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Charcoal and fossil wood from palaeosols, sediments and artificial structures indicating Late Holocene woodland decline in southern Tibet (China)

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ABSTRACT

Charcoal and fossil wood taken from palaeosols, sediments and artificial structures were analysed in order to evaluate the regional pedoanthracological potential and to obtain information on Holocene environmental changes, particularly on possible past tree occurrences in southern Tibet. This research was initiated by the question to what extent this area is influenced by past human impact. Even recent evaluations have perceived the present treeless desertic environment of southern Tibet as natural, and the previous Holocene palaeoenvironmental changes detected were predominantly interpreted to be climate-determined. The material analysed – comprising a total of 53 botanical spectra and 55 radiocarbon datings from 46 sampling sites (c. 3500–4700 m a.s.l.) – represents the largest systematically obtained data set of charcoal available from Tibet so far. 27 taxa were determined comprising trees, (dwarf-) shrubs and herbs as well as grasses. The predominant tree taxa were *Juniperus*, *Hippophae*, *Salix* and *Betula*. According to their present-day occurrence in the region, the genera *Juniperus* and *Hippophae* can be explicitly attributed to tree species. Further, less frequently detected tree taxa were *Populus*, *Pinus*, *Quercus*, *Taxus* and *Pseudotsuga*. Charcoal of *Juniperus* mainly occurred on southern exposures, whereas *Betula* was associated with northern exposures. In contrast, the (partly) phreatophytic taxa *Hippophae* and *Salix* showed no prevalent orientation. The distribution of radiocarbon ages on charcoal revealed a discontinuous record of burning events cumulating in the Late Holocene (c. 5700–0 cal BP). For southern Tibet, these results indicated a Late Holocene vegetation change from woodlands to the present desertic pastures. As agrarian economies in southern and south-eastern Tibet date back to c. 3700 and 5700 cal BP, respectively, and the present-day climate is suitable for tree growth up to c. 4600 m a.s.l., we concluded that the Late Holocene loss or thinning out of woodlands had been primarily caused by humans.

1. Introduction

Over the last decade several new studies have dealt with the questions what changes the vegetation cover of central and high Asia underwent during the Holocene and whether the present vegetation is primarily natural or was secondarily established following (past) human impact. Traces of a forest history, as represented by pollen, charcoal and fossil wood, indicate that larger areas of western China, Mongolia and of several Himalayan countries have undergone drastic vegetation changes in the last few millennia (e.g. Beug and Miehe, 1999; Ren, 2000; Shen, 2003; Schlütz and Zech, 2004; Byers, 2005; Feng et al., 2006; Huang et al., 2006; Miehe et al., 2007a; Zhao et al., 2007).

On the Tibetan Plateau, forming the largest alpine area in the world (c. 2.2^6 km^2), treeless vegetation belts in the eastern sector between c. 3000 and 5000 m a.s.l. were often assumed to be natural. Studies dealing with the present-day vegetation and also those on the Late Holocene vegetation history have repeatedly claimed that the region's harsh climatic regime has been the main factor preventing the recent growth of trees and that human impact on vegetational changes has been limited to the recent past (e.g. Ni, 2000; Yu et al., 2001; Ren and Beug, 2002; Luo et al., 2004, 2005; Song et al., 2004). However, there are a growing number of studies which question this view. They point to the current distribution of zonal forest and woodland islands throughout the southern and north-eastern Tibetan Plateau, implying that viable and reproducing tree stands prove that current climatic conditions can support tree

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growth. Furthermore they point to the increasing palaeoecological evidence of larger forests still in the Mid- and at the beginning of the Late Holocene (e.g. Holzner and Kriechbaum, 1998; Frenzel, 2002; Bräuning, 2007; Kaiser et al., 2007; Mosbrugger et al., 2007; Ren, 2007; Schlütz et al., 2007; La Duo, 2008; Miehe et al., 2008a,b; Schlütz and Lehmkuhl, 2009). Consequently, as climatic conditions at the peak of the Holocene desiccation and cooling period (e.g. He et al., 2004; Herzschuh, 2006; Zhao et al., 2007; Zhu et al., 2008) could support tree growth (the tree stands had been established long before the current anthropogenic warming commenced), they claim that climatic changes during the Late Holocene cannot have been the single driving force for a large-scale forest decline. Accordingly forest disappearance or thinning out might be explained by human impact comprising grazing of domestic animals, clearing for the establishment of arable land and settlements, and burning. Furthermore, Kaiser et al. (2006) and La Duo (2008) discuss a combination of climatic effects and anthropic factors, arguing that after an initial climate-driven opening of the vegetation cover by aridification and cooling, human impact increased this process. Nevertheless, as both the evidence for larger Holocene forests and that for early human impact are infrequent, widely-scattered and inadequately discussed so far, the dispute is not settled. With the present paper we want to contribute to this discussion by presenting the so far largest systematically obtained data set of charcoal available from the Plateau in order to provide new regional records of fossil woody taxa. Furthermore, we hope to stimulate additional high-resolution studies by showing the pedoanthracological potential of sites along an 800 km transect.

In general, data on vegetation history can be obtained using several methods/plant remains (e.g. pollen, macro remains, charcoal) and archives (e.g. lake sediments, peat, palaeosols). Evidence and interpretation of past environmental changes substantially depends on how well the archive used represents the area. Palynology usually gains insights into *(sub-) regional* vegetation patterns (e.g. Berglund and Ralska-Jasiewiczowa, 1986; Seppä, 2007; Sugita, 2007). However, because of possible long-distance pollen transport, it remains uncertain whether certain taxa really did grow on the respective sites. In contrast, macroscopic charcoal and fossil wood reliably reflect the *local* growth of woody taxa (e.g. Schoch, 1986; Lynch et al., 2004; Carcaillet, 2007) except for some potentially problematic archives (e.g. fluvial-lacustrine sediments, artificial structures). In comparison to palynological research, which is comparatively well-established on the Plateau, charcoal analysis (anthracology) and fossil wood analysis (xylology) have been rarely performed so far. The charcoal and fossil wood presented in this study were primarily derived from palaeosols and sediments during research on the Late Quaternary geomorphic evolution of the Lhasa area in southern Tibet (Kaiser et al., 2006, 2009, in press-a), and in the context of biogeographical research on the distribution of juniper forests in south-eastern Tibet (Miehe et al., 2008a). They were thus not obtained in a strict anthracological framework. Nevertheless, as the whole material comprised 53 botanical spectra and 55 radiocarbon datings from 46 sampling sites covering a biogeographical transect from the coniferous forests in the east, via the present border of the closed forest area, to forest outposts/relics in the west (Fig. 1, Appendix 1), a palaeoecological appraisal is very much worthwhile.

The overall question to be addressed by this paper is: What can charcoal and fossil wood primarily found in palaeosols and sediments tell us about the Holocene environmental history of southern and south-eastern Tibet? More specifically we wanted to i) describe taxa composition, topographic pattern and dating of (woody) plant fossil assemblages; ii) interpret and discuss the results with respect to the regional environmental history, including fire history, by means of further biogeographical–ecological, palaeobotanical, geoscientific and archaeological evidence; and iii) evaluate the regional pedoanthracological potential.

2. Study areas

We had two main study areas, comprising the Lhasa area in southern Tibet and the deep river gorges of south-eastern Tibet, which as currently classified in the Atlas of Tibet Plateau (1990) belong to two biogeographical zones: open dwarf shrubland pastures and coniferous forests, respectively (Fig. 1, Appendix 1). In the following, mainly information on climate and vegetation/land-use will be given. Further aspects, such as details on geology, geomorphology and pedology, can be taken from e.g. Atlas of Tibet Plateau (1990), Kaiser et al. (2006, 2009, in press-a-b) and Miehe et al. (2008a).

The sites in southern Tibet are located in the Kyichu Valley and its tributaries (Figs. 1 and 2). The deeply incised valley bottoms lie at c. 3500–4200 m a.s.l. surrounded by mountain ridges and peaks up to 5400 m a.s.l. (altitudes sampled: 3500–4600 m a.s.l.). According to climatic data as given in Fig. 1, the present climate on the valley floors at c. 3550–4150 m a.s.l. is characterised by mean annual air temperatures (MAATs) of 2.4–8.5 °C and mean annual precipitations (MAPs) of 361–549 mm a^{-1}, derived from c. 10- to 40-year series of measurements (Domrös and Peng, 1988; Miehe et al., 2001). Rainfall on the higher slopes is considerably higher as exemplary rain-gauge measurements in the Lhasa area showed with an annual rainfall of 485 mm a^{-1} at 3750 m a.s.l. and of 715 mm a^{-1} at 4650 m a.s.l. (Miehe et al., 2003). Penman-Monteith potential evaporation estimates of Lhasa amount to 1328 mm a^{-1} (Thomas and Chen, 2002). There are six to seven months with relatively arid conditions, suggesting a semiarid climate. Domrös and Peng (1988) assign the Lhasa area to a semiarid subtype in the 'Temperate Plateau Zone' of the climate zones of China. The recent snowline is calculated at about 6000 m a.s.l. (Lehmkuhl et al., 2002). Despite the high altitudes, temperatures are suitable for tree growth: between May and September mean monthly temperatures are above 10 °C. The growing season with mean monthly temperatures above 5 °C covers eight months (Miehe et al., 2008a).

The floodplains are characterised by mobile cobbles to sands, sparsely overgrown by grasses, and grazed wetlands with a dense cover of sedges, grasses and herbs, or – if inactive – by irrigated arable land and wood plantations. Grazed remains of the natural phreatophytic woodlands, consisting of tree-forming buckthorn (*Hippophae rhamnoides*), willow (*Salix* spp.) and poplar (*Populus* spp.), are preserved only locally (Figs. 2C and 3A, C, Appendix 2). The valley slopes are exposed to a strong, year-round grazing impact, having a grass-dominated vegetation with low thorny shrubs (e.g. *Sophora moorcroftiana*) and wormwoods (*Artemisia* spp.). In some protected slope positions, shrubs several metres high occur (e.g. *Buddleja* spp., *Cotoneaster* spp.). However, above the valley bottoms large areas are desertic pastures and strongly eroded badlands (Fig. 2A). Above c. 4500 m a.s.l. dense sedge mats of *Kobresia pygmaea* accompanied by cushions prevail. There are several dry-site woodland patches ('forest islands') or single trees of juniper (*Juniperus convallium*, *Juniperus tibetica*) in the study area (Miehe et al., 2008a). The term 'woodland' is used here in the sense of open forests or 'ecosystems that contain widely spaced trees with their crowns not touching' (Hobbs, 2002). The largest woodland is a south-exposed mature *J. tibetica* stand around Reting Monastery, comprising hundreds of trees of 10–15 m high and up to c. 1000 years old; it shows regeneration (c. 4200–4850 m a.s.l.; Miehe et al., 2003, 2008a; Bräuning, 2007; Figs. 2B and 3A, B). Furthermore, small remains of the natural woody vegetation on north-facing slopes consisting of birch (*Betula* spp.), willow (*Salix* spp.) and rhododendron (*Rhododendron* spp.) are preserved in the Kyichu valley and its tributaries at altitudes of c. 4100–4500 m a.s.l. (Figs. 2D and 3A, D).

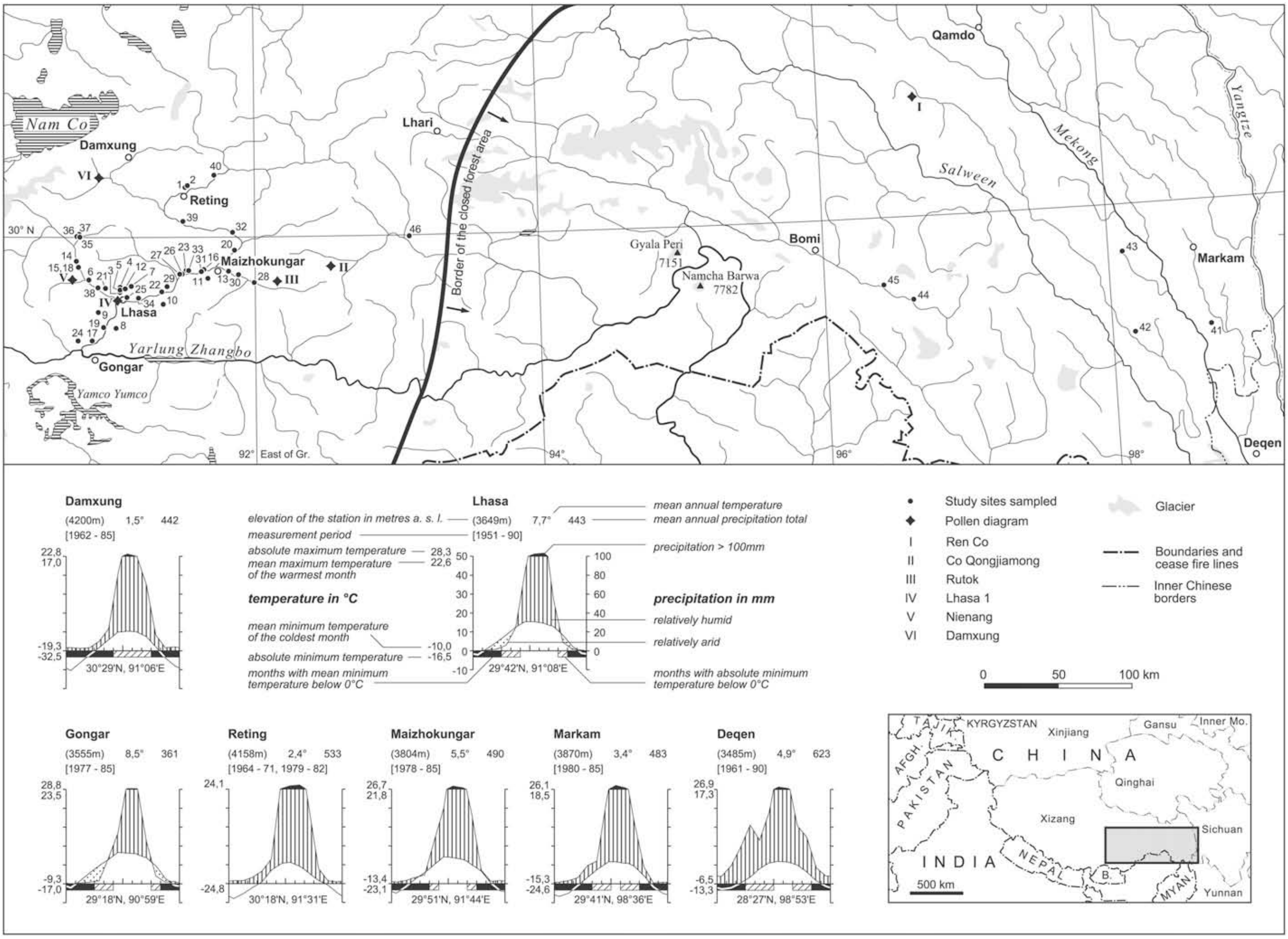

Fig. 1. Location of the sites sampled and of the pollen diagrams discussed (map adapted from Miehe et al., 2001; border of the closed forest area adapted from Atlas of Tibet Plateau, 1990).

The sites in south-eastern Tibet are located within the catchment of the lower Yarlung Zhangbo, Salween and Mekong rivers (Figs. 1 and 2). As the sampling sites are located at c. 3500–4700 m a.s.l., only the meteorological stations Markam (3870 m a.s.l.) and Deqen (3589 m a.s.l.) seem useful for characterising the sites. Their records show MAATs of 3.4 and 4.8 °C and MAPs of 483 and 664 mm a^{-1}, respectively, derived from c. 5- to 26-year series of measurements (Miehe et al., 2001). The area is assigned to a subhumid subtype of the 'Temperate Plateau Zone' of China (Domrös and Peng, 1988).

The deeply incised river gorges display a sequence of altitudinal vegetation belts, starting with open dwarf shrublands of the dry river valley bottoms roughly between 2500–3500 m a.s.l. The sequence continues with conifer forests of juniper (*Juniperus* spp.), fir (*Abies* spp.) and spruce (*Picea* spp.) as well as sclerophyllous thickets and forests of oak (*Quercus* spp.) between 3500–4800 m a.s.l. (Fig. 2E–G). The forests are succeeded by thickets ('krummholz') and alpine pastures.

3. Material and methods

3.1. General remarks and sampling

In general, (pedo-) anthracological studies have already been performed at several (sub-) alpine sites throughout the world, mostly comprising areally high-resolution palaeoecological case studies (e.g. Tessier et al., 1993; Carcaillet and Thinon, 1996; Tinner et al., 1996; Carcaillet and Brun, 2000; Carnelli et al., 2004; Di Pasquale et al., 2008). In contrast, our data have so far been collected mainly for geomorphical purposes and characterise palaeosols and sediments. Thus we commonly obtained one dated charcoal or fossil wood spectrum per site only, yielding a low areal and temporal resolution. Nevertheless, since the data were derived from a transect extending over c. 800 km west–east distance comprising 46 sampling sites, they represent a valuable cross-section to shed light on the regional vegetation history, particularly of the Lhasa region. Most of both the botanical spectra and datings are published here for the first time, although some have been previously published, comprising 15 spectra and 22 ^{14}C datings (Kaiser, 2004; Kaiser et al., 2006, 2009, in press-a; Appendix 3, Tables 1 and 2).

Field work for the samples presented here took place in between 2003 and 2007. There is a strong disparity in the geographical distribution of the sites sampled, comprising 40 sites in southern Tibet and 6 sites in south-eastern Tibet (Fig. 1). Both natural and anthropogenic exposures with a thickness of 2–13 m were used after preparation of the profiles. In this study, only some selected site properties, such as topographic features (altitude, coordinates and relief), stratigraphical characteristics (sample depth, sediment type, palaeosol and parallel archaeological evidence) and recent vegetation, are documented (Appendix 3). Detailed pedological and sedimentological descriptions of the profiles as well as further analyses (e.g. geochemical and luminescence data) can be obtained from Kaiser et al. (2006, 2009, in

Fig. 2. Photographs of selected sites investigated (an extended caption is available in Appendix 2). (A) Lower Kyichu Valley c. 50 km southwest of Lhasa, southern Tibet (3800 m a.s.l.). The northeast-facing slope in the foreground is covered by an open *Juniperus convallium* stand. (B) Relic *Juniperus tibetica* forest on a south-facing mountain slope (c. 4200–4650 m a.s.l.) in the middle Kyichu Valley west of Reting Monastery, southern Tibet. (C) Valley ground of the Madromachu, southern Tibet (3850 m a.s.l.) covered with *Hippophae rhamnoides* trees up to 5 m high. (D) North-facing slope in the Madromachu Valley, southern Tibet (4150 m a.s.l.), covered by *Betula platyphylla* trees (max. c. 4 m high), *Salix* and *Rhododendron*. (E) Descent from pass west of Garthok, south-eastern Tibet (4250 m a.s.l.). Forest on the southwest-facing slope is mainly made up of *Picea* with *Quercus* and *Juniperus*. (F) View from sampling site LO-04-H6 at the outflow of Rawu Lake, south-eastern Tibet (3950 m a.s.l). Forest on the northwest-facing slope is mainly made up of *Picea purpurea*. (G) Single *Juniperus* trees on a southwest-facing slope in south-eastern Tibet (4130 m a.s.l.). The north-facing slope in the background is covered by *Picea* forest. (H) Large piece of *Juniperus* charcoal (max. 13 cm in length) in profile SHE 1, southern Tibet (3700 m a.s.l.), dating to 2624 ± 103 cal BP. (I) Large pieces of *Populus* (max. 30 cm in length) in profile CHU 5, southern Tibet (3770 m a.s.l.), dating to 3586 ± 59 cal BP. (J) Profile FAN 1, southern Tibet (3720 m a.s.l.), showing a palaeosol (red dot) with fluvial sand below and above. Charcoal (e.g. *Juniperus*) extracted from the palaeosol dates 2511 ± 129 cal BP. (K) Profile STA 1, southern Tibet (3660 m a.s.l.), showing a palaeosol (red dot) with aeolian sand below and above. Charcoal (*Juniperus*) extracted from the palaeosol dates 2817 ± 34 cal BP. (L) Profile CHS 1, southern Tibet (4040 m a.s.l.), showing two palaeosols (red and blue dot) developed from fluvial sand and silt. Charcoal (e.g. *Hippophae*) extracted from the palaeosol dates 6603 ± 59 cal BP (red dot) and 6808 ± 62 cal BP (blue dot). (M) Profile CHU 5, southern Tibet (3770 m a.s.l.), showing a peat layer (red dot) below fluvial and colluvial silt. Fossil wood (*Populus*) extracted from the peat dates 3586 ± 59 cal BP.

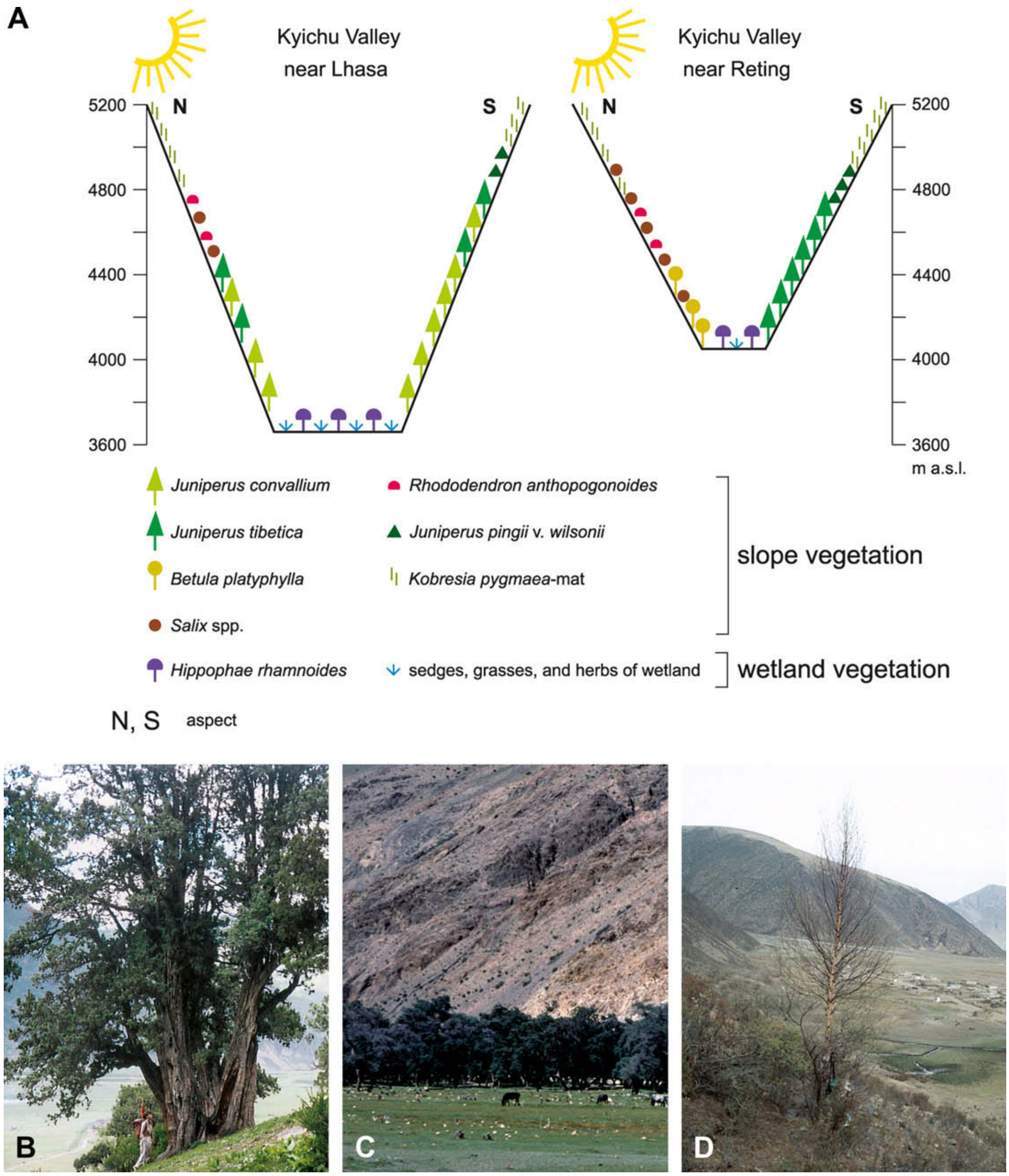

Fig. 3. Vegetation characteristics of valleys in southern Tibet. (A) Natural altitudinal vegetation belts in the Kyichu Valley derived from isolated tree stands and vegetation records (adapted from Miehe et al., 2008a). (B) *Juniperus tibetica* tree (c. 13 m high, c. 2.3 m breast height diameter, DBH) on a south-facing lower slope at Reting site (4200 m a.s.l., 30°18′N, 91°30′E). (C) *Hippophae rhamnoides* trees (c. 10 m high, c. 0.5 m DBH) in the upper Arun Valley (c. 4000 m a.s.l., 28°20′N, 87°12′E). (D) *Betula platyphylla* tree (c. 8 m high, c. 0.2 m DBH) on a north-facing lower slope near Reting site (4100 m a.s.l., 30°17′N, 91°30′E).

press-a). The charcoal samples ($n = 50$) and fossil wood samples ($n = 3$) were picked out macroscopically, using knives and tweezers, from the whole layer sampled (e.g. palaeosol). After air-drying and sieving, c. 50–200 particles per (charcoal-) sample comprising a bulk volume of c. 5–20 cm^3 were stored in plastic tubes.

3.2. Botanical determination

The microscopic examination of charcoal and fossil wood samples was carried out on fracture surfaces and microsections, respectively, on the three fundamental planes (transverse, longitudinal–radial and longitudinal–tangential; Appendices 4 and 5) under the stereomicroscope Olympus BX-60 (magnifications for botanical determination: 50–500×). Identification was performed by means of comparison with preparations from living material or from digital photographs of recent wood species (Hoadley, 1990; Schweingruber, 1990; Schoch et al., 2004).

The fossil taxa determined were arranged into 'ecological groups' showing properties (growth form, exposure) of their probable *present-day* equivalents in southern and south-eastern Tibet (Table 1). The assignation of certain taxa to growth forms is discussed in detail in chapter '5.1. Assignation of growth forms'.

3.3. Radiocarbon dating

Radiocarbon (^{14}C) dating was performed on a total of 55 samples in the Erlangen Radiocarbon Laboratory by accelerator mass spectroscopy (AMS; Table 2). The majority of ages were obtained from

Table 1
Fossil plant taxa determined in southern and south-eastern Tibet and their arrangement in ecological groups.

Ecological group	Taxon determined	English name	Growth form[a]	Remark
Upland tree species I (southern Tibet)	*Juniperus sp.*	juniper	Tr	probably *J. tibetica*, mostly south-facing growth
	Betula sp.	birch	Tr	probably *B. platyphylla*, mostly north-facing growth
	Salix sp.	willow	Tr	partly north-facing growth (partly phreatophytic)
	Pinus sp.	pine	Tr	imported timber?
Upland tree species II (south-eastern Tibet)	*Juniperus sp.*	juniper	Tr	mostly south-facing growth
	Betula sp.	birch	Tr	mostly north-facing growth
	Taxus sp.	yew	Tr	mostly north-facing growth
	Pseudotsuga sp.	Douglas-fir	Tr	mostly north-facing growth
	Pinus sp.	pine	Tr	mostly south-facing growth
	Quercus sp.	oak	Tr	mostly south-facing growth
	Salix sp.	willow	Tr	partly north-facing growth, partly phreatophytic
Wetland tree and shrub species	*Salix sp.*	willow	Tr	partly phreatophytic (partly north-facing growth)
	Populus sp.	aspen	Tr	–
	Hippophae sp.	buckthorn	Tr	probably *H. rhamnoides*
	Tamaricaceae	tamarisk family	Sh	probably *Myricaria* spp.
Shrub species of the forest understorey and above treeline	*Buddleja sp.*	butterfly bush	Sh	mostly south-facing growth
	Lonicera sp.	honeysuckle	Sh	–
	Sophora sp.	necklacepod	Sh	probably *S. moorcroftiana*, mostly south-facing growth
	Caragana sp.	pea shrub	Sh	–
	Clematis sp.	clematis	He	–
	cf. *Rhododendron*	rhododendron	Sh	mostly north-facing growth
	cf. *Vaccinium*	blueberry	Ds	mostly north-facing growth
	Rosaceae/Maloideae	stone fruit family	Sh	–
	Ericaceae	heath family	Ds	–
	Spiraea sp.	spirea	Sh	–
Cultivated species	Poaceae	grasses	Gr	probably barley (*Hordeum vulgare*)
Further species	*Rosa sp.*	rose	Sh	–
	Fabaceae	pea family	He	–
	cf. Liliaceae	lily family	He	–

[a] Abbreviations: Tr = tree, Sh = shrub, Ds = dwarf-shrub, Gr = grass, He = herb.

charcoal ($n = 50$) and fossil wood ($n = 3$). Most analyses ($n = 44$) were performed on genus- or, infrequently, family-specific plant material. In two cases, charcoal spectra could be dated only indirectly using bone and bulk-soil matter (samples QUG 1, SAI 1b), respectively, bearing a clear risk of data rejuvenation by infiltration with younger carbon. Treatment of the samples followed the standard methods of the Erlangen Radiocarbon Laboratory (Scharf et al., 2007). All ^{14}C ages presented were calibrated (cal BP-values, 1 sigma-calibration) using the program 'CalPal-2007' (Weninger et al., 2007).

4. Results

4.1. Origin and taphonomic aspects of the samples

Most samples derived from palaeosols ($n = 34$). Further samples originated from fluvial-lacustrine ($n = 6$), aeolian ($n = 6$) and colluvial sediments ($n = 5$). Four samples (RET 1, RET 8, LSW 3, GHU 1) were taken from artificial structures (burial mounds, field terraces), partly in combination with palaeosols. The sampling depth varied from 20 to 1000 cm (mean = 281 cm), whereas the thickness of the layers sampled ranged from 2 to 200 cm (mean = 24 cm). In six cases different levels per profile were sampled (Appendix 3). Thus, in general, the samples provided a proper proxy for the local species composition with high spatial precision in contrast to low temporal resolution.

Most sites investigated were footslopes ($n = 22$), followed by alluvial fans ($n = 7$), floodplains of rivers and streams ($n = 6$), middle slopes ($n = 5$), river terraces ($n = 4$), and lower slopes ($n = 2$). The altitudinal range of the sites sampled was c. 3500 to 4700 m a.s.l. More detailed relationships between relief characteristics and the botanical spectra determined will be addressed in chapter '4.2. Botanical determination'.

According to the lack of properties for redistribution (e.g. layering, soil clasts, enrichment of coarse particles), the palaeosols sampled can be widely regarded as *in-situ* formations (see Kaiser et al., 2006, 2009, in press-a) implying a more or less (para-) *autochthonous* position of the charcoal and fossil wood particles. The palaeosols represented both dry-site conditions (Phaeozems, Kastanozems, Calcaric Cambisols, Arenosols and Regosols) and wet-site conditions (Gleysols, Histosols). Taking the mountainous relief into account, a potential short-distance input of the charcoal particles from the immediate surroundings – e.g. transported by slope runoff – cannot be precluded. In contrast, the samples from fluvial-lacustrine and colluvial sediments must as a rule be considered to be in *allochthonous* position, potentially originating from sources a few hundred metres to many kilometres away. Most of the palaeosols and sediments sampled had strongly dispersed and fragmented charcoal only.

The combined appearance of artificial (archaeological) objects and charcoal is a matter of particular interest comprising 10 spectra (Appendix 3). There were combinations both with human occupation layers (profiles DRE 2, DRE 14, GAR 1, QUG 1, BRI 1, FAN 1, GUZ 1), containing e.g. pot shards, lithic artefacts and bones, and with anthropogenic constructions (burial mounds, field terraces; profiles RET 1, RET 8, LSW 3, GHU 1).

The charcoal particles sampled were normally of 1–5 mm in length. Larger objects up to 2 cm in length were scarcely found – mostly in connection with human occupation layers. The largest charred object found is a tree stem or branch of 13 cm in length and 5 cm in diameter (sample SHE 1a; Fig. 2H). In contrast, fossil wood normally attains larger dimensions with a maximum length and diameter of 30 cm and 8 cm, respectively (sample CHU 5; Fig. 2I).

Table 2
Radiocarbon datings from southern and south-eastern Tibet.

Code	Sample	Altitude [m a.s.l.]	Northing	Easting	Depth [cm]	Material dated[a]	Lab. No.	δ^{13}C [‰]	Age uncalibrated [BP]	Age calibrated [cal BP]	Reference
Sites in southern Tibet											
5	DRE 14	3846	29°40′42.8″	91°02′58.0″	200	*Juniperus* charcoal	Erl-6778	−21.6	−13 ± 42	–	Kaiser et al., 2006
3	DRE 2	3654	29°40′04.6″	91°02′57.4″	145–150	*Juniperus* charcoal	Erl-6776	−21.6	203 ± 41	175 ± 111	Kaiser et al., 2006
2a	RET 8a	4224	30°19′07.3″	91°31′32.8″	20–50	*Juniperus* charcoal	Erl-6780	−22.2	243 ± 55	280 ± 123	Kaiser, 2004
40a	GUZ 1a	4080	30°22′55.6″	91°42′52.3″	90–95	*Juniperus* charcoal	Erl-11518	−19.9	246 ± 48	284 ± 120	this study
2b	RET 8b	4224	30°19′07.3″	91°31′32.8″	110–140	*Rosa* charcoal	Erl-6781	−25.2	891 ± 46	826 ± 64	Kaiser, 2004
29	BON 1b	3684	29°41′57.8″	91°22′47.6″	195–285	*Salix* charcoal	Erl-10943	−25.8	903 ± 46	833 ± 61	this study
1	RET 1	4200	30°18′28.7″	91°30′33.6″	80–114	*Juniperus* charcoal	Erl-6779	−22.0	1197 ± 45	1131 ± 59	Kaiser, 2004
35a	CNG 4a	4043	30°00′44.9″	90°45′37.0″	200–250	TS charcoal	Erl-11512	−21.0	1480 ± 51	1383 ± 50	this study
17	BRI 1	3566	29°21′58.1″	90°51′17.8″	115–150	*Sophora* charcoal	Erl-10938	−24.8	1865 ± 51	1803 ± 61	Kaiser et al., 2009
12a	LSW 3	3684	29°41′10.6″	91°05′10.9″	380	*Hippophae* wood	Erl-11522	−25.2	1869 ± 37	1806 ± 53	this study
27	ZAN 2b	3670	29°46′31.0″	91°28′24.3″	270–280	*Hippophae* charcoal	Erl-10952	−24.9	2055 ± 50	2030 ± 68	this study
31	MOG 2e	3777	29°47′40.4″	91°37′33.5″	390–410	*Betula* charcoal	Erl-10942	−25.5	2159 ± 51	2183 ± 99	Kaiser et al., 2009
33	GHU 2	3755	29°47′50.9″	91°31′41.1″	200–210	TS charcoal	Erl-11510	−21.1	2162 ± 52	2185 ± 98	this study
4	DRE 9	4583	29°41′42.1″	91°03′01.8″	30–57	*Juniperus* charcoal	Erl-6777	−21.0	2194 ± 41	2227 ± 68	Kaiser et al., 2006
23	GHU 1	3722	29°47′47.1″	91°31′02.5″	150–170	*Juniperus* charcoal	Erl-10949	−21.1	2296 ± 50	2276 ± 72	this study
40c	GUZ 1c	4080	30°22′55.6″	91°42′52.3″	200–202	*Hippophae* charcoal	Erl-11520	−22.9	2362 ± 55	2447 ± 94	this study
38	FAN 1	3721	29°41′32.3″	90°53′40.5″	370–390	TS charcoal	Erl-11516	−24.9	2399 ± 51	2511 ± 129	this study
40b	GUZ 1b	4080	30°22′55.6″	91°42′52.3″	160–180	TS charcoal	Erl-11519	−22.4	2409 ± 53	2519 ± 131	this study
12b	LSW 2	3684	29°41′10.6″	91°05′10.9″	250–265	DW charcoal	Erl-10944	−25.0	2500 ± 49	2590 ± 101	this study
34	SHE 1a	3699	29°37′43.6″	91°10′45.9″	210–230	*Juniperus* charcoal	Erl-11511	−22.3	2548 ± 57	2624 ± 103	this study
25	STA 1	3658	29°37′59.4″	91°05′52.0″	135–150	*Juniperus* charcoal	Erl-10940	−20.9	2713 ± 38	2817 ± 34	Kaiser et al., 2009
22	DAR 1	3662	29°40′01.7″	91°20′35.6″	300–325	*Hippophae* charcoal	Erl-10948	−25.5	2970 ± 52	3152 ± 83	Kaiser et al., 2009
7	QUG 1	3679	29°42′03.9″	91°07′42.2″	135–170	animal bone	Erl-6783	−14.8	3053 ± 45	3275 ± 58	Kaiser et al., 2006
39	NAN 1b	3997	30°05′57.6″	91°29′35.2″	330–340	*Hippophae* charcoal	Erl-11517	−23.8	3073 ± 52	3289 ± 61	this study
18	SAI 2	3804	29°49′03.6″	90°45′25.0″	200–400	*Juniperus* charcoal	Erl-11521	−18.1	3075 ± 39	3300 ± 47	this study
9	CHU 5	3770	29°32′27.7″	90°53′49.8″	385–438	*Populus* wood	Erl-10117	−27.1	3353 ± 40	3586 ± 59	this study
30	MAN 1b	3960	29°46′13.5″	91°52′57.0″	110–120	*Betula* charcoal	Erl-10945	−24.4	3485 ± 51	3766 ± 63	this study
6	GAR 1	3800	29°44′25.5″	90°49′49.3″	200–208	*Juniperus* charcoal	Erl-6782	−20.5	3668 ± 57	4005 ± 79	Kaiser et al., 2006
20	DON 2	4027	29°55′13.4″	91°51′22.5″	70–100	*Betula* charcoal	Erl-10950	−24.7	3872 ± 55	4298 ± 89	this study
32a	TAG 1a	3920	30°01′49.2″	91°50′35.5″	350–365	TS charcoal	Erl-11508	−23.4	4088 ± 60	4645 ± 125	this study
28	BAL 1b	4085	29°43′16.7″	91°59′34.4″	430–470	*Betula* charcoal	Erl-10951	−25.5	4804 ± 58	5535 ± 58	this study
8a	CHS 1a	4044	29°26′36.8″	91°01′17.7″	255–280	TS charcoal	Erl-10115	−24.5	5803 ± 48	6603 ± 59	Kaiser et al., in press-a
8b	CHS 1b	4044	29°26′36.8″	91°01′17.7″	450–485	*Hippophae* wood	Erl-10116	−26.7	5964 ± 49	6808 ± 62	Kaiser et al., in press-a
32b	TAG 1b	3920	30°01′49.2″	91°50′35.5″	390–400	*Juniperus* charcoal	Erl-11509	−23.2	6402 ± 63	7341 ± 60	this study
10	DAV 2	3909	29°35′27.8″	91°21′10.8″	500–535	*Buddleja* charcoal	Erl-10118	−26.3	6586 ± 55	7499 ± 48	this study
26	ZAN 1b	3705	29°46′33.9″	91°28′59.4″	220–250	*Hippophae* charcoal	Erl-10941	−23.0	6925 ± 69	7771 ± 70	Kaiser et al., in press-a
24	QUX 2	3536	29°21′57.3″	90°45′20.2″	325–330	DW charcoal	Erl-10946	−24.8	6943 ± 65	7784 ± 70	Kaiser et al., 2009
21	DYU 1	3704	29°41′19.9″	90°56′51.9″	590–600	*Sophora* charcoal	Erl-10947	−25.1	7375 ± 67	8196 ± 100	Kaiser et al., in press-a
35b	CNG 4b	4043	30°00′44.9″	90°45′37.0″	300–330	*Hippophae* charcoal	Erl-11513	−22.5	7666 ± 71	8477 ± 60	this study
19	NYM 1	3511	29°26′55.1″	90°56′03.6″	240–255	*Sophora* charcoal	Erl-10939	−24.8	7827 ± 70	8654 ± 105	Kaiser et al., 2009
37	CNG 1	4256	30°00′25.0″	90°45′44.1″	120–130	Liliaceae charcoal	Erl-11515	−23.5	8183 ± 65	9155 ± 96	this study
15	SAI 1b	3804	29°49′03.6″	90°45′25.0″	460–470	bulk-soil matter	Erl-10122	−19.8	8233 ± 68	9216 ± 109	Kaiser et al., 2009
36	CNG 2	4074	30°00′25.7″	90°45′11.2″	100–113	*Hippophae* charcoal	Erl-11514	−24.7	12106 ± 607	14453 ± 889	this study
14	MAR 1	3890	29°51′18.1″	90°44′30.4″	1000	*Caragana* charcoal	Erl-10121	−22.2	30050 ± 654	34247 ± 619	this study
16	MOG 1c	3778	29°47′57.0″	91°38′06.2″	860–885	*Lonicera* charcoal	Erl-10123	−25.5	36273 ± 2327	40305 ± 2312	Kaiser et al., 2009
11	GYA 3	3840	29°44′54.6″	91°40′02.5″	380–395	Rosa./Malo. charcoal	Erl-10119	−24.4	44235 ± 3388	48681 ± 3786	Kaiser et al., 2009
13	MOG 4	3894	29°47′30.0″	91°48′45.2″	720–760	TS charcoal	Erl-10120	−22.6	45682 ± 5438	51024 ± 6148	Kaiser et al., 2009
Sites in south-eastern Tibet											
45	LO-04-H7	3500	29°35′16.6	96°24′50.8	180	*Pinus* charcoal	Erl-10135	−22.4	597 ± 36	601 ± 38	this study
43	LO-04-H5	4670	29°42′31.6	98°05′58.5	155	*Juniperus* charcoal	Erl-10132	−21.5	1200 ± 37	1130 ± 49	this study
46	LO-04-H9	3568	29°59′38.8	93°05′20.6	160	*Quercus* charcoal	Erl-10136	−25.2	2445 ± 40	2535 ± 126	this study
44a	LO-04-H6-J	3950	29°29′28.0	96°37′06.3	120	*Juniperus* charcoal	Erl-10133	−24.7	4498 ± 46	5165 ± 97	this study
44b	LO-04-H6-Ps	3950	29°29′28.0	96°37′06.3	120	*Pseudotsuga* charcoal	Erl-10134	−24.1	4632 ± 46	5385 ± 61	this study
41b	LO-04-H2-T	4020	29°13′58.4″	98°41′22.8″	60	*Taxus* charcoal	Erl-10130	−24.6	6768 ± 56	7627 ± 37	this study
41a	LO-04-H2-J	4020	29°13′58.4″	98°41′22.8″	60	*Juniperus* charcoal	Erl-10129	−24.4	6805 ± 54	7648 ± 38	this study
42	LO-04-H3	3600	29°12′45.3″	98°09′18.2″	240	*Juniperus* charcoal	Erl-10131	−23.9	9456 ± 66	10792 ± 173	this study

[a] Abbreviations: TS = total spectrum, DW = deciduous wood.

4.2. Botanical determination

In general, identification to the species level was unfeasible due to the lack of a regional wood anatomy reference database. Furthermore, the charcoal particles available were mostly relatively small (often <1 mm). Thus it was hardly possible to consider the variability of structures within a taxon (e.g. size, number and distribution of pores and parenchymacells, width of rays) for delineation down to a species level. Additionally, the small fragments did not allow the origin of the wood (from stem, branch, twig or root) to be distinguished. Often only late wood was preserved. Thus important features were not clearly recognisable (e.g. shape of ray cell pits, character of ray tracheid walls) preventing the determination of species.

Therefore most of the charcoal and fossil wood samples were determined on a genus level, with some exceptions that could only be determined on even higher taxonomic levels (Fig. 4, Appendix 3). Some taxa may represent either trees or shrubs (*Juniperus*, *Hippophae*, *Salix*). Nevertheless, an assignation to certain growth forms ('species') is possible considering both the current regional vegetation cover and the regional environmental history (see chapter '5.1. Assignation of growth forms').

The number of particles determined per sample (spectrum) amounted to 2–129 for charcoal (mean = 39.3, $n = 50$ samples) and to 1–7 for fossil wood ($n = 3$ samples; Appendix 3). In general, most of the taxa determined (Appendix 3) represent shrubs/dwarf-shrubs ($n = 13$), followed by trees ($n = 9$) and herbs/grasses ($n = 4$). With respect to the frequency of the trees recorded, the genera *Hippophae* and *Juniperus* prevail (Fig. 4). The tree genera *Quercus*, *Taxus* and *Pseudotsuga* were restricted to south-eastern Tibet only, corresponding to their current distribution area (Atlas of Tibet Plateau, 1990). A relationship between tree taxa and general relief position (valley floor, alluvial fan, different slope sections) cannot be derived due to the preferential sampling of footslope and valley floor positions. However, a relationship between exposure and taxon (Fig. 5) is apparent among *Juniperus*, which was mainly recorded on or below south-facing slopes, and *Betula*, which was mainly associated with a general north exposure. In contrast, the (partly) phreatophytic *Hippophae* and *Salix* show no clear prevalent orientation.

Several attempts were made to extract pollen from the palaeosols, aiming at a further palaeobotanical proxy in addition to the charcoal record (F. Schlütz, Göttingen, pers. comm.). However, with a few exceptions of wet-site palaeosols, most of the buried soil horizons did not contain pollen, which was probably caused by the long-term corrosion of plant remains in the well-aerated soil (Havinga, 1984).

4.3. Dating

There is a strong disparity of prevalently Holocene ages ($n = 50$) in comparison to a few Pleistocene ages ($n = 5$; Fig. 6A). The Holocene (charcoal) data set on its own also shows disparity, with a dominance of Late Holocene ages (c. 5700–0 cal BP, $n = 24$), followed by Mid-Holocene ages (c. 8900–5700 cal BP, $n = 9$) and Early Holocene ages (c. 11,500–8900 cal BP, $n = 2$; Fig. 6B).

Radiocarbon dating of charcoal raises no difficulties provided that there is no contamination by younger humic substances carried by groundwater or stagnant water (Alon et al., 2002). The majority of datings ($n = 36$) represent a single radiocarbon age per profile (Table 2). Consequently, in most cases a given charcoal or fossil wood age can only be assumed to be reliable, i.e. synchronous with the formation age of its bearing palaeosol or sediment. But for some profiles ($n = 19$) either two or more ^{14}C dates are available or independent age control is available from further geochronological (OSL, IRSL) and archaeological data (Kaiser et al., 2006, 2009, in press-a). This exemplary control shows that the *Holocene* ages, except sample QUX 2 (a Mid-Holocene charred root in Pleistocene sediments), can be widely regarded as reliable. Two of the five *Pleistocene* ages, however, are considered to be unreliable (samples MOG 1, MOG 4). Considering the parallel OSL ages available (Kaiser et al., 2009) and keeping in mind the limits of the radiocarbon dating technique (e.g. Geyh, 2005), these ^{14}C age estimates should be regarded as minimum ages only. They may have been contaminated with younger carbon by infiltration of humic substances in palaeosols and are at the upper age limit of the technique.

Most datings were performed on one selected taxon per botanical spectrum only (= *direct* dating). Charcoal layers have been shown to accumulate charcoals for up to a few hundred years depending on the duration of soil and sediment genesis. For the purpose of this study age classes of a few hundred years provided sufficient resolution. Therefore the single datings were considered representative for all specimen of that particular spectrum (= indirect or *assigned* dating; Fig. 7), which has to be verified in the future for a wider spectrum of samples. This assumption was checked in two cases where two taxa per spectrum were dated. These datings confirmed the assumption with LO-04-H2 dates of 7648 ± 38 cal BP (*Juniperus*) and 7627 ± 37 cal BP (*Taxus*), and LO-04-H6 dates of 5165 ± 97 cal BP (*Juniperus*) and 5385 ± 61 cal BP (*Pseudotsuga*). The totals of direct and assigned datings were 24 for *Hippophae*, 20 for *Juniperus*, 13 for *Salix,* 9 for *Betula* and 1–3 for *Populus*, *Pinus*, *Quercus*, *Taxus* and *Pseudotsuga*.

According to these fossil records *Hippophae* was present both in the Pleistocene and Holocene, whereas *Juniperus* and *Betula* are recorded from the (entire) Holocene. The 13 *Salix* records are all

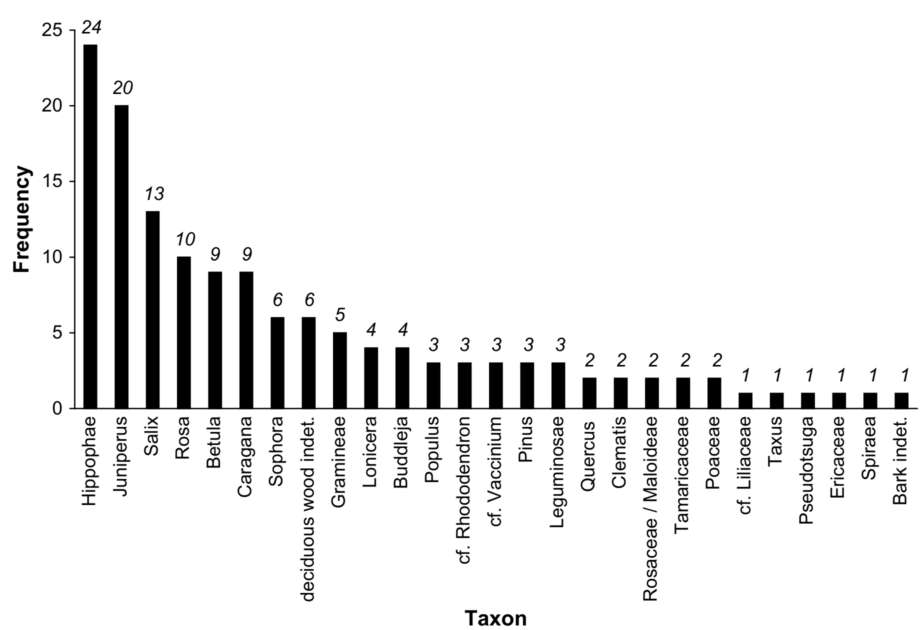

Fig. 4. Frequency distribution of the taxa recorded. The term 'Poaceae' comprises charred Poaceae seeds (a cereal, probably barley).

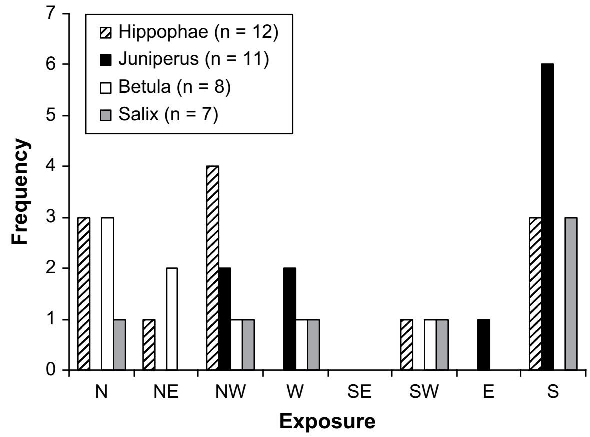

Fig. 5. Exposure of sampling sites (slopes) for selected taxa recorded.

attributed to the Late Holocene. In absolute numbers, there is a clear cluster of Late Holocene ages.

5. Discussion

5.1. Assignation of growth forms

As the *Juniperus* species cannot be distinguished from each other on the basis of their wood anatomy, so far the assignment of charcoal and fossil wood must consider both shrubby and treelike growth forms. Juniper trees (e.g. *J. tibetica*; Fig. 3B) are found up to an altitude of c. 4900 m a.s.l., whereas juniper shrubs (*Juniperus pingii* v. *wilsonii*) form thickets ('krummholz') in the treeline ecotone between c. 4200 and 5300 m a.s.l. (Farjon, 2005; Miehe et al., 2007b, 2008a). According to palaeoclimatic results for the Tibetan Plateau (e.g. He et al., 2004; Herzschuh, 2006; Zhao et al., 2007; Zhu et al., 2008), a Mid- to Late Holocene *lower* treeline than at present, which would affect the altitudinal distribution of *Juniperus* species, can most probably be precluded. Thus all of our records of *Juniperus* originate from sites clearly below the treeline. Furthermore, most of our *Juniperus* records (15 of 20) are from sites below the altitudinal distribution range of the shrubby junipers. Of the remaining five sites, three are still forested even today. It thus seems reasonable to assign the juniper charcoals to treelike growth forms.

The same line of argument can be employed regarding *Hippophae*. This taxon comprises tree species and dwarf-shrub species in the region as well: *Hippophae rhamnoides* occurs on river floodplains and further water-surplus sites (stream valleys, lower slopes, basin floors) forming trees up to 10 m high (Wu, 1983–1987; Fig. 3C). In contrast, the dwarf-shrub species *Hippophae tibetana*, which is maximally 0.5 m high, grows along streams in alpine altitudes (>c. 4200 m a.s.l.). Of the 23 *Hippophae* records in this study only one fitted the known distribution range of *H. tibetana* with an elevation higher than 4200 m a.s.l.

Finally several *Salix* species below c. 4500 m a.s.l. (c. 70 species in southern and south-eastern Tibet; Wu, 1983–1987) and all *Betula* species (prevailing *Betula platyphylla*; Miehe et al., 2008a; Fig. 3D) occurring in the study areas are trees.

In conclusion, it seems justified to generalise by referring to trees when discussing *Juniperus*, *Salix*, *Hippophae* and *Betula* remains in this study.

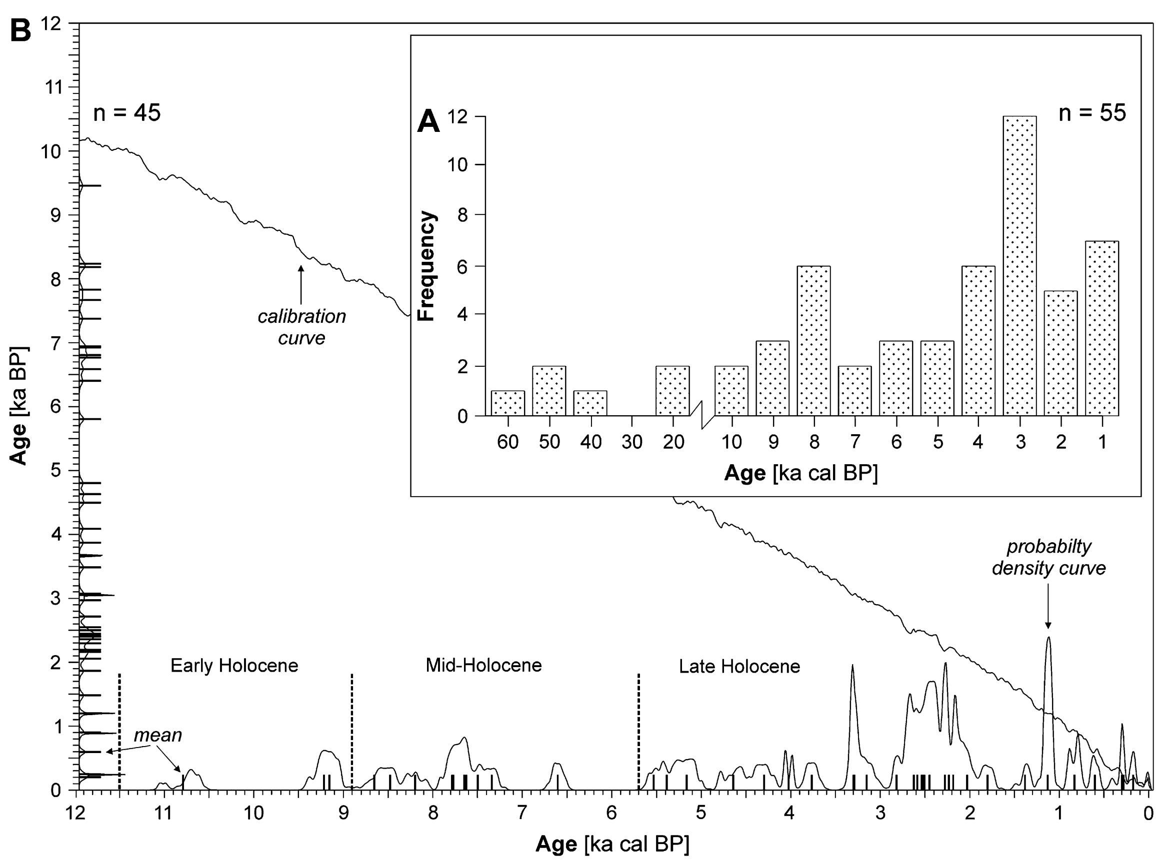

Fig. 6. Frequency and temporal distribution of the radiocarbon ages yielded. (A) Frequency of the age means in terms of millennia for all data yielded. (B) Calibration of the Holocene ages on charcoal.

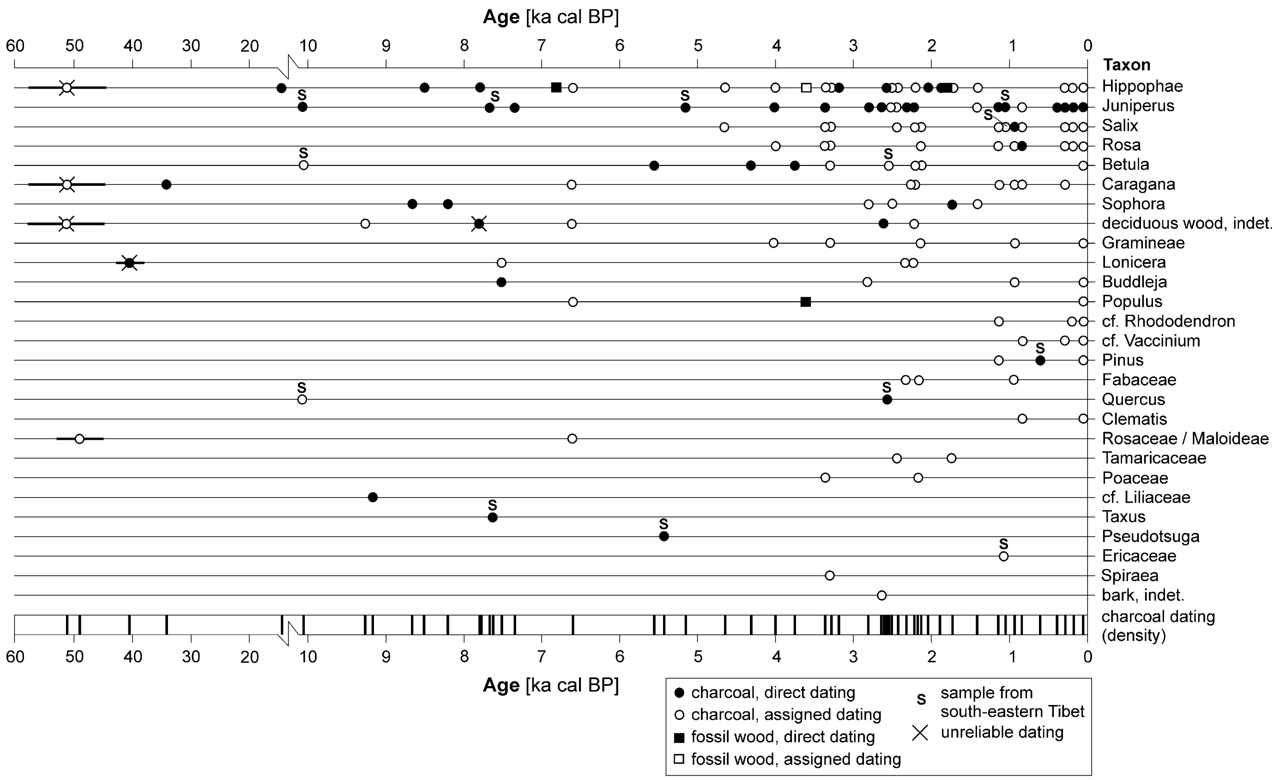

Fig. 7. Age spectra of the taxa determined. Most datings were performed on one selected taxon per botanical spectrum only (= *direct* dating) and were considered representative of all specimens of that particular spectrum (= indirect or *assigned* dating).

5.2. Past woodland composition and distribution

Local ('isolated') *present-day* occurrences of trees covering slopes (*Juniperus*, *Betula*) and valley grounds (*Hippophae*, *Salix* and *Populus*) played a significant role for both the assignation of growth forms in our data set (= identification of possible species) and for the reconstruction of past vegetation in the study area. A correlation with tree stands and rainfall data of some climate stations reveals that the drought line of *Juniperus* trees in southern Tibet is c. 200–250 mm a^{-1} (Miehe et al., 2008a). Accordingly, all of our study sites (c. 3500–4700 m a.s.l.) belong to an area of *potential* present-day tree growth.

On the one hand our study indicated *former* growth of tree taxa at various sites in the treeless desert pastures of southern Tibet. Deduced from the properties of present-day tree occurrences, and corroborated by the charcoal record presented, three *fossil* woodland types can be designated: (1) *Juniperus* woodland on (in general) south-facing slopes, (2) *Betula*(-*Salix*) woodland on north-facing slopes, and (3) *Hippophae*-dominated woodland with *Salix* and *Populus* on water-surplus sites, such as valley floors, basins and footslopes. The temporal distribution of selected tree taxa shows a predominant Late Holocene record in southern Tibet (Fig. 8). Further fossil woody taxa, such as *Rosa*, *Caragana*, *Sophora* and *Buddleja*, which also presently occur in the pastures, may have originally represented shrub species of the forest understory and/or may represent elements of a secondary vegetation. In most cases their presence in the charcoal spectra was paralleled by the presence of tree taxa (e.g. *Juniperus*).

On the other hand the charcoal record from sites in *south-eastern* Tibet partly shows former tree growth (*Juniperus*, *Taxus*) at sites with present-day *Kobresia* sedge mats (c. 4000–4700 m a.s.l.), and partly reveals the continuous Holocene presence of forests (mixed deciduous and coniferous forests, c. 3500–4000 m a.s.l.) by the record of accordant tree taxa (*Quercus*, *Betula*, *Juniperus*, *Pseudotsuga* and *Pinus*).

More highly resolved evidence on the Holocene vegetation history of the study areas is available from six pollen diagrams virtually forming a c. 800-km-long east–west transect from the closed forest area in south-eastern Tibet to the alpine pastures in southern central Tibet (Fig. 1, Table 3). The sediments investigated are predominantly lacustrine deposits and peats allowing reliable reflections of the Holocene vegetation history. However, three of the diagrams do not contain Late Holocene sediment sections (hiatuses), suggesting either that none were deposited or that they were subsequently eroded. The sites are currently treeless except Damxung, where a small stand of *J. tibetica* (up to 4 m high) occurs.

To sum up, five of the six pollen diagrams presented show a Late Holocene replacement of tree-related vegetation types with treeless vegetation types. The authors refer to former 'forest', 'woodland', 'forest steppe', or 'shrubland' and show their replacement by open vegetation comprising 'alpine meadow', 'alpine steppe' or '(steppe-, desert-, pasture-) shrubland'. However, the reconstruction of vegetation formations may to a certain extent be debatable. For example, the assignation of some woody taxa to growth forms in the Rutok and Nienang diagrams is ambiguous (e.g. *Juniperus*, *Hippophae*; van Leeuwen in La Duo, 2008; Fig. 1, Table 3). Generally, they argue for shrubs, knowing that even several natural occurrences of both *Juniperus* trees (*J. tibetica*) and *Hippophae* trees (*H. rhamnoides*) presently exist in the Lhasa area. With respect to *Juniperus* they differentiate two pollen types, '*Juniperus* (small)' and '*Juniperus* (large)', which represent shrubby (*J. pingii* var. *wilsonii*) and treelike taxa (*J. convallium*, *J. tibetica*), respectively (J.F.N. van Leeuwen, Bern, pers. comm.). Using this interpretation at least the Nienang diagram shows an expansion and local occurrence of treelike *Juniperus* between 9500–6000 cal BP, which consequently reflects woodland rather than shrubland vegetation. In this regard

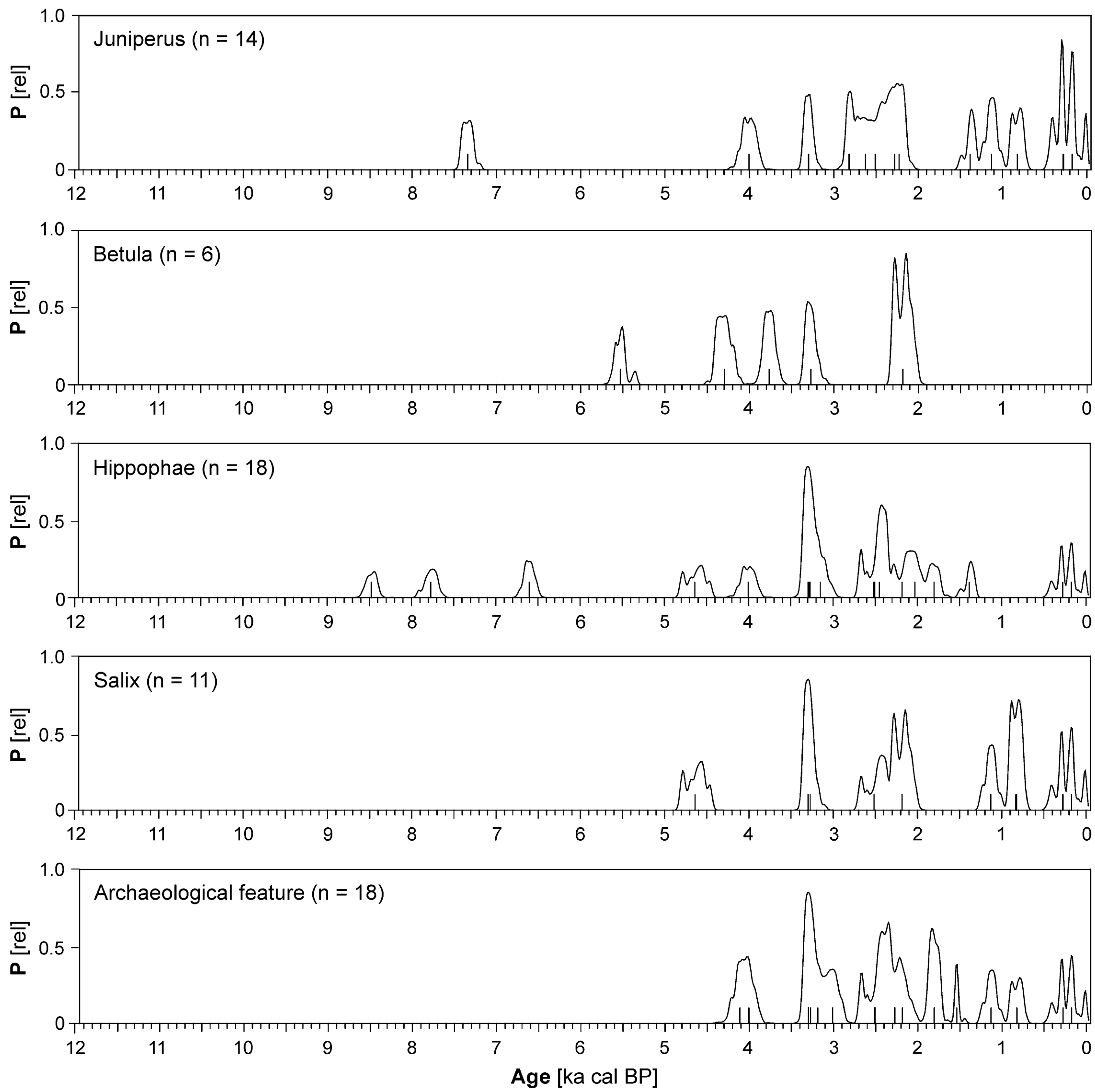

Fig. 8. Radiocarbon datings on charcoal of selected tree taxa recorded and of archaeological sites in southern Tibet thus comprising a selection of the total data set presented. The data sets used refer to both direct and assigned datings. The archaeological record is referenced in Appendix 6. It comprises 18 ^{14}C ages from 15 sites of a c. 100 to 100 km large area with Lhasa nearly in the centre.

their general reconstruction of 'shrublands' for the Early and Mid-Holocene is questionable.

Only the Damxung diagram (Fig. 1, Table 3) possibly shows the local presence of *Juniperus* trees throughout the Holocene.

For the Tibetan Plateau a Late Holocene decrease of temperature and moisture in comparison to the Early and Mid-Holocene has been concluded (e.g. He et al., 2004; Herzschuh, 2006; Morrill et al., 2006; Zhao et al., 2007; Shen et al., 2008; Yang et al., 2008; Zhu et al., 2008). There is no strong synchronism of the cooling and desiccation trend throughout the Plateau (An et al., 2006). Furthermore, most pollen records from the eastern sector reveal Early to Mid-Holocene forests and forest steppes, which were replaced by open vegetation in the Late Holocene (e.g. Yan et al., 1999; Tang et al., 2000; Frenzel, 2002; Herzschuh et al., 2005; Shen et al., 2005). The vegetation of the second part of the Holocene was considered to be of natural status and vegetation change has been assumed to be primarily caused by climatic impact. However, as the existence of 'Neolithic' economies in that area can be assumed for the last c. 4000–6000 years (Aldenderfer, 2007; Rhode et al., 2007), potential human impact (e.g. clearing of forests for expanding pastures and establishing arable land) might have strongly changed the regional vegetation cover as well (alternatively or additionally).

For several sites in the area in between the above-mentioned pollen diagrams in southern and south-eastern Tibet (Table 3), our charcoal record reveals the occurrence of trees – probably of woodlands – during the whole Holocene, forming a 'peak of burning' in the Late Holocene (see chapter '5.3. Fire and human impact'; Fig. 8). Accordingly, there is strong evidence for the assumption that this territory as a whole was formerly wooded.

5.3. Fire and human impact

In general, *macroscopic* charcoal (>200 μm) represents stand- to local-scale fires, whereas *microscopic* charcoal (<100 μm) is considered as a proxy of both local and regional burning activity (Carcaillet, 2007). However, as microscopic charcoal might originate at least partially from long-distance aeolian transport (e.g. Whitlock and Larsen, 2001; Benedict, 2002; Duffin et al., 2008), assumptions on local fires should be regarded most cautiously and need further research.

Table 3
Late Quaternary regional vegetation development derived from pollen diagrams in south-eastern and southern Tibet. Sites are mapped in Fig. 1. Nomenclature of vegetation forms (e.g. 'forest', 'steppe', 'meadow') follows the original references. Plant names in parentheses refer to characteristic genera and families.

Pollen diagram	Ren Co	Co Qongjiamong	Rutok	Lhasa 1	Nienang	Damxung
Reference	Shen, 2003 [a]	Shen, 2003 [a]	La Duo, 2008	Miehe et al., 2006	La Duo, 2008	Schlütz et al., 2007 [b]
Coordinates	30°44′N, 96°41′E	29°49′N, 92°32′E	29°41′N, 92°16′E	29°10′N, 91°04′E	29°43′N, 90°42′E	30°23′N, 90°53′E
Altitude (m a.s.l.)	4450	4980	4400	3650	3950	4250
Current vegetation (regional)	alpine meadow–steppe mosaic	alpine meadow	alpine meadow–shrubland	degraded pasture–shrubland	alpine meadow–desert shrubland	alpine sedge mat with some *Juniperus* trees
Site situation	Lake basin	lake basin	peatland in river valley	peatland in river valley	foothill depression	peatland in river valley
Vegetation development (regional)	0–4500 cal BP, hiatus	0–5000 cal BP, alpine meadow (Cyperaceae)	0–300 cal BP, steppe-shrubland (Gramineae, *Juniperus*, *Hippophae*)	0–600 cal BP, degraded pasture-shrubland (*Artemisia*, *Juniperus*)	0–600 cal BP, open steppe-desert shrubland (*Artemisia*)	0–1200 cal BP, degraded alpine mat-woodland (Cyperaceae, *Juniperus*)
	4500–6300 cal BP, alpine steppe (*Artemisia*)	5000–8000 cal BP, forest (*Pinus, Betula*)	300–6800 cal BP, hiatus	600–4700 cal BP, shrubland (*Hippophae*, *Betula*, *Artemisia*)	600–3500 cal BP, hiatus	1200–8500 cal BP, alpine mat (Cyperaceae)
	6300–11,000 cal BP, forest steppe (*Betula*, *Abies*, *Picea*)	8000–13,500 cal BP, alpine meadow (Cyperaceae)	6800–11,300 cal BP, meadow-shrubland (Gramineae, Cyperaceae, *Hippophae*, *Juniperus*, *Betula*, *Salix*)	4700–5000 cal BP, woodland (*Juniperus*, *Betula*, *Hippophae*, *Rhododendron*)	3500–6000 cal BP, dry steppe-shrubland (*Artemisia*, Gramineae, Chenopodiaceae, *Juniperus*, *Salix*, *Betula*)	
	11,000–14,000 cal BP, alpine steppe (Chenopodiaceae)	13,500–14,000 cal BP, alpine steppe (*Artemisia*)	11,300–11,900 cal BP, desert steppe-shrubland (*Artemisia*)		6000–9500 cal BP, temp. steppe-shrubland (*Artemisia*, Gramineae, *Hippophae*, *Juniperus*, *Salix*, *Betula*)	8500–13,000 cal BP, steppe-shrubland (Poaceae, *Hippophae*, *Myricaria*, *Juniperus*)
			11,900–13,000 cal BP, temp. steppe-shrubland (Gramineae, Cyperaceae, *Hippophae*, *Salix*, *Juniperus*)		9500–10,000 cal BP, steppe-shrubland (*Artemisia*, Gramineae, *Hippophae*, *Salix*)	

[a] A simplified version of this diagram is available in Tang et al. (2000).
[b] The original diagram was published in German. A simplified English version of this diagram is available in Kaiser et al. (2008).

The distribution of ^{14}C ages in our macroscopic charcoal samples shows no continuous record of burning events in southern and south-eastern Tibet throughout the Holocene. Instead, burning conspicuously cumulated in the Late Holocene about 5700–0 cal BP (Figs. 7 and 8).

The few regional records of Late Quaternary microscopic charcoal deposition yielded by pollen-analytical studies provide incomplete insights so far due to the fragmentary preservation of Late Holocene sediments (hiatuses). The records from Rutok and Nienang comprise the intervals c. 13,000–6800 and c. 10,000–3500 cal BP, showing charcoal peaks at 11,300–7500 and c. 10,000–6000 cal BP, respectively (van Leeuwen in La Duo, 2008). The completely preserved Damxung sequence (base c. 13,000 cal BP) shows peaks at c. 10,500–9000 and 3000–2000 cal BP (Schlütz et al., 2007; Kaiser et al., 2008). Consequently, these studies reveal fire activity in the region throughout the Holocene. However, the proper identification of distinct 'fire periods' (peaking) and their reasons for the whole Holocene remains unclear.

The question arises, what caused the Late Holocene peak of our macroscopic charcoal dataset – an increase in human-induced burning activity or climate-induced natural changes (increase of natural ignitions, increasing potential of fire spread)? An answer initially requires a consideration of the *present* fire regime in the region.

So far, knowledge on the fire dynamics on the Tibetan Plateau is poor. An overview of recent forest fuel and wildfire characteristics of southeast Tibet has shown that – although, in general, the 'fire cycle' is long (c. 17,200 years) and the 'fire probability' is very low ($P = 0.00006$) – specific regional ecosystems (esp. coniferous forests) tend to have a high fire incidence especially in the dry winter season, which is obviously caused by current *human* impact (Wang et al., 2007). A case study from the Jiuzhaigou Nature Reserve, north-eastern Plateau, revealed a graded impact of fire on present-day forest types on *south-facing* slopes (Winkler, 2000). According to field observations, interviews and historical data, the local population utilises fire as a means of extending and maintaining livestock pasture, favouring the lower and upper altitudes. Obviously, after clearing of the primary forests, continuous grazing and repeated burning prevents forest regrowth there at present.

Generally speaking, all episodically or periodically *dry* ecosystems throughout the world – forests, woodlands, (dwarf-) shrublands, grasslands – are considered to be fire-sensitive (e.g. Berrio et al., 2002; Hobbs, 2002; Brown et al., 2005; Carcaillet et al., 2007). In the semiarid (monsoonal) climate of southern and south-eastern Tibet any shift to higher precipitations and temperatures during the wet season (summer) will provide more phytomass (fuel) to be set on fire during the dry season (winter) influencing the possibility of fire spread. The summer is the only season with potential natural causes of fire (lightning). However, based on our own observational data of the last c. 20 years from the region, we have no evidence of naturally caused fires during the frequently occurring thunderstorms: Lightning has always been followed by torrential rains. Furthermore, in an ecosystem (1) not characterised by the prevalence of pyrophytes and (2) with a proven present-day climate suitable for tree growth (see above), the human factor is the more likely explanation for the accumulation of Late Holocene burning events. A similar conclusion was drawn by Meyer et al. (in press) for the adjacent northwest Bhutan. In general, the significant increase in fire frequency accompanying human activities is a known phenomenon and is often detected in palaeoenvironmental studies (e.g. Carcaillet and Brun, 2000; Burney and Burney, 2003; Huang et al., 2006).

Our charcoal data (record of trees and shrubs) and the present-day vegetation of the sites (mostly tree- and shrubless) indicates a probable link between fire activity and vegetation change. Several factors may be involved in fire dynamics and mediate vegetation changes (e.g. climatic conditions, such as frequency of lightning and length of drought; structure of tree- and ground-cover; availability of combustible biomass; recovery potential of woody species; occurrence of herbivores; several human activities, such as burning, grazing, tree cutting; e.g. Pyne, 1995; Johnson, 1996; Higgins et al., 2000; Gillson, 2004; Long et al., 2007). However, reliable data is largely lacking on the regional characteristics of these factors in the past. There are no palaeoecological data on fire-driven plant community changes in our study area so far. An example from a nearby comparable environment is from Lake Rukche in the central Nepalese Himalayas (c. 600 km to the southwest, 3500 m a.s.l.) showing fire-affected replacement of dense oak forest by open pine forest at c. 2850 cal BP, interpreted as initiated by man (Schlütz and Zech, 2004). Furthermore, the joint occurrence of macroscopic charcoal and cereal pollen grains at c. 4500 cal BP in northwest Bhutanese palaeosols (c. 200 km to the south, 3700–4000 m a.s.l.) was interpreted as evidence for human use of fire and for forest clearing due to Neolithic agriculture (Meyer et al., in press).

There is some archaeological evidence for early human impact both in south-eastern and southern Tibet. The most important 'Neolithic' sites – implying (at least locally) a strong human influence on the landscape by sedentary settlement and agriculture – are Kha rub/Karou next to Chamdo (5732 ± 114 to 4372 ± 117 cal BP) and Chugong/Qugong next to Lhasa (c. 3700 cal BP; Aldenderfer, 2007; Fig. 1). Further 'Neolithic' sites between the Mekong River and the Nyainqentanglha Range have been only initially investigated so far, yielding radiocarbon ages from 4162 ± 130 to 3010 ± 82 cal BP (Fu et al., 2000; Kaiser et al., 2006, 2009, in press-a; Aldenderfer, 2007).

In the Lhasa area, our charcoal record is variously linked with local archaeological evidence comprising a total of 10 spectra (Figs. 1 and 8, Appendices 3 and 6). In general, archaeological charcoal may be considered as a proxy of past vegetation, provided that the database is large enough (Carcaillet, 2007) and/or that diversity of species in a study area is poor. Human collection of firewood may affect the reflection of the past composition and abundance of woody species (Shackleton and Prins, 1992). However, both the charcoal spectra and the present-day vegetation of the Lhasa area reflect a species-poor woody vegetation with the same taxa occurring (e.g. *Juniperus*, *Hippophae*, *Betula* and *Salix*). Accordingly, the charcoal taxa can be considered as elements of the local flora. The charcoal-bearing palaeosols of six profiles contained numerous archaeological remains as well (pot shards, bones, stone flakes, in some cases slag), thus representing occupation layers. Most of the datings are scattered over the last c. 4000–2000 years (4005 ± 79–1803 ± 61 cal BP; GAR 1, QUG 1, FAN 1, GUZ 1b, BRI 1); only one age attains the recent past (175 ± 111 cal BP; DRE 2). Two burial mounds (GHU 1, LSW 3) could be dated using charcoal and fossil wood, giving ages of 2276 ± 72 and 1806 ± 53 cal BP. Possibly, even charred Poaceae seeds (a cereal, probably barley) from two charcoal spectra (SAI 2, GHU 2) can be associated with human cultivation (see a further regional record made by Fu et al., 2000). The seeds occur together with charcoal of *Juniperus* and *Betula*, respectively. Finally, in the Reting area, buried soils from anthropogenic (field-) terraces could be dated to 1131 ± 59 and 826 ± 64 cal BP (RET 1, RET 8) by means of charcoal, giving first chronological data for this regionally widespread and now mostly abandoned land-use feature. Strikingly, if we include a dated human skeleton from Lhasa-Drepung (2272 ± 68 cal BP; Kaiser et al., 2009, in press-a) and further archaeological, dendroecological and geomorphic evidence from the Lhasa area (Kaiser, 2004; Kaiser et al., 2006; Aldenderfer, 2007; Bräuning, 2007) most datings are scattered over the time interval c. 3500–1500 cal BP, presumably revealing an intensified occupation hence human impact on the Lhasa area in that time (Fig. 8).

According to the investigation of colluvial sediments in the Kyichu Valley and its tributaries, it can be hypothesised that the barren valley slopes in that area were primarily formed by a Late Pleistocene erosion phase (probably triggered by ice-age climatic effects) followed by a secondary, probably human-induced Late Holocene erosion phase (Kaiser et al., 2006; Kaiser et al., in press-a). A similar conclusion can be drawn for this area from the investigation of aeolian sands showing local, probably human-induced Late Holocene aeolian activity (Kaiser et al., 2009).

To sum up, the synchronous record of Late Holocene human occupation (archaeological evidence), burning events (charcoal dating), vegetation changes (charcoal determination, pollen record) and erosional processes (dated colluvial and aeolian deposits) suggest that above all man might have induced the environmental changes from woodlands to desertic rangelands in southern Tibet.

5.4. Regional pedoanthracological potential

Only in recent years have the first systematically determined charcoal *spectra* from southern and north-eastern Tibet been published in international journals (Kaiser et al., 2006, 2007, 2009, in press-a), succeeding initial studies on the south-eastern Plateau (Iwata et al., 1993; Iwata, 1994). Further but incompletely reported charcoal determinations are available from archaeological sites at Qinghai Lake in northeast Tibet (Madsen et al., 2006; Rhode et al., 2007). Fossil wood – usually botanically undetermined – has been extracted on the Plateau mostly from moraines, lacustrine sediments and archaeological sites so far (e.g. Xu et al., 2003; Kuhle, 2005; Yang et al., 2008). In general, a search for studies using soil-derived charcoal in central Asia, the Himalayas and further Chinese mountain areas (e.g. Saijo, 1993; Rost, 2001; Saijo and Tanaka, 2002; Byers, 2005; Wang et al., 2005; Huang et al., 2006; Miehe et al., 2007a; Srivastava et al., 2007; Jiang et al., 2008; Power et al., 2008; Meyer et al., in press) reveals that pedoanthracology is not a still well-established palaeoecological method in these regions.

Our study presents the largest regional data set of both botanically determined and geochronologically dated charcoal available from the Tibetan Plateau so far. Most of the palaeosols recorded contain charcoal. In particular, the buried Histosol (peat layer) of profile CHU 5 – a fossil floodplain site with a large quantity of both charcoal and well-preserved fossil wood – offers a promising archive for detailed palaeoenvironmental studies. Similar wet-site palaeo-positions in a present-day 'dry environment' have been repeatedly recorded (CHS 1, DAV 2, CNG 1, CNG 2). Normally, the palaeosols sampled had strongly dispersed and fragmented charcoal only. As rather thick layers were sampled for this study (mean = 24 cm), a future check for a possible higher botanical and temporal resolution is needed.

In summary, the pedoanthracological potential of southern and south-eastern Tibet seems promising for future high-resolution studies. Especially data for specifying the prehistoric and historic fire regimes would be a tremendous asset, both for regional palaeoecology and human settlement history.

6. Conclusions

(1) In southern and south-eastern Tibet, charcoal frequently occurs in palaeosols, various sediments and artificial structures forming an important palaeoecological proxy. In particular dry-site palaeosols regularly contain strongly dispersed and fragmented macroscopic charcoal. Moreover, wet-site palaeosols bear well-preserved fossil wood.
(2) Most taxa determined represent (dwarf-) shrubs, followed by trees and herbs/grasses. The genera *Hippophae* and *Juniperus* statistically prevail, representing tree species in our study area.

(3) Charcoal of *Juniperus* mainly occurs on or below south-facing slopes, whereas *Betula* is mainly associated with a general north exposure. In contrast, the (partly) phreatophytic taxa *Hippophae* and *Salix* show no clear prevalence of an orientation.
(4) There is a strong disparity of prevalently Holocene ages in comparison to a few Pleistocene ages. Most datings are scattered over the Late Holocene (c. 5700–0 cal BP).
(5) The charcoal and fossil wood spectra analysed give evidence for a Late Holocene change in southern Tibet from a tree- and shrub-dominated vegetation to the present plant cover widely consisting of sparse grasses, herbs and dwarf-shrubs. It is assumed that the Late Holocene disappearance of woodlands has been primary caused by humans.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi: 10.1016/j.quascirev.2009.02.016.

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