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Holocene paleosols and colluvial sediments in Northeast Tibet (Qinghai Province, China): Properties, dating and paleoenvironmental implications

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Abstract

Colluvial deposits consisting of silts and loams were detected in several climatologically different areas of NE Tibet (3200–3700 m a.s.l.). Layering, distinct organic content and low content of coarse matter as well as location in the relief revealed an origin from low-energy slope erosion (hillwash). Underlying and intercalated paleosols were classified as Chernozems, Phaeozems, Regosols and Fluvisols. Fifteen radiocarbon datings predominant on charcoal from both colluvial layers and paleosols yielded ages between 8988±66 and 3512±56 uncal BP. Natural or anthropogenic factors could have been the triggers of the erosional processes derived. It remains unclear which reason was mainly responsible, due to controversial paleoclimatic and geomorphic records as well as insufficient archaeological knowledge from this region. Determinations of charcoal and fossil wood revealed the Holocene occurrence of tree species (spruce, juniper) for areas which nowadays have no trees or only few forest islands. Thus large areas of NE Tibet which are at present steppes and alpine pastures were forested in the past.

Keywords: Paleosol; Colluvial sediment; Charcoal; Radiocarbon dating; Quaternary; Qinghai–Xizang (Tibet) Plateau

1. Introduction

The present-day ecosystem of the ca. 2.2 Mio km^2 large Tibetan Plateau is considered to be largely natural except a few urban centres, local exploitation of raw materials and tillage, which is restricted to certain altitudes (e.g. Ren, 2000; Yu et al., 2001; Song et al., 2004). Even studies on Holocene climatic and ecological changes using lake sediments, ice cores and terrestrial sediments have assumed either only a weak human impact in the *recent* past or have not considered this factor at all (e.g. Da et al., 1989; Feng et al., 1993; Lehmkuhl and Haselein, 2000; Herzschuh et al., 2005; Shen et al., 2005). From the eastern half of the Plateau, however, a growing number of archaeological, paleobotanical and geobotanical records point to a serious human impact already in the *distant* past (e.g. Schlütz, 1999; Miehe et al., 2003; Aldenderfer and Zhang, 2004). Analogous to other regions in Eurasia, the beginning of an intensive land use by agriculture dates from the Neolithic (NE Tibet: ca. 4800 BP, Chayet, 1999; E Tibet: ca. 5000 BP, S Tibet: ca. 3700 BP; Aldenderfer and Zhang, 2004). Consequently, the paleoclimatic and paleoecological interpretations from archives assumedly not influenced by humans can go astray at least for the Late Holocene.

Using a pedogeomorphological approach (e.g. Jungerius, 1985), possible evidence of human impact in the past can be traced by colluvial sediments originating from slope erosion: The land use of mountainous and hilly landscapes unavoidably causes soil erosion by runoff. Correlate sediments are often colluvial silt and sand bodies at footslopes and valley floors burying older soil surfaces. During the last 20 years, such geoarchives have frequently been investigated by geoscientists and archaeologists mostly in Europe to obtain proxy data for reconstructing past environments and land use (e.g. Bell and Boardman, 1992; Bork and Lang, 2003;

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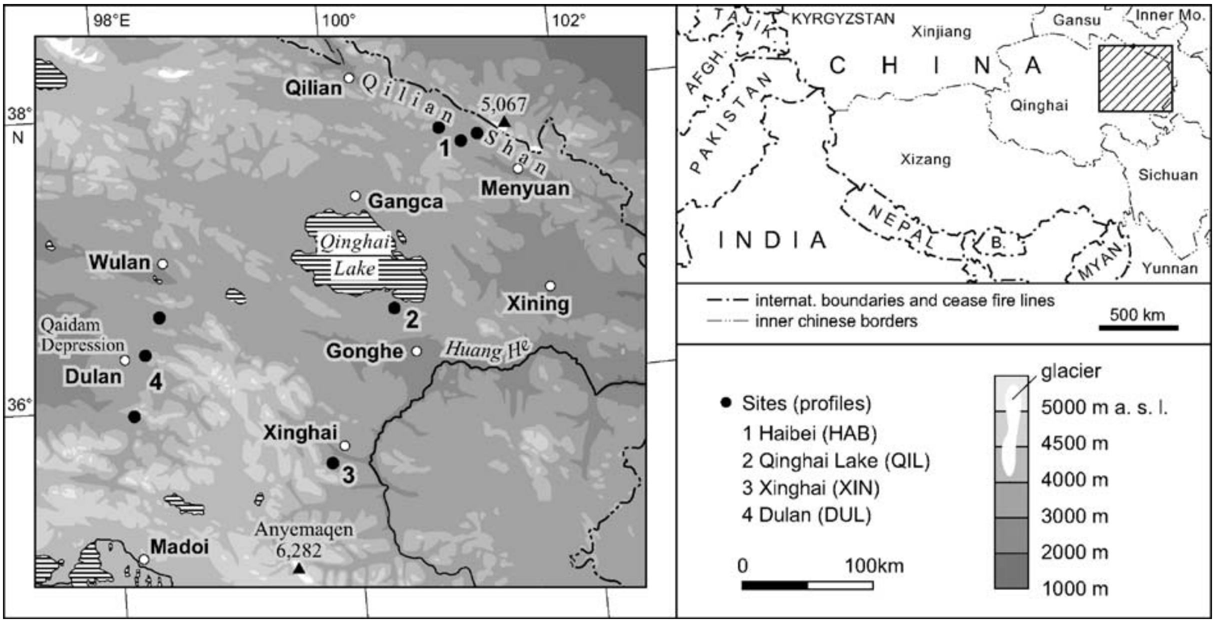

Fig. 1. Study sites in Northeast Tibet.

Brierley and Stankoviansky, 2003; Fuchs et al., 2004). However, also unambiguous natural erosion can be represented by colluvial deposits; for instance following a downward shift of vegetation zones caused by climatic changes (e.g. Reider et al., 1988; Tinner et al., 1996; Carcaillet and Brun, 2000). Consequently, the interpretation of this geoarchive needs additional paleoecological, archaeological and historical information, and should be interpreted most carefully.

In Tibet, only a few studies were performed using the paleoecological potential of colluvial sediments so far (Cui et al., 1995; Geldmacher et al., 2004; Kaiser et al., 2006). Thus there is not sufficient geoscientific data available, either on the distribution and properties of colluvial deposits or its possible relationships to the climatic or settlement development. Also with a broader perspective on pedology, and in contrast to the adjacent Chinese Loess Plateau (e.g. Kemp et al., 1995; Feng et al., 1998), only few pedogenic research from Tibet has been published in international journals so far (Smith et al., 1999; Fang et al., 2003).

In the framework of the multidisciplinary research project 'Present-day dynamics and Holocene landscape history of fragmented forests in Tibet' (DFG-project Mi 271/15), new studies on colluvial sediments and related paleosols were performed to gather paleoenvironmental data from NE Tibet (Fig. 1). They aimed at properties, dating and genesis of these geoarchives. Furthermore, the detection and analysis of charcoal and fossil wood in soils, contributing to the question whether larger forests once existed on the Tibetan Plateau, set a further priority.

2. Materials and methods

Colluvial sediments are represented by several badly sorted deposits whose transport and sedimentation took place gravitationally in a water-supported setting. The transport was often over a short distance. In a broader sense, the material comprises Pleistocene and Holocene sediments such as slope deposits ('purely' gravitationally as well as periglacially caused) and valley-floor deposits; furthermore deposits from mudflow, debris flow and rock fall (e.g. Moss and Walker, 1978; Van Vliet-Lanoë, 1998; Bertran and Texier, 1999). In the focus of this study, however, only badly sorted sediments on slopes and valley floors relatively poor in gravels and boulders without periglacial interferences shall be considered as 'colluvial'. The frequent occurrence of layering and, sometimes, a low amount of coarse matter points to a colluvial facies as well. A further criterion is given by the distinct content of organic matter generally pointing to a Holocene origin.

In 2002 and 2004, a total of 47 soil sections in NE Tibet (Qinghai Province, China) were recorded both at single sites and along geomorphological transects (Fig. 1). The profiles were described and sampled according to both an international (FAO, 1990) and a German soil science standard (AG Boden, 1994). The majority of profiles was classified only by means of field properties due to export limitations for soil samples. Horizon designations and soil types are given using WRB (ISSS-ISRIC-FAO, 1998). A slight modification concerns the term 'Colluvisol', which denotes explicitly colluvial soils/sediments, following the usual German practice. Furthermore, a new designation was created for a widespread Tibetan topsoil phenomenon which is called '*Kobresia* turf ' (Miehe, 1988; Kaiser, 2004). This horizon has a thickness of 5–20 cm and basically consists of felty remains of fine sedge-roots (genus *Kobresia*), and also of amorphous humus and minerogenic matter ('Afe': suffix *fe* from *fe*lty; organic content ca. 10–35%). Only soil profiles having additional chronological and botanical data are documented here with selected parameters (Table 1, Fig. 2, Appxs. 1–7). After sieving to 2 mm, humus and carbonate destruction and dispersion with sodium pyrophosphate, a combined pipette and sieving test was used to determine the grain size distribution. Samples were treated by burning for 2 h at 550 °C to estimate the organic content (loss-on-ignition = LOI). $CaCO_3$ was determined volumetrically. Soil pH was analysed potentiometrically in 0.01 M $CaCl_2$.

Table 1
Pedological data of selected profiles (hyphen = no data)

Horizon	Depth [cm]	Colour [Munsell]	LOI [%]	$CaCO_3$ [%]	pH [$CaCl_2$]	Clay, silt, sand [%]	>2 mm [%]
***HAB 3**, Colluvisol/Phaeozem, colluvial loam (1)/aeolian loam (2)/morainic sand (3)*							
CAh	0–30	10YR4/2	9.1	0	7.5	25, 63, 12	7
2Ahb	30–60	10YR3/1	8.4	0	7.3	28, 65, 7	10
2Ahb/3C	60–100+	2.5Y5/3	1.6	0	7.4	8, 49, 43	60
***HAB 5,** Gleyic Phaeozem/Gleyic Phaeozem, aeolian silt (1)/colluvial sand (2)/aeolian silt (3)*							
Ahg	0–87	10YR3/1	11.0	0	6.0	24, 70, 6	0
Ahg/Cg	87–110	10YR3/1	–	0	–	–	0
Cg	110–160	10YR4/3	4.1	0	5.9	21, 68, 11	0
2Cg	160–205	10YR4/3	2.4	0	6.0	11, 41, 48	0
3Ahgb	205–215	10YR3/1	9.6	0	6.1	26, 72, 2	0
3Cg	215–250+	10YR5/4	4.3	0	6.0	20, 70, 10	0
***HAB 6A,** Colluvisol/Gleyic Phaeozem, colluvial loam and silt (1)/aeolian loam and silt (2)/fluvial gravel (3)*							
Ah	0–50	10YR3/1	16.7	0	6.2	23, 60, 17	15
CAh	50–80	10YR3/1	6.1	0	6.5	16, 52, 32	30
2Ahb	80–100	10YR2/1	20.5	0	6.5	27, 60, 13	15
2Ahgb	100–140	10YR3/1	19.2	0	6.4	28, 67, 5	0
2AhBgb	140–160	10YR4/3	11.8	0	6.5	14, 84, 2	0
3Cg	160–200+	10YR4/4	–	0	–	–	90
***QIL 3,** Colluvisol/Phaeozem, colluvial silt (1)/aeolian silt (2)/slope deposit (3)*							
Afe	0–5	10YR4/2	21.7	0.5	7.6	20, 67, 13	0
Ah	5–15	10YR3/2	–	0	–	–	0
CAhk	15–84	10YR4/2	–	9.5	–	–	0
2Ahb	84–140	10YR3/3	8.0	0	7.4	24, 73, 3	1
2CAhb	140–210	10YR5/4	–	2.3	–	–	5
2Ckb	210–230	10YR5/6	–	12.8	–	–	10
3C	230–350+	–	–	0	–	–	80
***XIN 13,** Colluvisol, colluvial sand (1)/colluvial silt (2)*							
Afe	0–10	10YR3/2	–	0	–	–	0
Ah	10–30	10YR3/2	–	0	–	–	0
2CAh1	30–190	10YR2/2	9.5	0	6.5	22, 72, 6	0
2CAh2	190–350+	10YR7/4	–	0	–	–	0
***DUL 1,** Colluvisol/Regosol, colluvial silt (1)/colluvial loam (2)*							
Ahk	0–20	10YR4/4	–	–	–	–	0
CAhk	20–227	10YR7/3	5.0	12.4	7.9	16, 66, 18	10
2Ahkb	227–232	10YR5/3	8.6	17.5	8.0	21, 64, 15	0
2CAhk	232–300+	10YR6/4	7.3	15.3	7.9	21, 62, 17	0
***DUL 6,** Colluvisol/Fluvisol, colluvial silt (1)/colluvial silt (2)/fluvial sand (3)/fluvial gravel (4)*							
Ahk	0–15	10YR5/4	–	–	–	–	0
Ck	15–295	10YR7/3	3.0	8.6	8.1	15, 72, 13	0, 15
2AhCb	295–300	10YR6/3	–	–	–	–	0
3C	300–360	10YR7/3	–	–	–	–	0
4C	360–400+	–	–	–	–	–	90
***DUL 9,** Colluvisol?/'Gelic' Chernozem, colluvial loam? (1)/aeolian loam (2)*							
AhAfe	0–10	10YR4/2	10.8	5.1	7.8	18, 63, 19	0
CAhBw	10–60	10YR5/3	6.8	7.5	7.6	18, 58, 24	0
2Ahb	60–90	10YR2/1	8.5	6.0	7.6	21, 60, 19	0
2Ahgb	90–110	10YR2/1	–	–	–	–	0
2C	110–150+	10YR5/3	3.1	9.5	7.5	20, 56, 24	0

Coordinates and altitudes are given in Table 2.

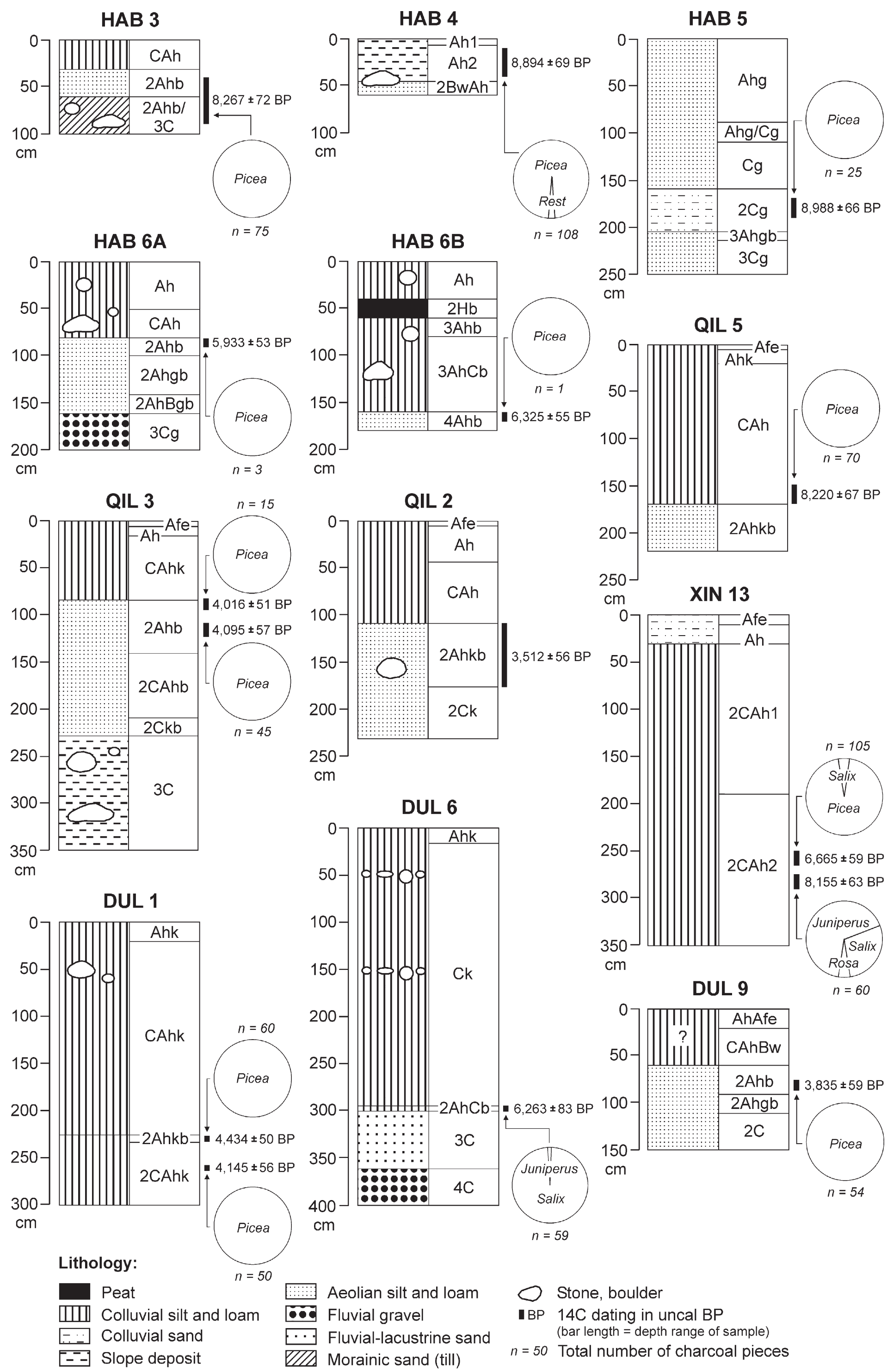

Fig. 2. Lithological, pedological, botanical and chronological data of the profiles investigated.

The charcoal and fossil wood analysed derives from both buried soils and colluvial sediments. It was extracted macroscopically from the sections (pieces up to 2 cm in length). An exact identification required an inspection of microscopic features by means of comparison with preparations from living material or from digital photographs of transverse, radial and tangential sections of recent wood species (Schoch, 1986; Schweingruber, 1990). The microscopic examination was carried out on fracture surfaces of the air-dried charcoal bits with surface illumination and magnifications of 5–50×. Charcoal/wood spectra and numbers of particles determined per sample (‘$n=$’) are shown in Fig. 2.

Fourteen AMS-radiocarbon dates, analysed in the Erlangen laboratory, were obtained from charcoal and wood. One

Table 2
Radiocarbon datings

Profile	Coordinates	Altitude [m a.s.l.]	Age [years BP]	$\delta^{13}C$ [‰]	Depth, lab code, material dated	Recent vegetation
HAB 3	37°40′09.4″N, 101°25′55.2″E	3619	8267±72	−25.7	40–90 cm, Erl-7509, *Picea* charcoal	shrubland (*Potentilla fruticosa, Salix*)
HAB 4	37°32′29.2″N, 101°19′43.7″E	3420	8894±69	−23.8	10–40 cm, Erl-7510, *Picea* charcoal	sedge mat (*Kobresia humilis*)
HAB 5	37°32′28.6″N, 101°18′44.6″E	3181	8988±66	−26.0	170–190 cm, Erl-7511, *Picea* charcoal	sedge mat (*Kobresia humilis*) with shrubs (*Potentilla fruticosa*)
HAB 6A	37°44′56.8″N, 101°13′46.3″E	3275	5933±53	−27.3	80–90 cm, Erl-7512, *Picea* wood	shrubland (*Potentilla fruticosa, Salix*)
HAB 6B	37°44′56.8″N, 101°13′46.3″E	3275	6325±55	−27.0	160–170 cm, Erl-7513, *Picea* wood	shrubland (*Potentilla fruticosa, Salix*)
QIL 2	36°32′52.1″N, 100°28′19.8″E	3636	3512±56	−26.7	110–175 cm, Erl-8075, humic acids	shrubland (*Potentilla fruticosa, Salix*)
QIL 3	36°33′09.5″N, 100°28′31.2″E	3535	4016±51	−24.5	84–94 cm, Erl-7506, *Picea* charcoal	shrubland (*Potentilla fruticosa, Salix*)
QIL 3	36°33′09.5″N, 100°28′31.2″E	3535	4095±57	−24.4	110–125 cm, Erl-7507, *Picea* charcoal	shrubland (*Potentilla fruticosa, Salix*)
QIL 5	36°33′27.8″N, 100°28′53.5″E	3396	8220±67	−25.0	150–170 cm, Erl-7508, *Picea* charcoal	sedge mat (*Kobresia humilis*)
XIN 13	35°29′59.7″N, 99°49′11.5″E	3550	6665±59	−24.9	250–270 cm, Erl-6773, *Picea* charcoal	sedge mat (*Kobresia pygmaea*)
XIN 13	35°29′59.7″N, 99°49′11.5″E	3550	8155±63	−23.8	270–290 cm, Erl-6774, *Juniperus* charcoal	sedge mat (*Kobresia pygmaea*)
DUL 1	36°28′46.0″N, 98°25′20.8″E	3648	4434±50	−22.1	230 cm, Erl-7502, *Picea* charcoal	sparse grassland with *Achnatherum splendens*
DUL 1	36°28′46.0″N, 98°25′20.8″E	3648	4145±56	−22.0	260 cm, Erl-7503, *Picea* charcoal	sparse grassland with *Achnatherum splendens*
DUL 6	35°54′29.1″N, 98°02′14.4″E	3246	6263±83	−22.2	295–300 cm, Erl-7504, *Juniperus* charcoal	sparse grassland with *Achnatherum splendens*
DUL 9	36°20′39.2″N, 98°13′59.1″E	3662	3835±59	−22.4	75–85 cm, Erl-7505, *Picea* charcoal	grassland with *Stipa*

dating was obtained from humic acids (Table 2). The ^{14}C ages presented in the text are uncalibrated.

Since the sites investigated belong to different types of landscapes, short descriptions of the natural environment will be given in the results chapter. According to the map of pedogeographical zones on the Tibetan Plateau (Atlas of Tibet Plateau, 1990), the sites belong to two major soil zones (Haibei, Qinghai Lake and Xinghai site: 'zone VI' comprising Kastanozems, Chernozems, Phaeozems and Humic Cambisols; Dulan site: 'zone X' comprising 'cool and cold desert soils' as well as salty soils).

3. Results

3.1. Haibei area

The profiles investigated from the Haibei area comprise three sites lying in a hilly landscape between main ranges of the Qilian Shan at ca. 3100 to 3600 m a.s.l. (station Haibei, 3240 m a.s.l.: mean annual air temperature = MAAT = −1.7 °C, mean annual precipitation = MAP = 560 mm; Cao et al., 2004; Fig. 1).

The first site consists of a ca. 8-km-long pedogeomorphological transect in the vicinity of the Chinese Academy of Science's Haibei Research Station (Fig. 3). In general, the landscape is widely covered by aeolian sediments (silty and loamy loesses); only few rocky outcrops of granite occur. The floors of valleys and basins are moist to wet; the deepest part is occupied by Lake Luanhaizi. Along the transect, mostly soil profiles of the Phaeozem type were recorded. Apart from the transect, Cambisols occur too. The vegetation at all expositions is dominated by dense alpine pastures mostly consisting of sedges (*Kobresia humilis*, *Kobresia pygmaea*).

Profile HAB 5 is situated at the footslope of a ca. 300-m-high hill and consists of topping aeolian silt, intermediate colluvial sand and basal aeolian silt (Table 1, Fig. 2, Appx. 1). Evidence of an aeolian facies is given by the grain-size distribution as well as the lack of a distinct layering and particles larger than 2 mm. The topping loess bears a 87-cm-thick and carbonate-free AhCg horizon pointing to a Gleyic Phaeozem as surface soil (LOI = 11.0%). The lower loess is terminated by an only 10-cm-thick humic horizon which is buried by colluvial sand. The colluvial sand shows a distinct layering and only little organic matter (2.4%). Some charcoal particles of *Picea* (spruce) were found in this layer dating to 8,988 ± 66 BP (Table 2). Charcoal of *Picea* of a similar age was obtained from the topsoil of profile HAB 4 (8,894 ± 69 BP; Table 2, Fig. 2) lying at the base of a rocky cliff. Further charcoal was determined as *Lonicera* (honeysuckle)

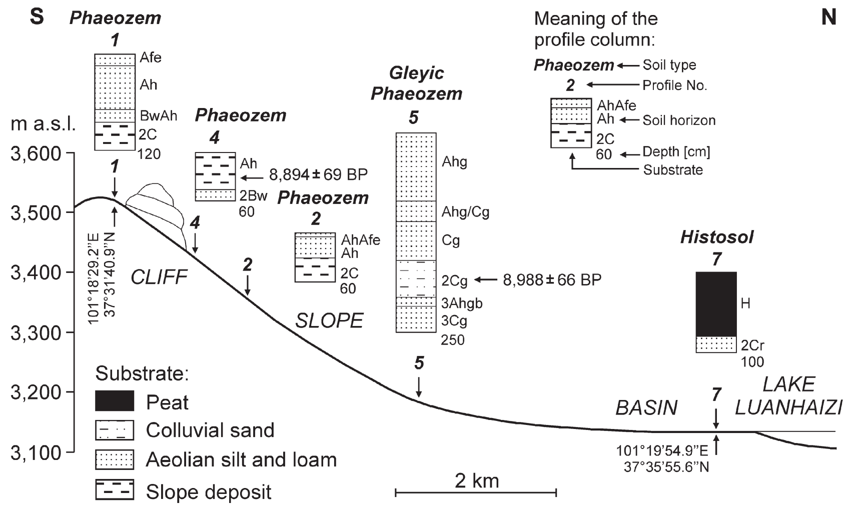

Fig. 3. Haibei transect.

and *Rosa* (rose). Since this site has been severely disturbed by the trampling of domestic animals in recent times, a former topping aeolian cover may have been similarly eroded in the past.

The second site is situated in a transversal valley of the Qilian Shan, ca. 15 km NE of the Haibei Research Station. Here, profile HAB 3 was recorded on a southeast-facing middle slope (3,619 m a.s.l.; Table 1, Fig. 2, Appx. 2) with *Potentilla fruticosa* (shrubby cinquefoil) and *Salix* (willow) shrubs growing on it. The profile consists of an only 30-cm-thick colluvial loam (LOI = 9.1%) covering layers of aeolian loam and morainic sand (till). Periglacial processes have probably inserted a distinct amount of gravel (10%) into the layer of aeolian loam. Besides granulometrical properties (very badly sorted, high proportion of gravels and pebbles), the morainic facies of the lowermost layer representing a lateral moraine is clearly proven by geomorphological evidence of glacial activities in the surroundings (terminal moraines downvalley, active glacier upvalley). According to cosmogenic radionuclide and luminescence datings from neighbouring valleys, the terminal moraines were most probably formed in the Late Pleniglacial at around 15,000 BP (Owen et al., 2003). The aeolian loam and the upper part of the morainic sand form a buried Phaeozem (LOI = 8.4%) which contained charcoal of *Picea* dating to 8267 ± 72 BP (Table 2).

The third site, ca. 20 km NW of the Haibei Research Station, has been accessed by road construction cutting a valley flank. Profiles HAB 6A and HAB 6B (3275 m a.s.l.) are situated with only 15 m distance at the footslope of a northeast-facing ca. 150-m-high hill which is covered by a dense *P. fruticosa–Salix* shrubland. Both profiles consist of a sequence of colluvial and aeolian deposits overlaying fluvial gravel (Table 1, Fig. 2, Appx. 3). The up to 100-cm-thick colluvial layers of loam and silt contain a distinct amount of gravels and boulders (maximal 30 × 20 cm in size). Signs of a periglacial movement, such as solifluction lobes, were not detected. HAB 6B shows a peat separating two colluvial layers. A ca. 80-cm-thick buried (Gleyic) Phaeozem is a mutual feature of the aeolian layers. It contains lots of 'fresh' (uncharred) remains from *Picea* (trunks, stumps, branches, cones, needles, roots). Two wood pieces were dated to 5933 ± 53 BP (HAB 6A) and 6325 ± 55 BP (HAB 6B; Table 2). The gleyic properties and the preservation of woods could be the result of either water concentration at the footslope or of relic permafrost conditions.

3.2. Qinghai Lake area

The southern shore of the Qinghai Lake, Chinas's largest salty lake (4600 km^2, 3194 m a.s.l.; Yu and Kelts, 2002; station Gangca, 3302 m a.s.l.: MAAT = −0.6 °C, MAP = 370 mm; Miehe et al., 2001), is bordered by a ca. 100-km-long and up to 4500-m a.s.l.-high mountain range separating the lake depression and the southward-lying Gonghe basin (Fig. 1). Next to the southeast edge of the lake, a ca. 7-km-long pedogeomorphological transect was investigated connecting the shore via a pediment to a lower part of this mountain range (Fig. 4). Here, aeolian and colluvial sediments as well as slope deposits cover the bedrock of granite. With increasing altitude-depending precipitation, the soils alter from a Kastanozem association to a Chernozem–Phaeozem association. Close to the lake, the natural vegetation has been changed for agriculture. The mountain range is covered by pastures rich in sedges (*Kobresia*) and feather grasses (*Stipa*).

On the middle slope and footslope, three profiles consisting of colluvial layers burying paleosols were recorded. In Profile QIL 2, a 65-cm-thick 2Akb horizon (3512 ± 56 BP, dated on humin acids; Table 2) which is developed from aeolian silt forms a buried Chernozem (Fig. 4, Appx. 4). The buried Phaeozem of profile QIL 3 (56-cm-thick 2Ahb horizon, LOI = 8%) shows an increasing degree of stratification with increasing depth pointing to a

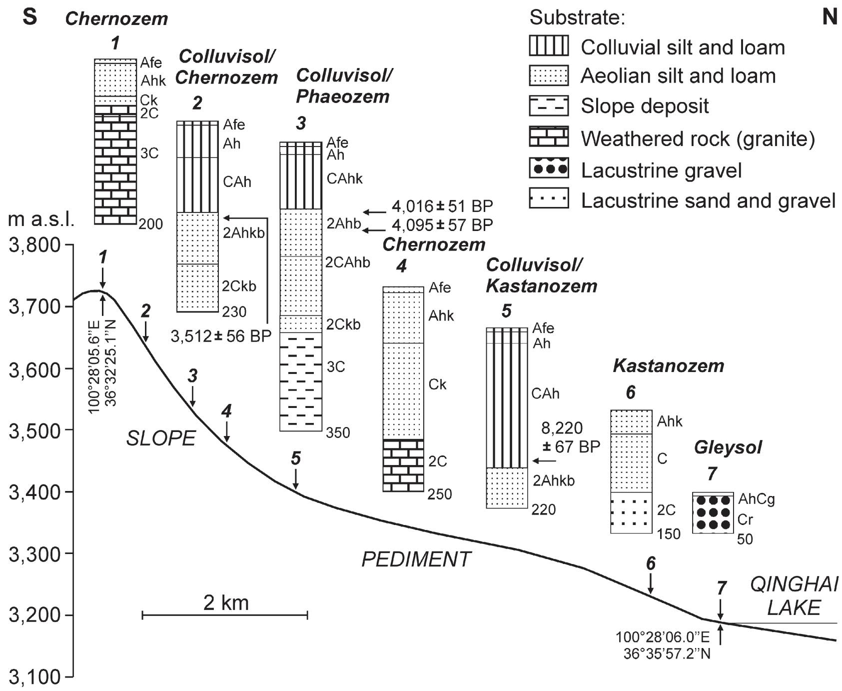

Fig. 4. Qinghai Lake transect.

syngenetic input of aeolian silt (Table 1, Fig. 2, Appx. 5). The soil data available combined with the Munsell chroma-value point to a transitional soil type from Phaeozem to (decalcified) Kastanozem. From the upper part of this paleosol, two radiocarbon datings on charcoal of *Picea* yielded ages of 4016±51 BP and 4095±57 BP (Table 2). The overlaying 84-cm-thick silty colluvial layer is rich in humus and sealed by sedge turf (LOI=22%) originating from *Kobresia*. Profile QIL 5 consists of 170-cm-thick colluvial silt overlaying a 50-cm-thick 2Ahkb horizon (Kastanozem; Fig. 2). The base of the colluvial layer dates to 8220±67 BP (*Picea* charcoal; Table 2).

3.3. Xinghai area

This site comprises a ca. 30-km-long pedogeomorphological transect (3100–4400 m a.s.l.) which has previously been described in detail (Kaiser, 2004; Fig. 1). Silty and loamy loesses are the predominant substrates of the surface. However, a high gradient of altitude-dependent precipitation (station Xinghai, 3,323 m a.s.l.: MAAT=0.9 °C, MAP=340 mm; Miehe et al., 2001) has caused a highly differentiated soil type pattern ranging from ('Salic') Kastanozems at semiarid sites via Chernozems at semihumid sites to Phaeozems at humid sites. Cambisols developed from debris and slope deposits as well as screes occur in the uppermost positions. Repeatedly, undated buried soils have been found in the loess-sections. Following the increase in altitude and precipitation, the vegetation changes from *Achnatherum splendens* pastures to alpine sedge-pastures dominated by *K. pygmaea*. Scattered trees of juniper at south-facing slopes and spruce at north-facing slopes occur.

Profile XIN 13 represents the colluvial infill of a brook valley lying at 3550 m a.s.l. (Table 1, Fig. 2, Appx. 6). The adjacent slopes are grown by *P. fruticosa* shrublands (northwest-facing) and *K. pygmaea* pastures (southeast-facing). The colluvial infill consists of a distinct layering of silt beds alternating rich and poor in organic matter. In the lower part, two concentrations of charcoal were dated to 6665±59 BP (250–270 cm, *Picea*) and 8155±63 BP (270–290 cm, *Juniperus*; Table 2).

3.4. Dulan area

This westernmost study area borders on the arid Qaidam-Depression (station Dulan, 3,191 m a.s.l.: MAAT=2.7 °C, MAP=179 mm; Miehe et al., 2001; Fig. 1). However, since the sites investigated are situated in mountain areas up to 4060 m a.s.l., a distinctly higher local rainfall can be assumed.

The first site represents a ca. 5-km-long pedogeomorphological transect located on a mountain ridge ca. 40 km NE of Dulan (Fig. 5). It connects a large river valley with the mountain top via a pediment. The braided river is only temporarily active. Outside the river bed, silty loesses widely cover the landscape except for rocky outcrops. Arenosols occur in coversand areas along the river bank. The lower part of the pediment is occupied by Solonchaks resulting in widespread salty precipitations on the ground surface. Kastanozems are developed on the middle slope and at the top. The vegetation changes from grass-rich *A. splendens* pastures along the river bank via a sparse Chenopodiaceae-shrub semi-desert (goosefoot species *Kalidium cuspidatum*, *Salsola arbuscula*) to an open juniper forest (*Juniperus*

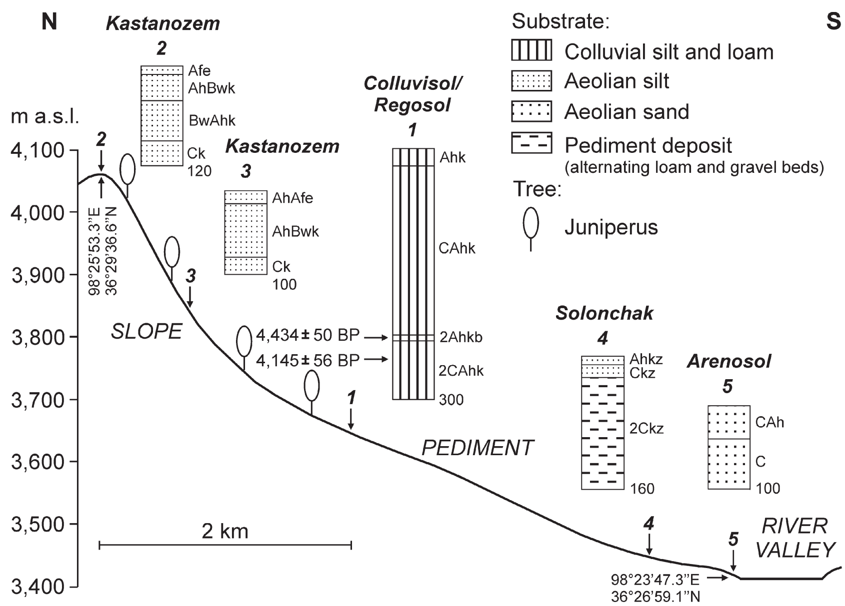

Fig. 5. Dulan transect.

przewalskii trees up to 12-m-high). The forest is grazed by domestic animals and bears traces of timber extraction.

Profile DUL 1 is located at the footslope (Table 1, Fig. 2). It consists of colluvial silt and loam relatively rich in organic content (LOI = 5.0–7.3%). A few sandy layers as well as gravels and boulders occur along linear concentrations. Observations on the present-day geomorphodynamics from the surrounding support the facies assumed. Remarkably, although only *Juniperus* covers the adjacent slopes at present, charcoal from *Picea* was extracted from the profile: On the one hand, an only 5-cm-thick 2Ahkb horizon (Regosol) yielded an age of 4434 ± 50 BP. On the other hand, charcoal pieces from the 2CAhk horizon beneath were dated to 4145 ± 56 BP (Table 2). The inversion in age is probably caused by the random way of erosion during colluvial processes. Nevertheless, both ages give reliable datings of the colluvial sedimentation and confirm the former existence of *Picea* in this catchment.

The second site is a single profile from a valley bottom lying ca. 40 km south of Dulan. This valley bears a temporarily flowing tributary of a major permanent river which flows to the Qaidam-Depression. Profile DUL 6 was recorded in a 20-m-wide and 5-m-deep gully at 3246 m a.s.l. The valley bottom is covered by sparse *A. splendens* pastures; surrounding west- and east-facing hills (100–200 m relative height) are grown by sparse grass-dominated pastures. The hills have thin layers of loess covering granite. In profile DUL 6, a 295-cm-thick layer of colluvial silts overlays a 5-cm-thick soil horizon (2AhCb) which have a small amount of humus only (Regosol) but lots of charcoal pieces (Table 1, Fig. 2). The colluvial facies of the topping sediment is clearly proven by some fluvial properties (sandy and gravely beds, ripples). A similar silt-dominated grain-size of the buried soil points to a colluvial origin as well. Here, the charcoal spectrum is dominated by *Salix* and supplemented by *Juniperus* providing an age of 6263 ± 83 BP (Table 2). The underlying layers down to 400 cm depth consist of fluvial-lacustrine sand and fluvial gravel.

Single profile DUL 9, representing the third site of this area, was recorded ca. 20 km E of Dulan. It lies at a north-facing upper slope (3662 m a.s.l.) just 15 m below the mountain top. The site is covered by a predominantly feather-grass pasture. Judging by the adjacent thickets of *J. przewalskii* and *Salix* growing at the same height and exposition, the local steppe represents a replacement vegetation. The profile consists of a topping layer of humic loam and a buried soil developed from loamy loess (Table 1, Fig. 2, Appx. 7). Both units lack particles > 2 mm. There is uncertainty with respect to the facies of the topping layer. All horizons analysed have a nearly identical grain-size distribution and bear calcium carbonate (5.1–9.5%). On the one hand, the distinct content of uniformly distributed organic matter (6.8%) could indicate a colluvial origin. On the other hand, location (upper slope) and granulometrical properties might alternatively be the expression for a loess sedimentation following a low-distance aeolian erosion. The buried soil is divided into an upper 2Ahb horizon (LOI = 8.5%) and a lower 2Ahgb horizon. Both horizons show a streaky and blurry distribution of amorphous humus. Charcoal of *Picea* was extracted from the 2Ahb horizon yielding an age of 3835 ± 59 BP (Table 2). The underlying 2Ahgb horizon, however, contained fossil (‘fresh’) wood remains of *Picea*. This well-preserved wood, the (relic?) stagnic properties and the mode of humus distribution indicate a (relic?) permafrost regime or long-term seasonally frozen ground. During the same field trip in July 2004, a Mollic Cryosol–frozen from 30 cm on downwards–was recorded in the Wulan area, located ca. 80 km to the NE

(3,671 m a.s.l., NE slope, *Picea crassifolia* forest, Fig. 1). According to Wang and French (1995), the Dulan–Wulan area borders on an area with 'alpine permafrost'. Consequently, the buried soil of profile DUL 9 is classified as (relic?) 'Gelic' Chernozem.

4. Discussion

Except for one doubtful record (DUL 9), the pedological and geomorphological parameters of the profiles investigated prove the widespread existence of colluvial layers overlaying paleosols in NE Tibet. The colluvial layers mainly consist of clayey silts and silty loams, rarely of silty sands. Layering was recorded frequently, but coarse matter (gravels, boulders) occurred only to a lesser extent. In general, field records and LOI values (2.4–16.7%) revealed a distinct organic content. Carbonate was detected only at the climatically drier sites Qinghai Lake and Dulan area ranging between 0.5% and 17.5%. In comparison to other colluvial facies such as mudflow and debris flow (Lehmkuhl and Pörtge, 1991; Shang et al., 2003), granulometry and location of the profiles point to low-energy slope erosion (hillwash).

The underlying and intercalated paleosols–the first mostly is developed from loess–are Phaeozems, Chernozems, Regosols and Fluvisols. This corresponds to Paleomollisols and Paleoaddendosols according to the paleosol classification by Nettleton et al. (2000). In some cases (e.g. HAB 6A, QIL 3, DUL 1), properties of both the buried soil and the surface soil–such as colour, organic content and thickness of A horizon–are quite similar probably reflecting comparable environmental conditions during soil formation.

The radiocarbon datings can be divided into *direct datings* of colluvial layers (HAB 5, QIL 5, XIN 13, DUL 1, DUL 6), providing *postdatings* for buried soils, and direct datings of buried soils (HAB 3, HAB 6A, HAB 6B, QIL 2, QIL 3), providing *predatings* for colluvial layers. However, the data represent only a *raw* framework for dating due to probable gaps (hiatuses) between dating material formation and soil formation on the one hand, and dating material formation and colluvial sedimentation on the other hand (Kaiser et al., 2006). In general, radiocarbon dating of charcoal raises no difficulties provided that there was no contamination by younger humic substances carried by groundwater or stagnant water (Alon et al., 2002). Thus the datings of some profiles (HAB 5, HAB 6A, HAB 6B, DUL 9) could contain an indeterminate error of rejuvenation. In contrast, radiocarbon dating on soil organic matter of buried soils (age on humic acids of profile QIL 2) could overestimate the true age of burial by as much as the steady-state age of the soil horizon (Wang et al., 1996). Taking these uncertainties for timing of colluvial processes into account, they took place between 8988 ± 66 and 4145 ± 56 BP comprising an interval of Early to Late Holocene. A similar age interval applies to the buried soils (8267 ± 72 to 3512 ± 56 BP). In both cases, there is a conspicuous lack of datings for the youngest part of the Late Holocene.

Colluvial processes require local disturbances of the soil cover (erosion) which can be triggered by natural causes (e.g. opening of the vegetation by desiccation and cooling) and/or human impact (e.g. forest clearing, agriculture). For the Tibetan Plateau, most of the studies on climate development have concluded a tendency from 'wet-warm' during the Early Holocene to 'dry-cold' during the Late Holocene both on a regional scale—comprising the Haibei and Qinghai Lake area (e.g. Da et al., 1989; Herzschuh et al., 2005; Shen et al., 2005), and on a supra-regional scale—comprising the whole Plateau (e.g. Starkel, 1998; Lehmkuhl and Haselein, 2000). However, there are records which contradict this conclusion, pointing to a complicate pattern of climatic *and* human-induced geomorphic responses in the landscape (see below). In some cases (HAB 5, QIL 5, partial XIN 13), our datings of colluvial layers fall into the Early Holocene and reveal local soil erosion in that time. So far, the paleoclimatic, geomorphological and archaeological records available allow no proper decision as to which cause (climate, geomorphological random, man) triggered erosion and produced colluvial layers at the study sites.

There are only a few comparable records on Holocene paleosols and colluvial processes in NE Tibet so far, whereby most of the geoscientific studies detecting paleosols dealt with glacial, periglacial and aeolian processes as well as tectonics (e.g. Lehmkuhl, 1995; Porter et al., 2001; Van der Woerd et al., 2002; Klinge and Lehmkuhl, 2005). In the Kunlun Pass area (4040 m a.s.l.), ca. 300 km SW of Dulan, a remarkable site with Late Pleistocene and Holocene hillwash bearing charcoal (3545 ± 90 BP, 3,475 ± 230 BP), ash and burned layers was found (Cui et al., 1995; Liu et al., 1999). The Holocene hillwash was connected to a Late Neolithic settlement occurring in the immediate vicinity at 3800 m a.s.l. Unfortunately, neither a determination of charcoal nor a precise pedological record was performed here. Furthermore, two sites with geoarchaeological records were detected next to Xining (Lajia site ca. 2290 m a.s.l., Fengtai site ca. 2540 m a.s.l.; Xu et al., 2003; Geldmacher et al., 2004). Both sites had occupations during the Neolithic and the Bronze Age leading to an intensive land use. In the Bronze Age, the associated clearing of the natural vegetation caused disastrous erosion, which led to a decline and colluvial coverage of both settlements.

A discussion whether natural or anthropogenic factors could have been the triggers of the erosional processes detected needs additional archaeological information. According to an evaluation of archaeological records from the Qaidam Basin, the first human occupation of NE Tibet is assumed at around 23,000–21,000 BP (Brantingham et al., 2003). Although several presumably Mesolithic sites have been discovered (Chayet, 1999; Aldenderfer and Zhang, 2004), the archaeology of NE Tibet between 10,000 and 6000 BP is essentially unknown. For the Late Holocene, however, several Neolithic sites comprising a so-called

'Neolithic cultural package' (domesticated plants and animals, ceramics, sedentary life; Aldenderfer and Zhang, 2004) were discovered east of the Qinghai Lake, dating between 3500 and 2800 BC (=ca. 4800–4200 BP; Chayet, 1999). Since the colluvial sediments detected date between 8988±66 and 4145±56 BP, but cluster around 9000–6000 BP, there is no stringent temporal correlation to a potential human impact. However, previous results of a running archaeological project from the south shore of the Qinghai Lake suggests–besides Late Pleistocene occupations (11480±60 to 10670±60 BP)–'a surprisingly early occurrence of potentially stable, food-producing communities in this region' (Olsen, 2004: 7). This assumption is based on an association of one Early Holocene radiocarbon date (8170±50 BP) with 'Neolithic' remains. Thus humans could have been responsible for erosion in the Early Holocene via land use. However, a confirmation of this single record would require further archaeological and geoscientific research.

The sites investigated also provided new insights into the former and present-day vegetation of NE Tibet. Comparing the sites with the 'Map of forest distribution' in the Atlas of Tibet Plateau (1990), isolated forests of *Picea* are only present E and S of Dulan. However, our own surveys and records made by Liu Jianquan and his team, Xining (Zhang et al., 2005), have detected present-day occurrences of *Picea* and *Juniperus* over a far more larger area (e.g. Xinghai area or NE of Dulan).

In the study area, *long-term* records on paleobotany and paleoclimatology covering the Late Quaternary are available only from Lake Luanhaizi and Qinghai Lake. Since ca. 45,000 BP, the pollen record of *Picea* from Lake Luanhaizi (Fig. 3) shows several maxima and minima caused by relatively warm/wet and cold/dry phases (Herzschuh et al., 2005). According to the pollen percentages, the growth of *Picea* around the lake is assumed for the time before the Last Glacial Maximum (ca. 45,000 BP) as well as for the Lateglacial and Early Holocene. The latter–but extended into the Mid-Holocene–is proven now by our charcoal and fossil wood record from the Haibei area (8988±66 to 5933±53 BP). A distinct decline of the *Picea* pollen curve was recorded for the Mid-Holocene, which is assumed to be for climatic reasons ('gradual decrease in moisture'). Unfortunately, the temporal resolution for the last 10,000 years is very low (only 2.6 m of Holocene sediments), thus preventing a clear record of both natural and possibly anthropogenic signals. Also from several loess–paleosol sequences of the adjacent Chinese Loess Plateau next to Lanzhou (1900–2000 m a.s.l., MAP=480–580 mm), *natural* fluctuations of the main ecotons steppe, forest steppe and coniferous forest were concluded palynologically for the Late Pleistocene (ca. 80,000 to 20,000 BP; Feng et al., 1998). However, Liu et al. (2005) denied an extensive forest coverage on the Chinese Loess Plateau during the past 130,000 years interpreting carbon isotopic signatures.

Frequently, sediment cores from the Qinghai Lake have been subjected to paleoenvironmental investigations (e.g. Da et al., 1989; Yu and Kelts, 2002; Zhang et al., 2003; Shen et al., 2005). However, the conclusions are still controversial. For instance, Da et al. (1989) outlined a vegetation history of the surroundings from steppe (11,000–10,000 BP), forest steppe (10,000–8000 BP), deciduous and coniferous forests (8000–3500 BP), shrub bearing steppe (3500–1500 BP) to steppe and desert (1500–0 BP). All vegetational changes were attributed to climatic changes; human impact was not considered. On the other hand, Yu and Kelts (2002) stated that the lake level during the Early Holocene was about 20 m shallower than today, indicating an effective moisture much *lower* than at present. Our charcoal records from the Qinghai Lake transect confirm the growth of *Picea* between 8220±67 and 4016±51 BP. Further to the (drier) west, in the Dulan area, dated charcoal (*Picea*: 4434±50 to 3835±59 BP, *Juniperus*: 6263±83 BP) and tree-ring records covering the last 2000 years (Yang et al., 2003; Sheppard et al., 2004) prove at least the Mid- to Late Holocene presence of trees.

In summary, the paleobotanical data confirm the widespread growth of tree species during the Holocene in NE Tibet. Furthermore, the present-day climatic parameters around Haibei, Qinghai Lake and Xinghai as well as in the high-lying surroundings east of Dulan point to a widespread *potential* natural growth of tree species (*Picea*, *Juniperus*) provided that human-induced disturbances (e.g. domestic animals, fire, timber extraction) are excluded. Records from climatologically comparable areas of southern and eastern Tibet support this view (Winkler, 1998; Miehe et al., 2003; Kaiser et al., 2006; Miehe et al., in press).

5. Conclusions

Silty and loamy colluvial deposits originating from low-energy slope erosion are widespread in climatologically different areas of NE Tibet (3200–3700 m a.s.l.). There are well-defined properties (layering, organic content, some coarse matter, location in the relief) to differentiate this hillwash from other colluvial facies such as mudflow and periglacial solifluction. The underlying and intercalated paleosols were classified as Chernozems, Phaeozems, Regosols and Fluvisols. In some cases, properties of both the buried soil and the surface soil are quite similar probably reflecting comparable environmental conditions during soil formation. Radiocarbon dating from colluvial layers and paleosols yielded ages between 8988±66 and 3512±56 BP comprising a time interval of Early to Late Holocene. There is a conspicuous lack of datings for the youngest part of the Late Holocene.

Natural or anthropogenic factors could have been the triggers of erosional processes causing colluvial sedimentation. However, a decision 'climate, random or man' for this region suffers from controversial paleoclimatic and geomorphic records as well as insufficient archaeological knowledge. Thus it remains unclear which cause is responsible for the formation of colluvial layers at the study sites.

The charcoal and fossil wood determinations revealed the Holocene occurrence of tree species (spruce, juniper) for areas which nowadays have no or only few trees. Furthermore, the present-day climatic parameters of the study sites points to a widespread *potential* natural growth of trees provided that human-induced disturbances are excluded. Consequently, large areas of NE Tibet which are at present steppes and alpine pastures were forested in the past.

The two processes derived–erosion and disappearance of forests–can be connected hypothetically. However, a sufficient number of local records and an identification of the chief causes (climate, geomorphological random, man) requires further research of different disciplines.

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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.catena.2006.04.028.

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