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Palaeoecological and experimental evidence of former forests and woodlands in the treeless desert pastures of Southern Tibet (Lhasa, A.R. Xizang, China)

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Abstract

Palaeoecological and palaeopedological investigations around Lhasa (3650 m, 29°40′N/91°04′E, A.R. Xizang, China) provide evidence of human induced environmental changes which have occurred over the past 4600 years. The present desert pastures of Southern Tibet most probably replaced forests of *Juniperus convallium*, *J. tibetica* and *Cupressus gigantea* along with *Prunus mira* and *Buddleja crispa* in the understorey. Paleosol investigations and determined charcoal indicate a likeliness of forest destruction followed by increased erosion and sedimentation of colluvial soils. For the first time cereal pollen types could be clearly distinguished in southern Tibet. *Juniperus* pollen has been proved to have only a short dispersal range. The presence of cereal pollen and other human indicator pollen proves that it is more likely that human activity rather than climatic changes caused the forest decline during the younger Holocene. Successful non-irrigated reforestation trial experiments since 1997 on southern slopes around Lhasa with indigenous Cupressaceae have demonstrated that desertification of southern Tibet is a reversible process. As Lhasa receives 443 mm annual precipitation and has summer temperatures of above 10 °C it follows that the natural vegetation should be a forest, as opposed to the desert status quo that presides at present.

Keywords: forest decline; human impact; juniper forest; forest potential; Tibet; Xizang–Qinghai Plateau; China

1. Introduction

The perception of environmental changes during the Holocene is nowhere more contradictory than in the Old World's desert belt. While it is meanwhile widely accepted that the Saharan savannas and lakes transformed into hyper-arid deserts (Pachur and Kroepelin, 1987), primarily due to desiccation, the Central Asian deserts seem to have a far greater ecological stability (Frenzel, 1992; Petit-Maire and Bouysse, 2002) and the human dimension of environmental changes is rarely even considered. The key issue is whether the Central Asian deserts were woodlands during the Holocene Climatic Optimum and whether the current treelessness was only driven by the climatic deterioration following in the younger Holocene or if humans accelerated the environmental changes. Moreover, a greater number of isolated forest stands

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surrounded by pastures raise the question as to whether those tree stands survived in a non-forest climate favoured by local water surplus or if they represent relicts of a continuous tree cover.

While the geochemical analysis of sediment cores (Wünnemann et al., 1998) or disjunctions of plant distribution patterns of non-wind dispersed species (Jäger, 2005) provide evidence about the extent and process of climate driven environmental changes, it is rarely possible to detect the duration and dimension of human impact. The lack of in-depth knowledge on the pollen-flora coupled with the uncertainty about human-indicator pollen is the main reason for this. In arid environments it is especially difficult to detect the presence of former forests or woodlands as tree stands are not as vigorous as they are in humid climates and they are often composed of taxa with low pollen dispersal (*Larix*, *Juniperus*). Therefore it might be difficult to reconstruct environmental changes solely based on pollen analysis. The present contribution therefore combines palynology, macro-remain analysis and paleosol investigation, as classical disciplines of Quaternary sciences, along with the more modern approaches of floristic analysis of recent vegetation and experimental reforestation trials with indigenous tree species. The objective of this multidisciplinary approach is to answer the question whether forests or steppes are natural in Southern Tibet. The authors would like to contribute to the general discussion concerning the human dimension of Global Change. This is especially challenging because environmental changes from human impact in Tibet have been largely denied until very recently (Ni, 2000; Ren, 2000; Yu et al., 2001; Luo et al., 2004; Song et al., 2004) despite the well-known presence of early people (see Aldenderfer and Zhang, 2004) and palynological evidence from the Chinese lowlands (Ren and Beug, 2002) and the eastern Tibetan Plateau (Thelaus, 1992, Frenzel, 1994). However, it seems necessary to give our definition of "forests" because this term has a confusing range of meanings worldwide. We consider forests as formation of scapose single to multi-stemmed phanerophytes (i.e. trees) no matter how tall they are. The juniper tree species of Tibet recorded in our inventory attain 2 m or more in height. The minimum crown cover degree is 10% ("open forest"), commonly classified as "woodlands" in the Anglophone literature. The climate data available in Tibet suggest that a minimum of 200–250 mm annual rainfall is the threshold of a "forest climate".

2. Study site, current vegetation and climate

The study site is a riparian wetland surrounded by desert slopes near Lhasa. The location of the pollen diagram "Lhasa 1" is in the floodplain of the Kyi Chu (river) in a wetland called "Lhalu Dhamra" (Lapager Duoje, 2002) in the northwestern outskirts of Lhasa at 3648 m at 29°10′N and 91°04′E (see Figs. 1, 2). The colluvial deposits lie 800 m from the drilling site at the foothills of the local mountain range. The slope with a southerly exposure reaches 5000 m. The granitic bedrock is widely exposed on steep ridges or on steep boulder cliffs surrounded by loams of the deeply weathered granite. The current wetland and aquatic vegetation is dominated by *Phragmites australis* and *Carex* spp. with *Hippuris*, *Myriophyllum*, *Potamogeton*, *Nymphaea* and the floating *Batrachium* dominating

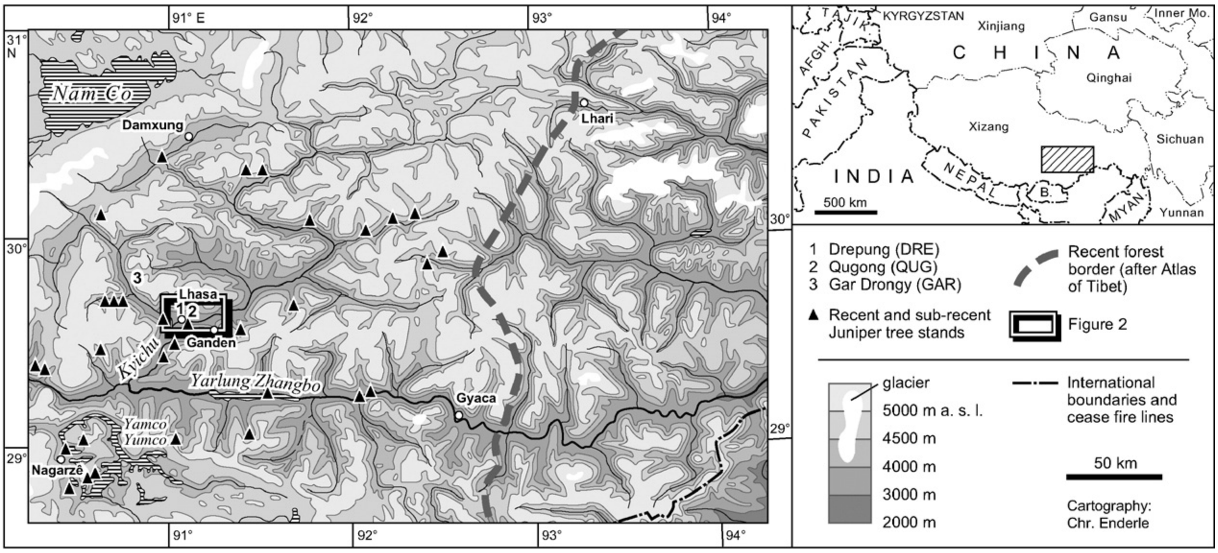


Fig. 1. Southern Tibet and the study site with relict juniper forest stands (after Miehe et al., submitted for publication).

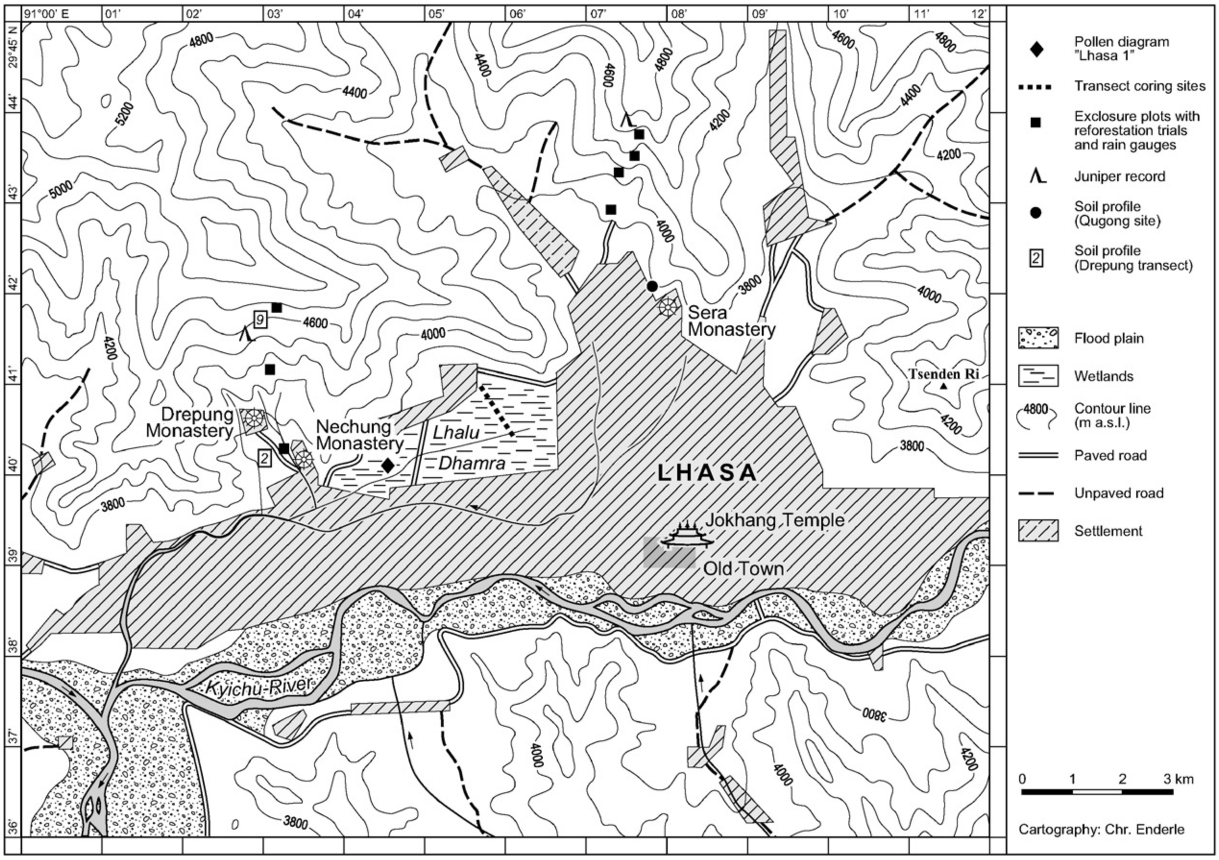


Fig. 2. The location of the pollen diagram "Lhasa 1" with experimental reforestation plots, soil profile plots and juniper relicts (after Kaiser et al., 2006).

the open waters. The adjacent slopes are represented by thorny open dwarf scrubland pastures which dominate the desert landscape of Southern Tibet covering 100 km between 95° and 83°E along the Yarlung Zhangbo (river). These common grazing lands are dominated by the thorny Fabaceae *Sophora moorcroftiana*, which is regularly cut for tinder and re-sprouts to a height of 1 m. The widely distributed Central Asian wormwood *Artemisia santolinifolia* is the second most widespread shrubby constituent and is a useful fodder plant during winter. Its height depends on the grazing pressure: close to villages it is browsed down to 10 cm but just like *Sophora* it can reach 2 m height in safe sites. The third important shrub is the Plumbaginaceae *Ceratostigma ulicinum* which is only browsed under high grazing pressure. *Rosa* spp. are most common along trails and are often cut for fencing. Larger shrubs of *Buddleja crispa* and *Cotoneaster* spp. can potentially become trees of 5 m height but are rarely found growing higher than 0.8 m at accessible sites. There are very few trees left other than those in irrigated, walled-in *Salix* and *Populus* plantations: Mostly around derelict monasteries, old trees of *Prunus mira*, a wild indigenous peach, grow high enough to exceed the browsing range of livestock and root deep enough to reach the groundwater. Other trees were most probably introduced by pilgrims as ornamental trees: there is one four metre tall *Ulmus pumila* tree a few metres outside the garden of Drepung monastery — most probably a garden recluse. *Ailanthus sinensis* are currently spreading around religious sites, though it does not grow higher than 2 m, most probably because it freezes back during winter. The largest trees, higher than 10 m, are *Platycladus* (syn. *Thuja*) *orientalis* and are found in irrigated monastery gardens. It can hardly be distinguished from the indigenous *Juniperus* species from a distance; it has the same vernacular name and is also religiously adored. The closest tree populations considered natural forest vegetation are *Juniperus convallium* stands on steep south-exposed cliffs at an altitude of 4600 m, north of Lhasa (see Fig. 2). The nearest forest stands are 30 km south of Lhasa and represent a community forest under religious protection. The site is one of approx. 60 forest relicts so far surveyed in Southern Tibet since 1994 (Miehe et al., submitted for publication). The thorny *Sophora* heathlands include a number of tropical grasses of which the rhizomatous *Pennisetum flaccidum* and *Orinus thoroldii* are resistant to trampling and grazing and quickly re-sprout after fire. The bunches of *Andropogon munroi* are more sensitive to trampling whereas the tiny *Trisetum*, *Agrostis* and *Chloris* are common on open sites with high trampling impact together with widespread ruderal weeds (*Plantago depressa*, *Tribulus terrestris*, *Erodium tibetanum*, *Elsholtzia flava*, *Malva pusilla*, Chenopodiaceae, Brassicaceae and Boraginaceae). Open soil surfaces unaffected by permanent trampling are covered in blue Algae and Hepaticae like *Riccia*. Steep loamy banks, mostly around the granite boulders, have additional carpets and rosettes of *Selaginella* spp., *Rhodiola* spp. (Crassulaceae), and *Corallodiscus* spp. (Gesneriaceae). In the shelter of boulders a multitude of grazing sensitive herbs grows in between thickets containing species recorded from *Cupressus* and *Quercus* forests which currently have their westernmost outposts 200 km further to the east.

With increasing moisture (but not necessarily lower grazing pressure) the plant cover reaches 60 to 80% above 4100 m. Only on easily accessible ridges is the ground cover kept to a minimum due to higher grazing and trampling impact. Shrubs like *Spiraea*, *Lonicera*, *Rosa*, *Berberis*, *Ribes*, *Cotoneaster* and *Potentilla fruticosa* form dense thickets of 2–3 m in height which are accompanied by tall forbs at their margins. Grazed slopes bear pastures with *Kobresia* and *Stipa* as the main graminoids. Gully erosion is less frequent than at altitudes below 4100 m, but chafing sites of yaks causing barren soil become more common. Above 4600 m alpine pastures of *Kobresia pygmaea* accompanied by cushions of *Androsace tapete* are dominant. In this zone the turf forms a nearly closed felt and protects the slopes from trampling damage and erosion. However, sub-alpine thickets of *Lonicera*, *Berberis* and *Spiraea* around boulders show that the prevailing sedge turf and cushions replace the taller vegetation more sensitive to grazing, browsing and trampling.

The north-facing slopes of the Lhasa area are treeless and have a pattern of highly disturbed dwarf thickets of *Salix*, *Berberis*, *Spiraea*, *Lonicera* and *Rhododendron anthopogonoides*. The latter is cut for incense and re-sprouts from the ground. Patches of exposed soil due to trampling damage are common; *Aconogonum tortuosum* (Polygonaceae) and *Ligularia lancifera* (Senecioideae) are prominent there above 4200 m.

Along streams patchy thickets of *Caragana* with lianas of *Clematis tangutica* and Cyperaceae swamps of *Kobresia schoenoides* and *Blysmus compressus* with *Primula* spp. occur.

The slopes above the drilling site belong to the grazing grounds of monasteries, and for religious reasons the shrubby vegetation is not extracted for firewood as it is common practise on other slopes around Lhasa. However, the grazing impact of cattle, sheep and goats is permanent all around the year.

The climate data of Lhasa clearly indicate a forest climate: annual rainfall amounts to 443 mm; summer precipitation prevails (June–September 400 mm) (1951–90, according to data from China Meteorological Administration; published in Miehe et al., 2001). The slopes above the floodplain however receive far more rainfall (see Fig. 2): rain gauge measurements since 1997 reveal that at 100 m above the floodplain, the foot of the slope at Nechung has 500 mm annual rainfall, at 4180 m the rainfall amounts to 650 mm and at 4650 m the rainfall is 720 mm/yr. The measurements in the eastern transect show slightly lower rainfall with 480 mm/yr at 3750 m and 580 mm/yr at 4500 m. Convective night time rainfalls following late afternoon thunderstorms are common, torrential precipitation prevails, and hail is also common. Snowfall in winter is rare and the snow melts within hours, at least on the sunny slopes. Squalls occur regularly in April and May. Southeasterly winds prevail during summer and strong westerlies dominate during winter. The study site has a year-round up-valley wind system which connects the area to the conifer and broad-leaved forests of the southeastern Himalayas. Temperatures also suggest conditions suitable for tree growth: between May and September mean monthly temperatures are above 10 °C, frost occurs from mid-October to May. The growing season, with mean monthly temperatures above 5 °C, spans eight months. On southerly exposures at altitudes of the upper treeline ecotone, soil temperatures at 4655 m at a depth of 10 cm show daily ranges of 15 K during fair weather, with only occasional subsoil temperatures below 0 °C. Thus permanently frozen ground during winter as a precondition of frost drought is not probable. Ice and frost heaving on exposed soil, which may destroy seedlings, occurs rarely.

3. Materials and methods

3.1. Floristic inventories and vegetation monitoring

As a precondition for the interpretation of the pollen diagram, an inventory of flowering plants, ferns, mosses and lichens occurring on the slopes north of the drilling site has been kept since 1984. The less accessible thickets in the shelter of cliffs have attracted special attention in terms of recording trampling sensitive plants which are no longer found on the slopes elsewhere. Specimens were determined by a number of plant taxonomists, mainly in the UK. Plant names are cited according to “Flora Xizangica” (Wu, 1983–1987). A quantitative approach was executed through vegetation records of standard plot size

(10 × 10 m) following the Zuerich–Montpellier approach (Mueller-Dombois and Ellenberg, 1974) from 1994 on. In order to estimate the grazing impact, seven monitoring plots were fenced-off to exclude grazing in 1997: above Nechung, three plots were established (3720 m: 320 m^2; 4180 m: 2800 m^2; 4650 m: 620 m^2) and northwest of Sera, four plots (3800 m: 620 m^2; 4150 m: 3500 m^2; 4280 m: 600 m^2; 4500 m: 210 m^2) were fenced. Species composition, percentage of cover of each species, structure and especially diameter and size of the woody phanerophytes have been monitored every two years since 1997. Changes of species composition and cover degree have been mapped for a permanent monitoring plot of 1 m^2 within a 10 cm grid. Since 1994 a comprehensive inventory of juniper tree relicts in Southern Tibet has been undertaken (see Fig. 1). GPS location, altitude, slope exposure, substrate, habitat condition (especially water surplus or non-water surplus site), BHD size, vitality, drought damage, parasites, fructification, number of female or male individuals and hermaphrodites, and distribution of young trees (if any) have been recorded. As the inventory revealed more than 60 isolated stands of groves of *J. convallium* and *Juniperus tibetica* trees in non-favoured habitats, seedlings were cultivated from mother trees nearest to the study site in a nursery and planted in the fenced-off monitoring plots in 1999 and 2000. *Cupressus gigantea* was also cultivated. The saplings were only watered once when planted. In parallel with the fencing-off of the permanent monitoring plot, rain gauges (200 cm^2, 1 m above ground in open situation) were established in the plots or on the flat roofs of buildings nearest to the plots. Subsoil temperatures were recorded with a "Hot Dog" data logger at an hourly resolution from August 1997 to August 1998.

3.2. Palynology

The site "Lhasa 1" was drilled in 1994 by Armin Schriever and Ubbo Wündisch during a Chinese–German Joint Expedition with a Dachnowski corer. The core is 150 cm long. The lower 60 cm section consists of minerogenic sediment, presumably deposited from the adjacent slope. The middle part is composed of an organic detritus mud and the upper 10 cm by Cyperaceae turf.

The pollen samples were prepared by standard methods using KOH, HF and acetolysis. Thereafter the suspension was sieved in an ultrasonic bath (mesh 5 × 8 μm, 50 kHz) and stored in glycerine (Erdtman, 1960; Moore et al., 1999). For the standard analyses a 500-fold magnification was used, and for the determination of subtypes of Poaceae and ambiguous pollen grains a magnification of 1250 was used in addition to phase contrast and oil immersion.

Around 100 palynological types were distinguished, most of which are presented in the pollen diagram (Fig. 3). Identification and nomenclature are based on type slides and literature (Beug and Miehe, 1999; Schlütz, 1999; Beug, 2004).

The calculation of pollen percentages is based on the sum of arboreal pollen (AP) and non-arboreal pollen (NAP) types; pollen grains of Cyperaceae, water plants and spores are not included. Due to the unfavourable sediment, pollen analyses had to be restricted to selected horizons. Evidence for selective preservation of palynological types resistant to corrosion was not observed. The pollen sum (AP + NAP) averages about 920 (130–3050) pollen grains and, without Poaceae (local high values in PZ 2), 260 (100–520). The taxa are arranged according to their modern ecology and chronological emergence. Radiocarbon dates were determined in Hannover (Hv., Germany) and Poznan (Poz., Poland) using conventional ^{14}C-dating (Hv.) and AMS-dating (Poz.) for bulk samples. Unfortunately the low amount and quality of the cored material are unsuited for additional dating. New drilling attempts already started in spring 2006 will hopefully provide a wealth of cores for further investigations.

Surface samples (mostly moss cushions) were collected in 2003 and analysed in the same way as the pollen profile. Only the results for juniper pollen are presented here (Fig. 4).

3.3. Plant macrofossils and microfauna

In 2002 a total of 11 cores were taken using a Russian peat corer in a transect stretching from the northwest edge of Lhalu Damra (see Fig. 2) to about one third of the way along the marsh basin towards the southeast to reconstruct the stratigraphy of the floodplain. All cores were described in terms of basic sediment type (Faegri and Iversen, 1989). From this information the sediment stratigraphy for the marsh basin was reconstructed.

Four cores were chosen for depth difference and sediment texture, and for the analysis of plant macrofossils, microfauna and loss-on-ignition (LOI). The determination of the sediment water content and the organic content was accomplished by taking weighted subsamples at 5 cm intervals. The samples were dried (105 °C, 15 h) and combusted (550 °C, 6 h). Percentages of water content and dry weight lost on ignition were calculated.

Using the displacement method (Birks, 2001, Solhøy, 2001), two cubic centimetre subsamples were taken irregularly for analyses of plant macrofossils and microfauna as well as to estimate the sediment composition.

The sediment composition of the samples was estimated in terms of coarse silt, fine silt, coarse material (vegetative roots etc.), fine organic material, sand and clay.

The proportion of each element in a sample (2 cm^3) was estimated based on five-point scale: + (less than 1%), 1 (1–25%), 2 (25–50%), 3 (50–75%) and 4 (greater than 75%), using a petri dish (10 cm diameter) which was divided by two crossed lines into four parts with the same proportions.

Identifications of both plant macrofossils and microfauna were made by comparing them to local reference materials and modern reference collections from the University of Bergen.

3.4. Palaeopedology

In 2003, palaeopedological investigations were carried out on Holocene colluvial sediments and related paleosols on slopes next to the drilling sites. They aimed at properties, dating and genesis of these 'geoarchives'. Alongside this, the detection and analysis of charcoal in paleosols was a further priority. It was partly possible to perform the investigations in conjunction with Neolithic archaeological sites (Lhasa-Qugong, Gar Drongy, see Figs. 1, 2).

23 soil profiles were described at single sites and along geomorphological transects. Here, only soil profiles having chronological and botanical data are presented. Horizon designations and soil types are given using World reference base for soil resources (WRB, 1998). Five AMS-radiocarbon dates (Erlangen laboratory) were obtained from the profiles. Further geochronological dating (IRSL) was carried out at the Marburg luminescence dating laboratory (Kaiser et al., 2006). In general, luminescence dating carried out on colluvial deposits have yielded comparative results to those from independent age monitoring (e.g. Kadereit et al., 2002). IRSL dates correlate numerically with calibrated ^{14}C dates (cal BP-values). The charcoal determined originates from buried paleosols. Identification by W. Schoch (Laboratory for Quaternary Wood Research, CH Langnau) was performed by means of comparison with living material or from digital photographs of transverse, radial and tangential microscopic sections of recent woody species (Schoch, 1986). The various *Juniperus* species present in the area cannot be distinguished on the basis of their wood anatomy.

4. Results and discussion

4.1. Floristic evidence

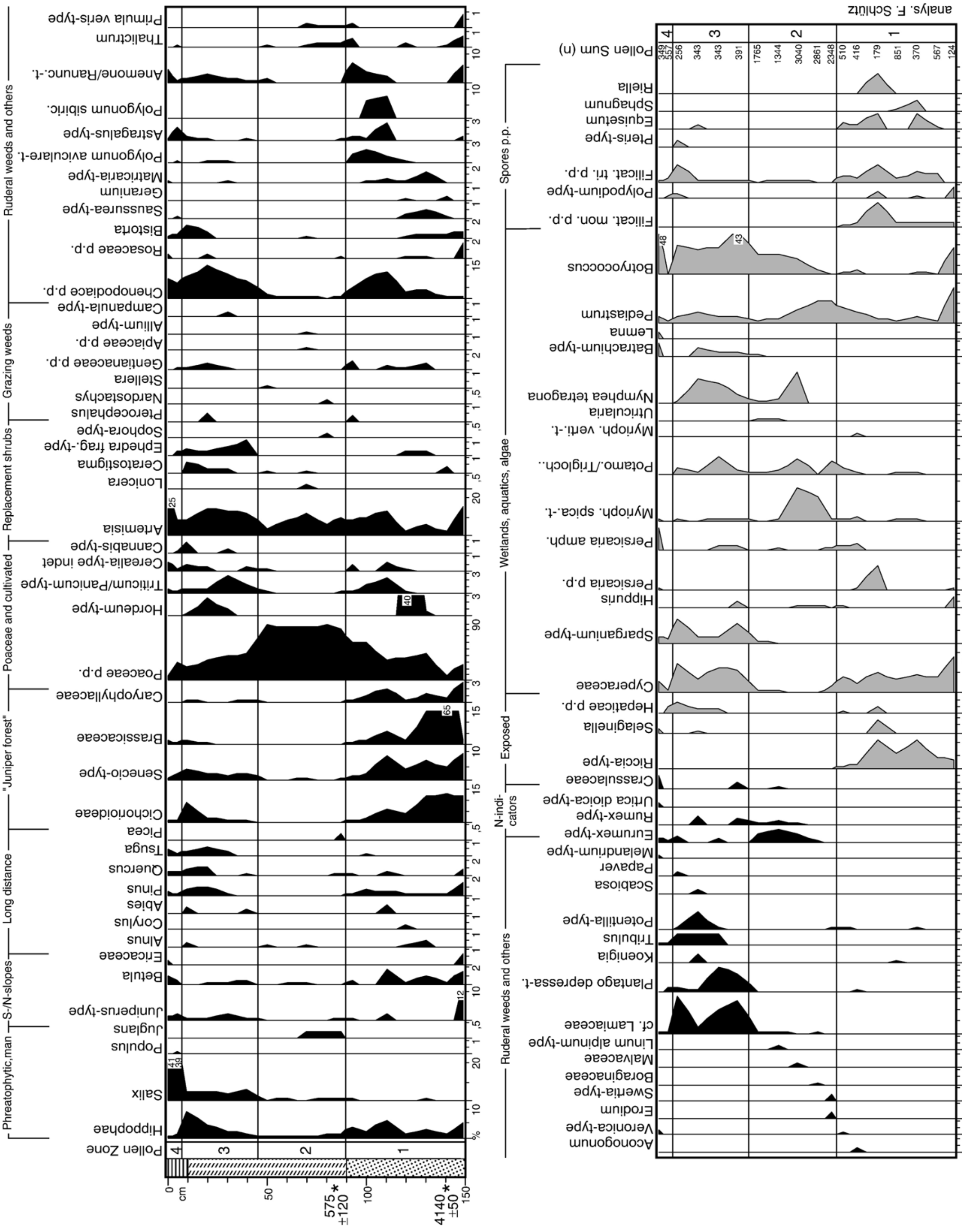
Floristic transect studies were carried out on the slopes adjacent to the drilling site and from the nearest *J. convallium* relict forest stands on the northern bank on the Yarlung Zhangbo, as well as in the nearest *C. gigantea* stands 200 km further east along the Yarlung Zhangbo between 93 and 94°25′E at altitudes of 3000–3200 m. They revealed a number of species widely known from forest understorey. Most prominent are shrubs known from oak forests of Southeast Tibet (*Jasminum humile*, *Leptodermis scabrida*) and herbs hidden between boulders (*Polygonatum cirrhifolium*, *Pteris cretica*). Grazing exclosure experiments on slopes 2 km above the drilling site (see Fig. 2) revealed an increase in shrub vegetation and perennial grasses from approx. 50 to 100% cover after only three years. Ubiquitous annual grazing weeds and ruderal plants disappeared under the litter of grass bunches. After only five years, the accumulation of phytomass increased to such a level that two plots were set on fire by children, providing evidence that the suppressed phytomass recovers after only five years and that fire clearing can be an effective tool of humans to design landscapes according to their needs. *A. santolinifolia*, *S. moorcroftiana* and the rhizomatous grasses (*P. flaccidum*) re-sprouted abundantly following the fertilization effect of the ash.

4.2. Experimental evidence

Since 1999, reforestation experiments have been conducted on exclosure plots between 3750 m and 4650 m with *J. convallium*, *J. tibetica* and *C. gigantea.* They reveal the forest potential of the Lhasa area: three year old saplings of *J. convallium* and *C. gigantea* are presently growing without any irrigation. The survival rate of three year old saplings reaches almost 100% and the *Cupressus* attained 1 m in height before they were burnt in spring 2004. Although the last five years have been marked by slightly higher rainfall than average, the reforestation trials prove the potential of forest growth on the hills around Lhasa. However, recent bioclimatic ecological scenarios (Song et al., 2004) do not consider Cupressaceae, and state that the "vegetation is undisturbed on the Tibetan plateau" (l.c., p. 166) which suggests a marked lack of field experience in the area.

4.3. Palynological evidence

The pollen diagram "Lhasa 1" (Fig. 3) is divided into four pollen zones (PZ). The base of PZ 1 dates before 4140 ± 50 years BP and shows a distinct decline of pollen of the *Juniperus*-type. It is assumed that this zone represents the first clearing of forests on the slopes adjacent to the drilling site. Charcoal fragments in the drilling transect east of "Lhasa 1" verify the presence of fire and the recent unintentional fire experiments of children on the exclusion plots demonstrate the potential of fire clearing. Recent analyses of surface pollen (Fig. 4) indicate that the pollen must have come from a local source, most likely from a former *Juniperus* forest


Phreatophytic, man
Hippophae
Salix
Populus
Juglans
S-/N-slopes
Juniperus-type
Betula
Ericaceae
Long distance
Alnus
Corylus
Abies
Pinus
Quercus
Tsuga
Picea
"Juniper forest"
Cichorioideae
Senecio-type
Brassicaceae
Caryophyllaceae
Poaceae and cultivated
Poaceae p.p.
Hordeum-type
Triticum/Panicum-type
Cerealia-type indet
Cannabis-type
Replacement shrubs
Artemisia
Lonicera
Ceratostigma
Ephedra frag.-type
Sophora-type
Pterocephalus
Grazing weeds
Nardostachys
Stellera
Gentianaceae p.p.
Apiaceae p.p.
Allium-type
Campanula-type
Ruderal weeds and others
Chenopodiace p.p.
Rosaceae p.p.
Bistorta
Saussurea-type
Geranium
Matricaria-type
Polygonum aviculare-t.
Astragalus-type
Polygonum sibiric.
Anemone/Ranunc.-t.
Thalictrum
Primula veris-type
Pollen Zone
4
3
2
1
cm
0
50
100
150
575 * ±120
4140 * ±50
%
41
39
12
25
40
65
Aconogonum
Veronica-type
Erodium
Swertia-type
Boraginaceae
Malvaceae
Linum alpinum-type
cf. Lamiaceae
Plantago depressa-t.
Koenigia
Tribulus
Potentilla-type
Scabiosa
Papaver
Melandrium-type
Ruderal weeds and others
N-indi- cators
Eurumex-type
Rumex-type
Urtica dioica-type
Crassulaceae
Exposed
Riccia-type
Selaginella
Hepaticae p.p.
Wetlands, aquatics, algae
Cyperaceae
Sparganium-type
Hippuris
Persicaria p.p.
Persicaria amph.
Myrioph. spica.-t.
Potamo./Trigloch..
Myrioph. verti.-t.
Utricularia
Nymphea tetragona
Batrachium-type
Lemna
Pediastrum
Botryococcus
48
43
Spores p.p.
Filicat. mon. p.p.
Polypodium-type
Filicat. tri. p.p.
Pteris-type
Equisetum
Sphagnum
Riella
Pollen Sum (n)
349
557
256
343
343
391
1765
1344
3040
2861
2348
510
416
179
851
370
567
124
analys. F. Schlütz

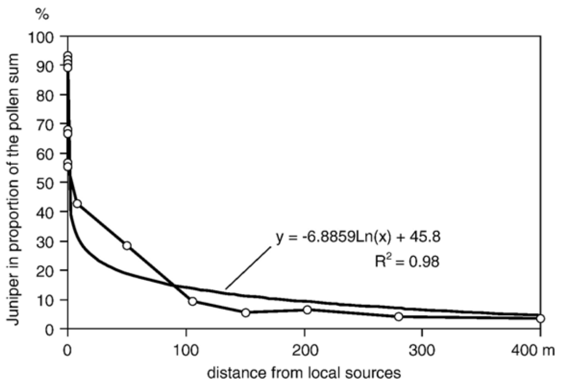


Fig. 4. Transect of low Juniper pollen dispersal: surface samples show a sharp decline of *Juniperus* pollen with growing distance from local sources like shrubs (*J. pingii*) and tress (*J. tibetica*, *J. convallium*). Only nearby the values are noticeable higher than the background signal from regional and long distance transport. The line of regression shows a high fit of $R^2 = 0.98$ (data F. Schlütz).

which stood approx. 200–300 m away on the nearest southern exposed slopes at the time represented by PZ 1. However, it can not be excluded with certainty that *Cupressus* stands were a source of the *Juniperus*-type pollen rain at that time. The reforestation experiments close to the site of “Lhasa 1” show that *C. gigantea* thrives under present-day climatic conditions. The decline of the *Juniperus*-type in parallel with high values of Cichorioideae, Brassicaceae and *Thalictrum* is somewhat similar to forest declines in the eastern Hindu Kush (Schlütz, 1999), the Tibetan Himalaya (Miehe et al., 2002) and the southeastern Gobi Altay (unpublished data) at the onset of the Subboreal time period after the Holocene Climatic Optimum.

Whether the juniper forest on the slopes burnt down because of lightning or because of human ignited fires in order to obtain predator free rangelands is not yet unanimously agreed. Thunderstorms around Lhasa occur frequently during the summer though they are usually followed by heavy rainfall which could thwart the potential of fire from lightning. It appears that, following the deforestation apparent from PZ 1, relatively large amounts of substrate were exposed and were subsequently colonised by *Riccia* and other Hepaticae. The occurrence of *Selaginella* spores can be interpreted likewise: even today *Selaginella* covers the steep banks around cliffs together with rosettes of *Corallodiscus lanuginosus*. Until the forest was cleared it was not very likely that the spores would have been deposited onto the wetland. During the post-deforestation period the first *Ceratostigma* pollen appears: *C. uliginosum* is presently the most common wasteland shrub and disappears after grazing exclosure, when grasses and other shrubs grow denser. The same applies to *Ephedra*. Soon after the presumed clearing, the first Cerealia pollen (*Hordeum*-type) appears, followed by an increase of Poaceae either belonging to *Triticum* or *Pennisetum* (here *Triticum*/*Panicum*-type; for details see Beug, 2004). As *P. flaccidum* actually invades wastelands, this can be interpreted as a human induced increase of open soil in parallel with cultivation and fallows. The same applies to the *Astragalus*-type: *Astragalus monbeigii* actually colonizes the most degraded open sites nearest to settlements and is avoided by cattle. *Polygonum aviculare* shows the same preferences. The presence of *Hordeum*-type is corroborated by *Hordeum* macro-remains indicating barley cultivation approx. 40 km south of Lhasa at 3500 BP (Fu et al., 2000). The oldest findings of *Triticum* on the Tibetan Plateau date back to 2900 BP (Fu et al., 2000). Perhaps the cattle and, to a greater extent, an ineffective irrigation of the cornfields led to the saline conditions indicated by the presence of *Polygonum sibiricum* and *Riella*.

The current distribution of *Betula* in Southern Tibet, its ecology, the climate of Lhasa and the presence of shrubs known from the presently standing nearest birch forests (80 km north of the drilling site), makes it likely that north-facing slopes around Lhasa were also forested, with *Betula platyphylla*, and with *R. anthopogonoides* being prevalent in the understorey. *Pinus*- and *Quercus*-pollen show the same decline. However, the distance of the closest stand of these species to the drilling sites is twice than that of birch. Despite the well-known capability of both species for long-distance pollen dispersal, it cannot be excluded with certainty that *Pinus densata* and *Quercus aquifolioides* were never present in the area. Besides, the current shrubberies above Lhasa share some herb species with the *Pinus*–*Quercus* forests of the lower Yarlung Zhangbo valley (e.g. *Codonopsis convolvulacea*).

Hippophaë is regarded as a phreatophytic tree species in the Kyi Chu floodplain. Even the founding legends of the city of Lhasa comprise references to buckthorn forest (Sörensen, 2003). With the onset of the historical period coinciding with the foundation of the Tibetan realm under the leadership of Songtsen Gampo, we may causally assume an increased human impact on

Fig. 3. Pollen diagram “Lhasa 1” (3650 m, 29°10′N/91°04′E). Taxa arranged in ecological indicator groups according to their actual habitats. Pollen sum = all pollen taxa except Cyperaceae and water plants. Note different scales. Sedimentology from top to base: Cyperaceae-turf, turf/detritus mud, silty and sandy minerogenic sediments. Dates in uncal BP.

the natural vegetation, and especially on the timber resources: historical mural paintings in the Jokhang temple in Lhasa (Fig. 5) show how logs from the neighbouring slopes were carried to the construction site situated on a wetland. As the only trees shown on the painting are growing on the slopes, poplar as the other common timber is excluded being exclusively a phreatophytic species. The conclusion would be that the logs refer to the trees shown on the painting. The presently remaining juniper trees in Southern Tibet are mostly gnarled and seem not suitable as timber; however on remoter slopes, not easily accessible for logging, juniper would provide trunks as seen on the painting. A conclusion from that illustration would be that the slopes around Lhasa were still supporting forests exploitable for construction at the time the Jokhang was built (639 to 647 AD; Chang, 1994). Topographical names support this historical finding: a promontory northeast of Lhasa is called “Tsenden Ri”, most probably because the mountain was known for its juniper trees or cypresses (P. Sörensen, pers. comm.). *B. crispa*, an understorey tree of the nearest Cupressaceae-forests and a rather common shrub in the pastures around Lhasa, is called “Tsenden” as well.

The pollen diagram offers no hints on a hiatus between the mineral sediments (PZ 1) and the following organic part of the profile. Nevertheless further research and cores are needed for a detailed view on and a better age control of the vegetation history before PZ 2. PZ 2 documents an incisive environmental change starting at about 600 BP. This is roughly the foundation period of the largest monasteries in Southern Tibet: Ganden (1409 AD), Drepung (1416 AD), Sera (1419 AD) and Tashilhünpo (1447 AD, Everding, 2001). Drepung, only 3 km northwest of the drilling site “Lhasa 1”, certainly had an important environmental impact because thousands of monks would have needed supplies of barley, butter, fuel and incense. In contrast to the salty conditions in PZ 1, freshwater conditions occurred at the drilling site from then on, giving rise to the occurrence of a variety of aquatic plants (*Myriophyllum*, *Nymphaea* etc.). This strong hydrological change may be a consequence of the construction of irrigation channels for the cultivation of cereals.

At the base of PZ 2, pollen from the insect pollinated *S. moorcroftiana* is traceable. It is evident that the presence of this non-wind dispersed pollen type points to extended heathlands of *Sophora*. One can conclude that since that time period, *Sophora* dominated heathlands on lower slopes and river terraces were established as the most important replacement vegetation in the vicinity of irrigation oases in Southern Tibet. The occurrence of

Fig. 5. Wall painting in the Jokhang-temple of Lhasa (undated) showing the construction site in the flood plain of the Kyi Chu (river) with timber brought from the surrounding slopes. Photo: S. Miehe, September 2001.

Crassulaceae pollen represents the propagation of *Rhodiola* rosettes on steep clay slopes or annual *Sedum* species on open soils. Furthermore, pollen of common trampling and ruderal plants appears for the first time: *Tribulus*, *Erodium*, Malvaceae (i.e. *M. pusilla*) and Boraginaceae (most probably *Lasiocaryum*, *Eritrichium* and *Onosma*). The same refers to *Linum*. Today these trampling indicators are frequent only where firewood is harvested and/or browsing and trampling occur and thus woody phanerophytes are reduced until they cover less than 20% of the surface and the cover of higher plants seldom exceeds 50%. Grazing impact clearly increased during the PZ 2 period, and common grazing weeds appeared (*Pterocephalus*, *Nardostachys*) as well as disturbance indicators like *A. tortuosum*, which colonize open soil. Towards the end of PZ 2, as a result of an increasing impact of selective grazing, the widespread High Asian rangeland indicator of degradation *Stellera chamaejasme* (Thymelaeaceae) occurred.

During PZ 3 an increasing degradation of the slope vegetation is indicated. It seems that *A. santolinifolia* and *C. ulicinum* as well as Chenopodiaceae became dominant. Trampling indicators such as *Tribulus*, *P. depressa*-type, *Koenigia* and the *Potentilla*-type became more frequent than at any previous time. The pollen of the *Astragalus*-type increases as well and most probably reflects the increasing area of wastelands around the villages dominated by the currently ubiquitous *A. monbeigii*. Unprecedented concentrations of *Botryococcus* (algae) and *Nymphaea* pollen indicate a peak in cattle density with a higher dung influx around the drilling site. The *Potentilla*-type points most probably toward the spreading of *Potentilla anserina*, which commonly colonizes slightly saline clay surfaces around water holes. For the first time *Juglans* (walnut) pollen appears, indicating a more highly developed agricultural practice. Another example of the range of cultivated plants observed is *Cannabis sativa*, which is still being used today for fibre and oil. Quite surprising is the ostensible recovery of juniper. Concerning our field observations, we suggest that the higher values of the *Juniperus*-type reflect the planting of *Platycladus orientalis* trees in monastery gardens nearby. In the floodplain *Hippophaë* woodlands have increased even though the pollen signal of the slopes shows heavier anthropogenic pressure. This contradiction is plausible because stronger erosion on the slopes leads to larger gravel accumulation in the floodplain of the Kyi Chu giving more suitable substrate for the pioneer successions of buckthorn.

PZ 4 reflects the present grazing pressure and the highest level of impact to date. *Salix* has increased significantly obviously replacing *Hippophaë* thickets. The cultivation of willows and poplars has been proliferated in the recent past (Wardle, 1981) to meet the needs of construction and firewood. The aquatic plants now include the excess nitrate indicators *Batrachium*-type and *Lemna* and indicate the highest nitrate influx to date due to the greater number of cattle. *Artemisia* reaches its highest values dominating the commons and the importance of Poaceae has decreased. Plants which tend to colonize open soils, such as Crassulaceae (i.e. *Rhodiola chrysanthemifolia* or *Sedum roborowskii* and *Selaginella* spp.) are spreading.

4.4. Evidence from plant-macrofossils and microfauna remains

The analysis of plant macrofossils can provide an independent approach to the reconstruction of local vegetational and environmental development history (Lowe and Walker, 1997), assuming that autogenic successional processes are of primary importance in the long-term dynamics of wetland vegetation and are independent from changes in the regional vegetation. The analysis of plant macrofossils and microfaunal remains from the sediment sequence can only serve as a reflection of the local marshland vegetation history and hence the changes of the environment within the basin itself. There is no direct evidence for regional environmental changes caused by either climatic conditions and/or human activity. However, charcoal fragments were found at the base of all four studied soil profiles. Evidence of flooding and redeposition in the basin is given by the occurrence of coarse sandy silt and sandy gravel, indicating woody plants and fire presence in upper catchments and surroundings. Nevertheless, it is difficult to conclude whether the fires were natural or anthropogenically-induced.

The occurrence of the oribatids *Hydrozetes thienemanni* and *Thrypochthoniellus setosus* in high numbers in peaty mud and sandy fine silt layers (100–180 cm below the present surface) may simply provide evidence of local environmental and vegetational changes. Oribatid mites have considerable potential in the reconstruction of past plant communities and other environmental variables locally (Solhøy, 2001). The peaks in abundance of *H. thienemanni* and *T. setosus* are found in eutrophic lentic habitats on submerged water plants and mosses in Europe and Canada. However, information on present-day invertebrate composition, distributions and ecological requirements over the Tibetan Plateau is needed for a more clear interpretation of their implications for the reconstruction of past vegetational succession and environmental history.

Redeposited fossil seeds of Poaceae, Chenopodiaceae and *Taraxacum* were more common in the sandy fine silt layer in the upper part of the sediment profile. These plant-macrofossils from the surroundings of the marsh basin may also indicate the development of human-induced vegetation in adjacent areas of the basin. Other taxa present in this layer are *Carex*, *Cyperus* and *Stellaria*. The typical cold and flowing water indicators of chironomids such as *Tvetenia* and *Nimbocera* along with the genus *Thienemannia*, which live on wet rocks rich in mosses and lichens (Cranston et al., 1983), are present in the sandy silt layer as well. All these were probably transported from the upper catchment and surrounding areas by running water and redeposited in the basin.

The rapid deposition of coarse fluvial and alluvial sediments prior to the formation of the marshland peat suggests that the basin was periodically exposed to a significant degree of surface flow causing substantial soil erosion of the unstable deforested surrounding slopes. This led to an additional decline in surface vegetation coverage.

4.5. Paleosol and charcoal evidence

Human utilisation of mountainous and hilly landscapes unavoidably causes soil erosion by surface runoff. The subsequent sediments are often colluvial sand bodies at footslopes and valley floors burying older soil surfaces. Thus it appears that colluvial sediments and related paleosols can be important sources leading to conclusions on the extent of human impact in the past (e.g. Bell and Boardman, 1992).

The Profile QUG 1 from the late Neolithic Lhasa-Qugong site (Fig. 2, Institute of Archaeology of the Chinese Academy of Social Sciences and the Bureau of Cultural relicts of the Tibet Autonomous Region, 1999; Aldenderfer and Zhang, 2004) is situated at the footslope of a mountain ridge. It forms a sequence topped by sandy colluvial sediment covering a paleosol developed from slope deposits (Fig. 6). A buried 2Ahb horizon represents the occupation layer. Pedological properties assign this paleosol to an Arenosol. One radiocarbon sample derived from an animal bone was taken from the 2Ahb horizon and yielded an age of 3053±45 BP (= approx. 3270 cal BP, Erl-6783). Unfortunately, only some very small and smeary pieces of charcoal have been found, not allowing for extraction from the soil and further analysis. IRSL age estimates indicate an accumulation of the top layer of colluvial sand spanning, at most, the last thousand years. Two samples from the underlying slope deposits (8.0±0.8 ka and 20.0±2.0 ka) indicate sedimentation during the Early Holocene and the Last Glacial Maximum.

Profiles DRE 2 and DRE 9 belong to a pedo-geomorphological transect which runs from 3640 to 4890 m next to the Drepung monastery (Fig. 2). DRE 2 (3654 m) consists of a top layer of fan sediment, an intermediate layer of fluvial sand and a basal layer of fan sediment. The charcoal analysis of the buried 2Ahb horizon (Arenosol) shows a dominance of *Juniperus* (54.6%) followed by a high proportion of *Salix* (38.1%). A radiocarbon sample of juniper charcoal yielded an age of 203±41 BP (= approx. 170 cal BP, Erl-6776). DRE 9 (4583 m) is situated on the middle slope. An upper colluvial layer has a thickness of only 30 cm and consists of loamy sand. The buried soil beneath is constituted of aeolian silt and can be classified as Cambisol. A charcoal layer from the 2AhBwb horizon is dominated by *Juniperus* (96.8%). Juniper charcoal gave a radiocarbon age of 2194±41 BP (= approx. 2270 cal BP, Erl-6777).

Profile GAR 1 was recorded approx. 30 km NW of Lhasa on the north-eastern valley side of the Tolung Chu (river) at approx. 3800 m (Fig. 1). The site is situated on the footslope of a mountain ridge a few hundred metres high. Typologically, the artefacts from this site are comparable with the Qugong site representing the late Neolithic. GAR 1 comprises a succession of different colluvial layers of loamy sand overlying a fluvial–lacustrine deposit. The 2AhbC horizon forms the occupation layer. Shrubs dominate the charcoal spectrum (*Hippophaë* 70.5%, *Rosa* 23.3). Only a small proportion is represented by *Juniperus* (5.4%). The radiocarbon dating of juniper charcoal yielded an age of 3668±57 BP (= approx. 4000 cal BP, Erl-6782). For the 3AhbC horizon (Phaeozem) radiocarbon dating on humic acids yielded an age of 7908±99 BP (= approx. 8690 cal BP, Erl-8070). IRSL age estimates obtained for the upper 250 cm of the profile point to a successive deposition of the colluvial sands covering the last 4.3±0.5 ka.

Generally, the formation of colluvial sediments can be attributed to natural (e.g. exceptional rainfalls, climatic changes) and anthropogenic (slope instability after forest clearing, agriculture) causes. A combination of both causes is also conceivable — secondary human enhancement of a primary opening of the landscape by increasing aridity and/or reduced temperature would be plausible. The colluvial deposits investigated can be divided into i) coarse-grained sediments with a high proportion of stones and

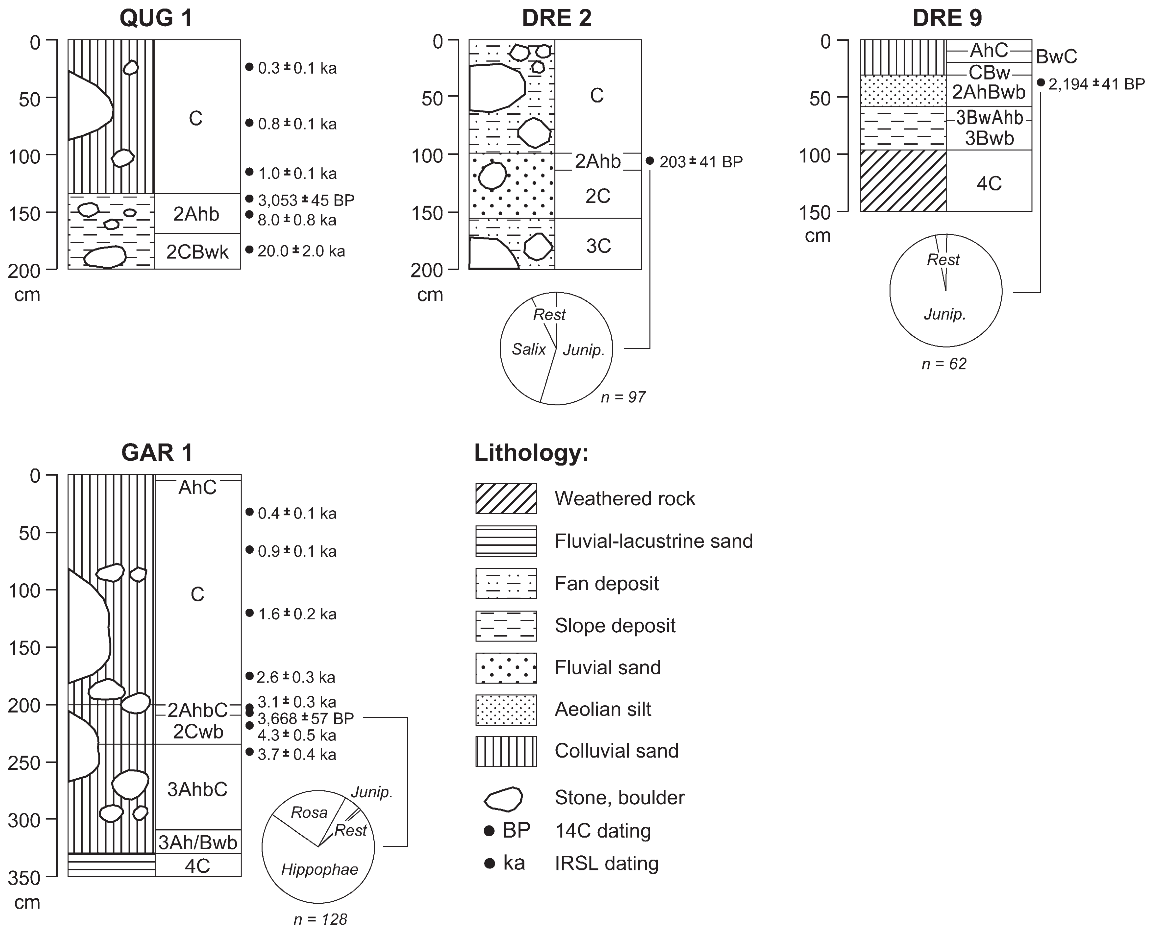


Fig. 6. Pedological, geochronological and charcoal data of soil profiles from the Lhasa region.

boulders originating from (high-energy) alluvial fans and debris flows (DRE 2), ii) matrix supported sediments with only some stones and boulders originating from mudflows or combined colluvial processes such as hill wash plus rock fall (QUG 1, GAR 1), and iii) more or less fine-grained sediments originating from (low-energy) hill wash (DRE 9). The multi-level dating of profile QUG 1 points to a relatively long hiatus of approx. 2000 years between the buried paleosol and the colluvial layer. The colluvial sedimentation mainly took place in a short interval between 1.0±0.1 and 0.8±0.1 ka. In contrast, the upper paleosol of profile GAR 1 (3668±57 BP) is already developed from a colluvial layer. Thus this paleosol postdates a first colluvial episode, which is predated by the lower paleosol (7908±99 BP). Afterwards, there is a relatively long hiatus of approx. 1500 years between the paleosol and a second colluvial episode around 2.6±0.3 ka. But contrary to QUG 1, the IRSL datings show that the upper colluvial sedimentation took place during several periods between 2.6±0.3 ('Metal Ages') and 0.4±0.1 ka (Historic period). Furthermore, the soil profiles presented show a marked difference in vegetation between the buried paleosols with charcoal of trees and the present surfaces with desert open dwarf scrublands.

5. Conclusions

A multiproxy approach to the study of Holocene environmental changes in Southern Tibet has provided evidence that Cupressaceae forests gave way to desert pastures sometime during the last 5000 years. In contrast to the common belief that the environment of the Tibetan plateau has not been disturbed by humans but reflects natural conditions (Ni, 2000; Ren, 2000; Yu et al., 2001), evidence from forest relict inventories, analysis of climate data, successful reforestation trials with indigenous tree species, palaeoecological analysis and data from pollen surface samples as well as paleosol investigations with determined charcoal fragments have all indicated that Southern Tibet would be forested, were it not subjected to the environmental impact of humans. This is in accordance with findings from the eastern Tibetan Plateau (Frenzel et al., 2003) and is a trivial conclusion from a wealth of archaeological data (Aldenderfer and Zhang, 2004). At least the surroundings of Lhasa could be forested again if large scale reforestation measures were instigated. The widely accepted climate driven Subboreal forest decline cannot explain the current treelessness of Southern Tibet moreover because the existence of vigorous forest relicts demonstrates the current forest potential. Thus it is evident that the human dimension of Global Change is underestimated here. As humans have been present since at least the Last Glacial Maximum (Zhang and Li, 2002), it must be considered that any climate impulse on the vegetation of the Holocene on the area was most likely exacerbated by human land use practices. It remains open as to whether human impact dates back more than 5000 years but it is highly probable because fire, as the then most widespread hunting tool of humans, was at hand far earlier than any impact deriving from animal husbandry or cultivation. According to historical evidence, it is probable that trees of natural forests were still available in the vicinity of Lhasa around 640 AD. Heavier human impact and the evolution of the present desert pastures, however, started around 1420 AD in the foundation period of the largest monasteries in Southern Tibet.

Therefore, we conclude that Southern Tibet suffered from similar environmental changes under human impact as those of the highlands of Afghanistan, Iran and Turkey. Southern Tibet was, furthermore, most probably part of a subtropical belt of highland Cupressaceae forests.

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