tsangpo river as well as further east where that river bends towards the south (see Fig. 1a). The valley floors of the Yarlung Tsangpo and its major tributaries range from 3700 to 3900 m asl, are relatively flat and the river gradient is gentle. There is a gradual increase in wetness towards the east which provides more favourable local environmental conditions compared to the uplands. The archaeological sites all reveal the so-called Qugong culture i.e. they are characterised by the same distinctive ceramics (a highly burnished blackware). The type-site at Qugong, situated 5 km north of Lhasa at an elevation of 3680 m asl was occupied from ca 3700 to 3050 cal a BP (Chayet, 1994; Aldenderfer and Zhang, 2004 and references therein). Analysis of faunal remains suggest that animal husbandry, including domesticated yak, sheep and pigs, was of great importance although hunting continued to be a significant part of the lifestyle. Most authors who have worked with Qugong materials argue that this archaeological culture has its origins in the earlier Kha rub culture with likely trade connections with cultures in Sichuan and possibly central Asia (Aldenderfer and Zhang, 2004).

More sites of Neolithic age are known from mid-elevation areas in the Qinghai region (NE margin of the Tibetan Plateau, Fig. 1a). The archaeological cultures encountered in Qinghai clearly originated from the adjacent lowlands (i.e. Gansu and the Yellow River region) and range in age from ca 5400 to 4100 cal a BP (Aldenderfer and Zang, 2004 and references therein; Brantingham et al., 2007).

The Qinghai area would probably have been of strategic importance in the colonisation of the Tibetan Plateau as it connects the low-elevation source area (in particular the Yellow river region with its very old Neolithic cultures) with the central Tibetan Plateau, where the average elevation is 5000 m asl. The peopling of the interior of the Tibetan Plateau via Qinghai has been proposed by various authors including Madsen et al. (2006), Brantingham et al. (2007) and Rhode et al. (2007a), all of whom stressed that population growth and adaptation in the low-elevation source area ultimately triggered migration waves into the northern fringes of the plateau and the plateau interior (e.g. adaptive spreading of foraging groups after 15,000 a BP prior to that of agriculturalists after ca 6000 a BP; Brantingham et al., 2007; Rhode et al., 2007a).

However, the archaeological record suggests that the Qinghai Neolithic cultures have few direct material affinities with the artefacts recovered from the central Tibetan Plateau (i.e. Kha rub, Qugong and related sites), leading Aldenderfer and Zhang (2004) to speculate that other (lowland) source areas might have been involved in the peopling of the Tibetan Plateau. They suggested that the Neolithic culture found in Qinghai arrived via Gansu and NW China but did not penetrate into the plateau interior, whereas Sichuan might be a more likely source area for the culture of the central Tibetan sites (Fig. 1a; Aldenderfer and Zhang, 2004, p. 39). The earliest Neolithic cultures emerged around ca 7000 a BP in Sichuan and date to ca 8000–7500 a BP in Gansu (Aldenderfer, 2007).

In each of these occupation models considerable distances and high elevation journeys have to be made by early Tibetan inhabitants. Several authors have suggested that such journeys, and in particular year-round full occupation of the high plateau, only became feasible after the successful domestication of yaks (Madson et al., 2006; Brantingham et al., 2007; Rhode et al., 2007b). As today, Tibetans probably needed yak dung for fuel, needed yak by-products such as milk, meat and hair for their daily life and might have relied on these animals to carry equipment (e.g. heavy tents made of yak hair for shelter) in order to survive in the harsh high altitude environment (Rhode et al., 2007b). Currently the Neolithic site at Qugong provides the earliest published evidence for yak domestication (3750 a BP, see above). Yak pastoralism might thus be regarded as a Neolithic adaptation, which is typical for Tibet (Aldenderfer, 2007). It is therefore reasonable to assume that Tibetan groups brought this Neolithic package (yak and barley based pastoralism, as reflected in the palaeoenvironmental record from Lunana) with them as they migrated into the high valleys of NW Bhutan. The Neolithic cultures in the Yarlung Tsangpo drainage system and along the Mekong river (i.e. Kha rub, Qugong and related sites) might both therefore be regarded as potential founder societies for the first settlements in the high valleys of NW Bhutan.

8.3. The Asian monsoon system and its significance for the Himalaya and Tibet

The most important climate driver for the Himalaya (particularly for the eastern and southern slopes) and for much of the Tibetan Plateau is the Asian monsoon system, which delivers substantial amounts of precipitation during the summer months via the northward migration of the Intertropical Convergence Zone (Chao and Chen, 2001; Gadgil, 2003; Yancheva et al., 2007). However, Tibet also experiences some winter precipitation in its northern and western parts due to the mid-latitude westerlies drawing moisture from the Mediterranean, Black and Caspian Seas. Several high resolution palaeomonsoon records suggest that the Asian monsoon system is strongly controlled by variations in insolation on orbital to decadal time scales. Phases of enhanced monsoon intensity for the last glacial-interglacial cycle occurred during MIS 5c, 5a, 4 and 3, the Late glacial and the Early to Mid Holocene (i.e. phases of high insolation correlate with high monsoon intensity, e.g. Fleitmann et al., 2003, 2007; Gupta et al., 2003; Dykoski et al., 2005; Wang et al., 2005, 2008).

Variations in the summer monsoon are vital for the summer accumulation type glaciers in the Himalaya (as well as for the glaciers in the monsoon influenced parts of the Tibetan Plateau). As outlined in Section 4.1, this glacier type is moisture limited and as long as precipitation increases, summer accumulation type glaciers are capable of advancing during even warm climatic periods. The mechanism is simple: with a stronger monsoon and thus greater snowfall in the frigid high altitude zone, avalanches will also increase in size and frequency and efficiently transfer ice to lower altitudes thereby causing more positive glacier mass balances than would otherwise be possible (Phillips et al., 2000; Owen et al., 2002).

A significant body of evidence suggests that glaciations were broadly synchronous throughout the Himalaya range and were driven by variations in the Indian summer monsoon, although the magnitude of a glacial advance in any particular catchment area would also have been dependent on a number of local parameters (e.g. hypsometry, regional precipitation gradients and the amount of debris cover on glacier surfaces; see Owen et al., 2002, 2005 and Gayer et al., 2006 for a detailed discussion). Tight chronological control has been established for a number of areas with glacial systems closely comparable to those of NW Bhutan (i.e. high monsoon influence, debris-covered glacier snouts and avalanche nourishment).. Surface exposure and OSL dating of moraines in the Mount Everest region (Finkel et al., 2003), the Nanga Parbat (Phillips et al., 2000;Richards et al., 2000, 2001), the NW Garhwal (Sharma and Owen, 1996) or NE Nepal (Zech et al., 2003) clearly demonstrates that major glacier advances occurred during MIS 3 and earlier (probably MIS 4). The Lunana stage moraines stand comparison in style and extent with those of glacial stages such as the Thyangboche II glacial stage south of Mount Everest (Khumbu Himal, Finkel et al., 2003) as well as with MIS 3 glacial advances in other parts of the Himalaya, suggesting that the Lunana stage moraines may be diachronous in nature.

Significant glacier expansion during the Early to Mid Holocene in response to a prolonged period of high monsoon intensity is known from many monsoon influenced catchments where glacier advances vary between 1 and more than 10 km (e.g. Philips et al., 2000; Owen et al., 2002, 2005 and references therein; Finkel et al., 2003; Barnard et al., 2004b), highly comparable to the Thanza advances I and II in Lunana. It is an important aspect of many of these monsoon-dominated catchments that glacier expansion during the Lateglacial (more specifically the Bölling–Alleröd warm period) and/or the Early to Mid Holocene was greater than had been the case during the LGM. The LGM was cold but too dry to trigger strongly positive glacier mass balances in these areas. As a consequence, LGM moraines are sometimes not preserved in monsoon-influenced catchments at all (Barnard et al., 2004b, 2006; Owen et al., 2005). We may be looking at a similar situation in Lunana, where no LGM moraines have been identified so far. However, a more rigorous dating campaign, including cosmogenic radionuclide dating, will be required to clarify the chronology of Late Pleistocene deposition in this region beyond the morphostratigraphic correlation suggested in this study (assignment of the Lunana stage to the MIS 3).

During times of increased insolation (i.e. interstadials and interglacials) when the Asian summer monsoon strengthened and produced more positive glacier mass balances, it also penetrated further into central high Asia creating warmer and wetter conditions upon the Tibetan Plateau. Such northward shifts in the monsoon front profoundly influenced the hydrology on the plateau, hence its floral and faunal communities—factors, which in concert must have directly influenced the human colonization history of central high Asia. Many lakes mirror these (monsoon) changes and lacustrine sediments thus provide one of the most valuable palaeoenvironmental records from Tibet although some of these lake systems also receive hydrological contributions from the Eurasian westerlies and glacial ice melt and thus show a more complex response. In general, these records suggest that high lake stands occurred during MIS 5 and 3 (e.g. Pachur and Wünnemann, 1995; Zhang et al., 2004; Madsen et al., 2008), while warm and wet conditions on the plateau (with elevated lake levels) during the Early Holocene are generally recognized (e.g. Gasse et al., 1991; Brown et al., 2003; Morrill et al., 2006; Wu et al., 2006). It is interesting to note that in several of the Tibetan lake records, an abrupt weakening of the Asian monsoon system appears at ca 4500–5000 a BP (Morrill et al., 2003 and references therein; Morrill et al., 2006; but see also Fleitmann et al., 2007 for a detailed discussion of the nature of this abrupt change in the monsoon intensity). In the next section we will investigate climate–human–

environment relationships, which in our context means examining migration routes of yak pastoralists against the background of glacier and lake level fluctuations in the Himalaya and on the Tibetan Plateau, respectively.

8.4. Motivation for migration into the high valleys of NW Bhutan

As outlined above, glacier fluctuations as well as pro- and periglacial processes play a dominant role in the High Himalaya. These processes intensify during phases of strong monsoon like MIS 3, when huge ice-stream networks developed in several catchments (Lunana presumably included, Fig. 7a). Human occupation of most sectors of the High Himalaya was thus rendered impossible during much of the early part of the last glacial cycle (leaving aside the question of whether humans had ever been capable of foraging in these high valleys during earlier periods of strong monsoonal activity). On the other hand, periods of low monsoon intensity and thus limited glacier expansion (like the Late Holocene) made human colonization of the Himalayan valleys at least feasible (Fig. 7f). These periods also coincided with drier conditions and lower lake levels (or even desiccation) on the Tibetan Plateau. Throughout the Quaternary, however, precipitation on the southern Himalayan slopes was much higher than in the rain shadow on the Tibetan Plateau. Floral and faunal communities are enriched and much more diverse south of the main Himalaya chain due to this orographic effect. We therefore suggest that certain Himalayan valleys provided attractive living spaces for Tibetan tribes because of their natural resources, and that colonization of these valleys was probably dependent on factors like (1) availability of space (i.e. are the valley floors largely ice-free, morphodynamically stable, and broad and flat enough to allow habitation), (2) direct or indirect accessibility from the north (are there passes or a series of passes, which can be safely crossed by yak pastoralists), and (3) availability and diversity of natural resources (whether or not the territory provides sufficient liquid water, fuel material, pastures, arable soil and game to support a human population). However, other factors related to the Tibetan Plateau itself have to be considered as well, such as (4) palaeoenvironmental change and climatic stress in the source area (e.g. increasing dryness on the plateau due to a weakening monsoon might ultimately trigger migration) and (5) demographic and adaptive changes in the source area (population growth or domestication of yaks and development of yak pastoralism might have initiated new migration waves and adaptive radiations).

The abrupt shift towards drier conditions on the Tibetan Plateau at around 4500–5000 cal a BP inferred from Tibetan lake records (Morrill et al., 2003 and references therein, Morrill et al., 2006) coincides precisely with the retreat of glaciers in Lunana (the main valley becoming ice-free at ≥4700 cal a BP) and with the age of the charcoal horizons and inferred human arrival in NW Bhutan (ca 4500 cal a BP). Colonization of the high valleys in the Bhutan Himalaya might thus have been triggered by changes of climate on the Tibetan Plateau.

However, looking at the situation in more detail we might face a "chicken and egg" problem as with the current data set it is hard to decide whether (i) Tibetans would have migrated into the Himalayan valleys even earlier if the passes would have been ice free (but only a weakening monsoon and thus retreating Himalayan glaciers at around 4500 a BP allowed them to gain access to the valleys in the south) or if (ii) Tibetan people were forced to explore new habitats and thus to expand into the Himalaya range due to deteriorating climatic conditions on the plateau subsequent to 4500 a BP (they would not otherwise have had any incentive to cross the Himalayan passes). We favour the former hypothesis because the oldest charcoal in Lunana was retrieved from the Thanza palaeosol and gave an age of 6710 cal a BP. Assuming that fires in this ice-proximal environment are predominantly anthropogenic rather than natural in origin (compare Section 7.2) we speculate that Tibetan groups might already have explored the High Himalaya during the early part of the Mid Holocene.

There is a further hypothesis to be considered. Were humans ever to have been present upon the Tibetan Plateau prior to the LGM (Zhang and Li, 2002; Aldenderfer, 2007; Yuan et al., 2007), the Himalayan valleys in the south might have been an ideal refugium for such groups during the onset of the LGM as climate started to deteriorate and extreme drought started to grip the plateau. Entering these valleys despite dropping temperatures is conceivable due to the direct monsoon control of most glacier systems in the Himalaya, which resulted in very limited glacier advances in some catchments (Lunana included, Fig. 7b).

8.5. A model for human colonization of the high valleys in NW Bhutan

For Lunana we can now summarize our findings and ideas into the following glaciation–human colonization model (Fig. 7).

Whilst maximum glacier expansion probably occurred during MIS 3, glaciers might have been rather restricted in size during the LGM, both phenomena resulting from the strong monsoonal influence in this catchment (Fig. 7a and b). No firm evidence exists that humans occupied the interior of the Tibetan Plateau prior to the LGM but if they did, we consider that these people might have also been capable of migrating further south, and the Himalaya valleys could have served as a LGM refugium for them.

The Lateglacial–earliest Holocene period is characterized by glacier advances of up to 5 km relative to modern glacier positions (Thanza I advance), which also resulted in the creation of a number of pro-glacial lakes, enhanced pro-glacial discharge and sedimentation, and expansion of numerous cirque and hanging glaciers on the surrounding mountain slopes (Fig. 7c). During such phases of high geomorphological activity and sediment transfer Lunana would have been largely uninhabitable. A well-developed palaeosol within the Thanza lateral moraine indicates a subsequent geomorphologically stable phase, which ended at ≤6700 cal a BP. The exact degree of glacier expansion during this stable phase (i.e. the early part of the Mid Holocene) is unknown but we presume ice reached positions intermediate between the Thanza stage and the modern glacier termini. Centimetre-sized sedimentary charcoal in a clay horizon overlying the Thanza palaeosol—if attributed to anthropogenic use of fire—suggests human presence in Lunana by 6700 cal a BP (Fig. 7d, dotted lines).

A second glacier advance occurred between ca 6700 and 4700 cal a BP (Thanza II advance, Fig. 7e) again rendering habitation of Lunana rather problematic for two millennia. Several lines of evidence suggest permanent human colonization had been established in these high valleys by 4500 cal a BP. We propose that Neolithic yak pastoralists from Tibet were able to cross the passes connecting NW Bhutan with the Tibetan Plateau and introduced domesticated *Hordeum*, which they grew in favourable valley locations (Fig. 7f, broken lines).

The Late Holocene glaciers never subsequently reached the scale of the Thanza advances again, but instead were restricted to positions very similar (±1 km) to those of the modern glacier snouts. It is therefore possible that uninterrupted human occupation of Lunana may have continued for more than four millennia.

9. Conclusions

Palaeoenvironmental and archaeo-botanical data from Lunana support the concept that there has been permanent human colonization of the high valleys in NW Bhutan for the last 4500 years. The occurrence of charcoal horizons in the area coincides with the sudden disappearance of *Juniperus* and Ericaceae pollen in the Thanza peat core and the onset of cultivated *Hordeum*. The peat core reveals a clear pattern of over-grazing, trampling and peat deterioration further up-section. We have evaluated each of these phenomena separately and conducted detailed SEM analysis of the cereal pollen grains, in order to discriminate wild grass from cultivated *Hordeum* pollen. We conclude that, when viewed in concert, these data are strongly indicative of human impact on this high-alpine ecosystem (including use of fire for forest clearances and barley cultivation). It is suggested that Neolithic yak pastoralists from the adjacent Tibetan Plateau were the most likely founder societies (probably semi-nomadic pastoralists or small communities of mixed hunting, farming and herding of livestock). On a more speculative base, but still realistic given the Tibetan archaeological record, charcoal occurrences on top of a palaeosol might indicate the presence of Tibetan Neolithic groups in Lunana as long ago as ca 6700 cal a BP.

Glacier fluctuations in Lunana are driven by the Indian summer monsoon and, together with pro- and periglacial processes, form the primary controls on the accessibility of these Himalayan catchments. A detailed reconstruction of the post-LGM glacial history of Lunana reveals there to have been an Early Holocene advance and a secondary phase of Mid Holocene glacier expansion. A sudden glacier retreat then occurred just prior to 4700 cal a BP, which links with evidence for an abrupt shift towards dryer conditions on the Tibetan Plateau at around the same time. We have argued that these monsoon-related climatic and geomorphic changes in central high Asia not only opened up the High Himalayan valleys for human groups to enter but might have also induced (or reinforced) migration of yak pastoralists from the plateau into the Himalaya with its more favourable ecological niches.

We presented indirect evidence of human arrival in the high valleys of NW Bhutan (as opposed to direct archaeological evidence like artefacts or macro-remains of domesticated plants). However, the palaeoenvironmental and archaeo-botanical data discussed in this paper provide the probably earliest proof for human activity yet known for the High Himalaya range. Further investigations are required, both in different Himalayan catchments and in the bordering section of the Tibetan Plateau (e.g. the lake region between the Yarlung Tsangpo and the High Himalaya, Fig. 1b), to validate and refine the glaciation and human colonization model proposed here.

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Appendix A. Supplemental material

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