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RESEARCH ARTICLE

Black carbon record of the wildfire history of western Sichuan Province in China over the last 12.8 ka

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Abstract Wildfire is recognized as a critical Earth system process which affects the global carbon cycle, atmospheric chemistry, and ecosystem dynamics. Estimating the potential impact of future climate change on the incidence of fire requires an understanding of the long-term interactions of fire, climate, vegetation, and human activity. Accordingly, we analyzed the black carbon content and the pollen stratigraphy of sediments spanning the past 12.8 ka from Lake Muge Co, an alpine lake in western Sichuan Province, in order to determine the main factors influencing regional fire regimes. The results demonstrate that wildfires occurred frequently and intensively during the late deglaciation and the early Holocene when the regional vegetation was dominated by deciduous forests. Wildfire occurrence decreased significantly during the Holocene climatic optimum between 9.2 and 5.6 cal ka BP. Overall, the wildfire history of western Sichuan Province is similar to that of the Chinese Loess Plateau and of East Asia as a whole, suggesting that regional-scale fires depended mainly on changes in the intensity of the Asian summer monsoon. In addition, the fire regime of western Sichuan Province may have been influenced by the establishment of human settlement and agriculture in western Sichuan Province and the southeastern Tibetan Plateau after about 5.5 cal ka BP, and by an intensification of cereal cultivation coupled with population expansion in southwestern China during the last two millennia.

Keywords black carbon, wildfire, summer monsoon, human activity, Holocene, Lake Muge Co

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1 Introduction

Wildfire is widely recognized as a key environmental process in the Earth system. It influences the global carbon cycle, atmospheric chemistry and aerosols, as well as the structure of terrestrial ecosystems and biodiversity over multiple temporal and spatial scales, and hence imposing important feedback effects on climate (Conedera et al., 2009; Whitlock et al., 2010; Keeley et al., 2011; Marlon et al., 2013). In coming decades, many regions are expected to experience climatic warming which may lead to longer fire seasons and more frequent fires (Flannigan et al., 2009). However, fire regime is influenced by complex interactions between climate, fuels, and ignition (Whitlock et al., 2010), and thus there is a need for a long-term perspective to improve our understanding of wildfire history.

Fire history can be reconstructed from documentary records that extend back centuries, from dendrochronological data that span centuries to millennia, and from sedimentary records that can span several million years (Conedera et al., 2009; Whitlock et al., 2010). In the last few decades, an increasing number of studies have considered the influence of various natural and human drivers on biomass burning. For example, paleoenvironmental data from Europe, North America, and Australasia reveal that the evolution of fire history across these regions is closely related to temperature, with minimum temperatures limiting biomass production and thus the spread of fires (Power et al., 2008; Mooney et al., 2011; Marlon et al., 2013). In the Asian monsoon region, however, seasonal precipitation may be the most important driver of fire occurrence on orbital to millennial timescales (Yang et al., 2001; Wang et al., 2005, 2012), and, in addition, the fire regime may be modified by the spatial and temporal distribution of human activity during the Holocene (Tan et al., 2011, 2013, 2015; Wang et al., 2013). Complex fire patterns may reflect differences in the degree of climatic influences on vegetation changes, or contrasts in the settlement history of different regions (Marlon et al., 2013). Although there are an increasing number of studies of fire history from the Chinese Loess Plateau, relatively little is known about the interactions of fire, climate, vegetation, and human activity in southwestern China.

Here, we present a fire record for the last 12.8 ka from a lake sediment core from Muge Co on the southeastern margin of the Tibetan Plateau (TP), China. The fire history was reconstructed by analyzing the black carbon (BC) content of the sediments. BC is the by-product of the incomplete combustion of biomass, and comprises a continuum of carbonaceous material from char and charcoal to elemental or graphite carbon (Schmidt and Noack, 2000). In a given region, BC abundance is proportional to the total biomass burned (Marlon et al., 2006; Zhou et al., 2007). Due to its resistance to biochemical degradation, BC is unlikely to be subject to significant alteration once buried in sedimentary sequences (Bird and Gröcke, 1997). Therefore, BC abundance in geological deposits can be used as a geochemical marker of paleofires occurring in the surrounding area (Bird and Gröcke, 1997).

2 Regional setting

Muge Co (elevation 3,780 m a.s.l.) is an alpine lake in western Sichuan Province, southwestern China (Fig.1(a)). The lake is situated in a NW-SE-oriented valley in the Gongga Mountains, a mountain range in the Hengduan Mountains. Granitic bedrock occurs widely in the catchment. The lake has a surface area of 3.0 km^2, with the maximum water depth of ca. 31.4 m and a catchment area about 75 km^2. The lake is hydrologically recharged by seasonal snow melt derived from the higher altitude areas of the lake catchment, and by precipitation. There is an outlet on the northeastern side of the lake which flows into the Yala River.

The study region is located in the transition zone of the Indian and East Asian summer monsoons (Wang et al., 2003), and thus it exhibits a distinct seasonality of precipitation, i.e., wet in summer and dry in winter. Currently there is no weather station around the lake and the nearest station is Kangding Station (30°1'48″N, 101°34'48″E, 2,615 m a.s.l.) where the mean annual temperature is 7.2°C and the mean July temperature is 15.6 °C. The mean annual precipitation is ~ 830 mm, and the rainy season between May and September accounts for 77% of the total mean annual precipitation. In winter, dry and cold continental winds blow from Mongolia and Siberia over the TP. Currently the lake is ice-covered from December to February.

In the Hengduan Mountains, an intact and continuous vertical vegetation belt can be observed (Li et al., 2009). Below about 2,200 m most of the land is currently occupied by subtropical evergreen broadleaved vegetation. Between 2,200 and 2,800 m the vegetation types are temperate coniferous and broad-leaved mixed forest, with montane coniferous forest above 2,800 m. Between 3,600 and 4,200 m alpine frigid shrub and meadow vegetation dominate. Between the forest line and the snowline the vegetation consists mainly of alpine frigid meadow, alpine frigid sparse grassland, and alpine desert. Muge Co is situated close to the local tree line, and the surrounding vegetation is dominated by subalpine meadow containing alpine *Rhododendron* and *Salix cupularis*, together with sparse coniferous woodland consisting of *Picea*, *Larix potanini*, and *Abies*.

3 Materials and methods

3.1 Coring, sampling, and sediment dating

A 383-cm-long sediment core was obtained in 2011 from Muge Co using a Kullenberg Uwitech Coring Platform System. The water depth of the coring site was about 30 m (30.151°N, 101.856°E, Fig. 1(b)). In the laboratory the core sections were split longitudinally, photographed, and described visually. The lithology changes from brown fine silt in the lower part (383–323 cm) to dark brown silt between 323 and 140 cm, and to gray fine silt above 140 cm. From 331 cm to 323 cm the core may be affected by contamination from the upper part of the core. There are numerous white layers with the two thickest layers occurring at depths of 182–170 cm and 145–120 cm; the layers are dominated by silty clay. The core was sectioned at a 1 cm interval, yielding a total of 375 samples which were stored at 4°C prior to analysis.

The core chronology is based on AMS ^{14}C dating of 7 bulk sediment samples and one sample of concentrated pollen. The bulk sediment samples were dated by Beta Analytic Inc., Miami, USA, and the pollen sample was dated at the Oxford Radiocarbon Accelerator Unit, Oxford, UK. All of the 8 AMS ^{14}C dates obtained were calibrated to calendar years before present (0 BP = 1950 AD) using the IntCal13 calibration data set (Reimer et al., 2013).

3.2 Analytical methods

The sediment core was sampled at a 2-cm interval for measurement of BC content. BC was extracted using chemical oxidation (Lim and Cachier, 1996). About 1.0 g of dried, powdered sediment was subjected to removal of carbonate and part of the silicate fraction by acid treatment with 3 mol·L^{-1} HCl, 10 mol·L^{-1} HF/1 mol·L^{-1} HCl, and 10 mol·L^{-1} HCl, in sequence. The acid-treated samples were then oxidized using 0.2 mol·L^{-1} $K_2Cr_2O_7$/2 mol·L^{-1}

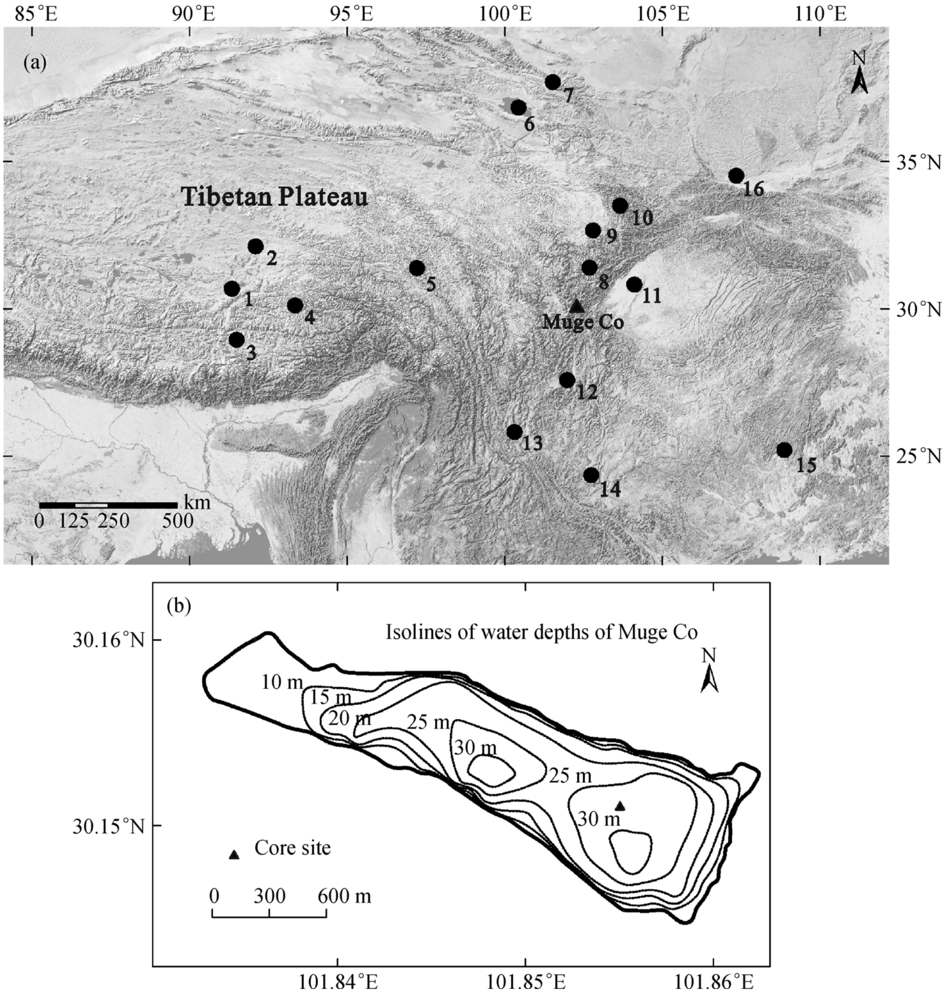

Fig. 1 (a) Location of Muge Co (triangle) and of paleoclimatic and archaeological sites mentioned in the text (circles): 1, Nam Co (Schütt et al., 2010); 2, Zigetang Co (Wu et al., 2007); 3, Chen Co (Zhu et al., 2009); 4, Puru Co (Bird et al., 2014); 5, Site Changdu Karuo (d'Alpoim Guedes, 2013); 6, Lake Qinghai (Shen et al., 2005); 7, Lake Luanhaizi (Herzschuh et al., 2006); 8, Site Yingpanshan (d'Alpoim Guedes, 2013); 9, Hongyuan peat bog (Hong et al., 2003); 10, Jiuzhaigou (Henck et al., 2010); 11, Site Baodun (d'Alpoim Guedes, 2011; d'Alpoim Guedes et al., 2013); 12, Lake Shayema (Jarvis, 1993); 13, Lake Erhai (Shen et al., 2006); 14, Lake Xingyun (Chen et al., 2014a; Wu et al., 2014); 15, Dongge Cave (Dykoski et al., 2005); 16, Site Liangjiayao (Tan et al., 2013). (b) Bathymetry of Muge Co and location of the coring site (triangle).

H_2SO_4 at 55°C for 60 h to remove soluble organic matter and kerogen. The remaining refractory carbon in the sample residue is operationally defined as BC. Dried samples were then ground and homogenized by crushing in an agate mortar. The BC content of the treated samples was determined using a Finnigan MAT Delta Plus mass spectrometer coupled with an elemental analyzer (Flash EA 1112). Replicate analyses of standard samples indicated a precision of 0.1%.

Pollen analysis was conducted at a 2-cm interval. The pollen samples were processed using successive treatment with HCl, KOH, and HF (Fægri et al., 1989). Tablets containing a known quantity of *Lycopodium* spores were added to each sample to determine the pollen concentration. The pollen samples were examined using a Zeiss microscope at a magnification of 10×40, and more than 400 terrestrial grains per sample were identified and counted in each sample. Terrestrial pollen percentages are based on the sum of total pollen grains excluding aquatic taxa. The deciduous broad-leaved trees, evergreen broad-leaved trees, and coniferous trees percentages are used to reflect the vegetation history.

4 Results

The AMS ^{14}C ages and the relationship between age and depth are shown in Table 1 and Fig. 2(a), respectively. The age-depth relationship is based on a linear interpolation between the radiocarbon-dated horizons, and the estimated

Table 1 AMS radiocarbon dates of organic materials from Muge Co. All of the AMS ^{14}C dates are calibrated to calendar years before present using the IntCal13 calibration dataset (Reimer et al., 2013)

Lab number	Sample depth/cm	Dated material	Conventional ^{14}C age/(yr BP±1σ)	$\delta^{13}C$/‰	2 σ calibrated age/(cal yr BP) (median probability)
Beta-306661	49.5	Bulk sediment	1760±30	−26.4	1568−1776 (1664)
Beta-306662	99.5	Bulk sediment	2400±30	−23.2	2348−2679 (2421)
Beta-308445	149.5	Bulk sediment	4170±30	−25.8	4584−4831 (4715)
Beta-306663	201.5	Bulk sediment	6140±30	−27.2	6951−7157(7049)
Beta-308446	249.5	Bulk sediment	7990±40	−25.9	8662−9005 (8868)
OX-2468-28	295.5	Pollen extract	8840±120	−25.7	9562−10198 (9910)
Beta-308447	330.5	Bulk sediment	9130±40	−24.2	10223−10405 (10275)
Beta-306664	372.5	Bulk sediment	10690±40	−22.8	12576−12715 (12661)

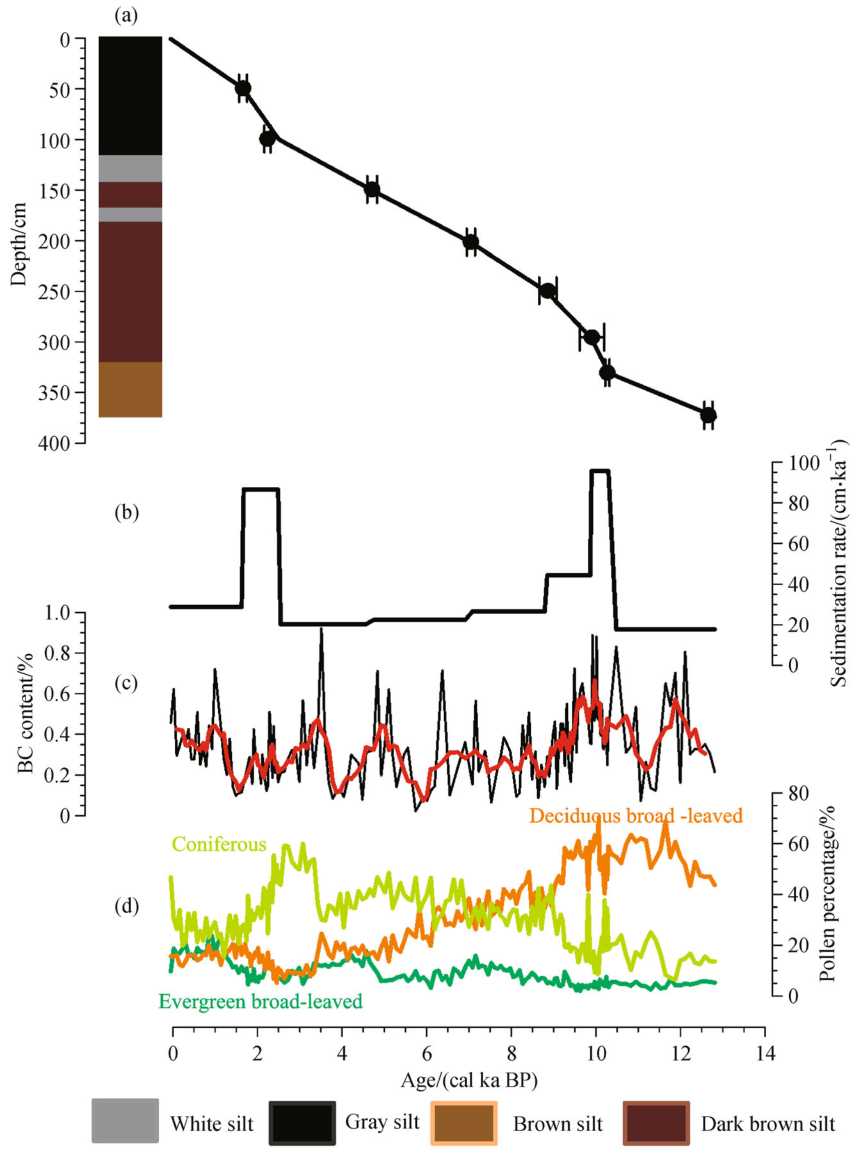

Fig. 2 Chronological model and stratigraphic variation of various proxy records from the Muge Co sediment core. (a) Lithology and age-depth model based on calibrated AMS ^{14}C dates (the disturbed layer was not included in the record- see text for further information); (b) sedimentation rate; (c) BC content (black line) and five-points running average (red line); and (d) pollen percentages of deciduous broad-leaved trees, evergreen broad-leaved trees, and coniferous trees.

basal age of the core is ~12.8 cal ka BP. The sedimentation rates vary from 17.6 to 95.9 cm/ka with a mean of 29.3 cm/ka (Fig. 2(b)). The sedimentation rates are relatively uniform, except for the interval from 10.3 to 8.8 cal ka BP and the interval from 2.5 to 1.7 cal ka BP. The BC content ranges from 0.02% to 0.92% with a mean of 0.33% (Fig. 2(c)). The BC content is relatively high from 12.8 to 9.2 cal ka BP with a mean of 0.44%; relatively low between 9.2 and 5.6 cal ka BP with a mean of 0.25%; and slightly higher after 5.6 cal ka BP with a mean of 0.3%. The pollen assemblages (Fig. 2(d)) are dominated by arboreal pollen. The deciduous broad-leaved tree pollen percentages range from 5.1% to 70.5% with a mean of 32.1%; evergreen broad-leaved tree pollen percentages range from 2.0% to 23.9% with a mean of 8.8%; and the coniferous tree pollen percentages range from 6.4% to 60.1% with a mean of 30.2%. The pollen spectra indicate that deciduous broad-leaved trees dominated the region from 12.8 to 9.2 cal ka BP, but then decreased gradually during the Holocene.

5 Discussion

5.1 The effect of changes in monsoon climate and vegetation on the fire history

Macroscopic charcoal reflects local fires, while both microscopic charcoal and BC are considered to be a long-distance transported component resulting from the incomplete combustion of biomass burning (Thevenon et al., 2010). On the TP, the steep altitudinal gradients can generate strong anabatic winds resulting in the transport of BC from the lower basins to the subalpine and alpine zones (Chen et al., 2007). Thus, variations in the BC content of the Muge Co sediments are likely to reflect changes in the regional occurrence of wildfires in western Sichuan Province. The wildfire history of the southeastern margin of the TP over the past 12.8 ka, as inferred from the BC content of the Muge Co sediments, is characterized by three stages: frequent and widespread wildfires from 12.8 to 9.2 cal ka BP, a low incidence of wildfires between 9.2 and 5.6 cal ka BP, and relatively frequent wildfires from 5.6 cal ka BP to the present.

On multidecadal-to-millennial time scales, changes in climate and vegetation play an important role in determining fire regime (Whitlock et al., 2010; Marlon et al., 2013). Climatic change can affect the occurrence of fire-weather, thereby influencing the burned area and influencing fire severity. Vegetation composition and distribution together determine the characteristics of the litter and the fuel type. Studies of modern fire regimes in southwestern China demonstrate that wildfire events frequently occur during spring, and are related to wind speed, duration of sunshine, and precipitation (Li et al., 2013; Chen et al., 2014b). Low precipitation with long rain-free intervals favor biomass burning as opposed to a climate with short rain-free intervals (Lafon and Quiring, 2012). In southwestern China the delayed onset of the Asian summer monsoon may prolong the length of the fire season and favor the desiccation of fuel, and then enhancing the occurrence and spread of fire. During the Younger Dryas, the climate was cold and dry in the Asian summer monsoon region due to the reduction in the Atlantic meridional overturning circulation and the resulting reduced heat transport (Fig. 3(d), Dykoski et al., 2005; Shen et al., 2005). It is possible that the weakened Asian summer monsoon during the last deglaciation was responsible for the frequent regional wildfires in the southeastern margin of the TP at that time. Although the climate became warmer and more humid in the early Holocene (Fig. 3(d), Dykoski et al., 2005), wildfires still occurred frequently in the region. Pollen records indicate that the vegetation cover in the early Holocene was dominated by deciduous broad-leaved forest (Fig. 3(e)). At Lake Shayema in southwestern China, *Betula* and deciduous *Quercus* flourished between 12.7 and 10.6 cal ka BP (Jarvis, 1993). Open conditions during spring facilitated the drying of fuel, thereby promoting the initiation of fires (Marlon et al., 2013). The broad distribution of deciduous forest may have strongly influenced both the extent and the intensity of fires during the last deglaciation and the early Holocene. In northern Alaska, a distinct increase in fire frequency between 14 and 13 cal ka BP was associated with the expansion of birch scrub, indicating that deciduous forest provides highly flammable fuel for fires (Higuera et al., 2009). Therefore vegetation and fuel are likely to have served as major determinants of the fire regime during the last deglaciation and the early Holocene.

The inferred low fire activity from 9.2 to 5.6 cal ka BP across the study region (Fig. 3(a)), is in accord with the occurrence of the Holocene climatic optimum in various records from the TP, which is suggested from 9–5.6 cal ka BP at Zigetang Co (Wu et al., 2007), from 9.6–5.2 cal ka BP at Nam Co (Schütt et al., 2010), from 10.1–5.2 cal ka BP at Puru Co (Bird et al., 2014), from 9–6 cal ka BP at Chen Co (Zhu et al., 2009) and Lake Luanhaizi (Herzschuh et al., 2006), from 10–6 cal ka BP at Lake Qinghai (Shen et al., 2005) and from 10.8–5.5 cal ka BP at Hongyuan peat bog (Hong et al., 2003). The slight differences in the timing and duration of the observed Holocene climatic optimum may be attributed to uncertainties in sediment dating related to the carbon reservoir effect (Hou et al., 2012). The early onset of the Asian summer monsoon shortened the duration of rain-free intervals, reducing the abundance of flammable fuel. In addition, the decrease in deciduous broad-leaved trees suggests that the forest was more luxuriant than during the early Holocene. It is also possible that limited fuel availability inhibited the occurrence and spread of fire during the Holocene climatic optimum.

The speleothem $\delta^{18}O$ record from Dongge Cave in

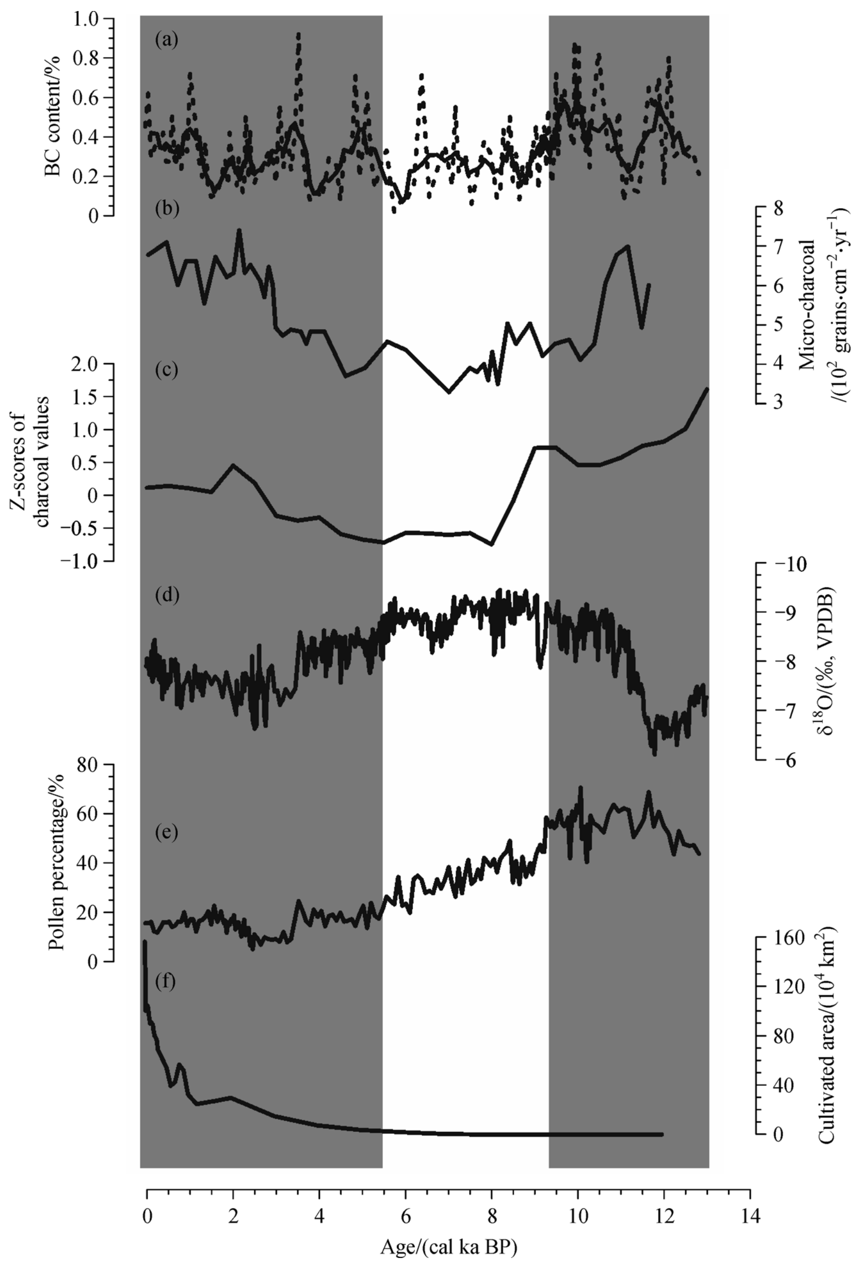

Fig. 3 Comparison of the BC and pollen records from the Muge Co sediments with other records during the last 13 ka: (a) BC record (black dotted line) and five-point running average (black line) from Muge Co (this study); (b) micro-charcoal influx at the site of Liangjiayao (Tan et al., 2013); (c) the East Asian average anomalies for the Z scores of charcoal values (Power et al., 2008); (d) speleothem $\delta^{18}O$ record from Dongge Cave in southern China (Dykoski et al., 2005); (e) deciduous broad-leaved tree pollen percentages from Muge Co (this study); (f) estimated changes in the cultivated area in China during the Holocene (Klein Goldewijk et al., 2011).

southern China exhibits a gradual increase towards heavier values, suggesting that the climate became drier in the late Holocene (Fig. 3(d), Dykoski et al., 2005). Multi-proxy records from Lake Xingyun indicate that mean annual precipitation gradually declined from 6 cal ka BP (Chen et al., 2014a). Pollen data indicate that the woodland was dominated by conifers, but that evergreen broad-leaved trees increased continuously (Fig. 2(d)). Spring drought-adapted sclerophyllous taxa were dominant components of the vegetation over the last 4.7 ka at Lake Shayema, indicating an increased seasonality of precipitation (Jarvis, 1993). The slightly increased amplitude of BC variations suggests that fire activity increased during this interval, probably caused by a weakened Asian summer monsoon

(Fig. 3(a)). From 2.5 to 1.7 cal ka BP, the high sedimentation rate (Fig. 2(b)) would have diluted the sedimentary BC content.

5.2 Effect of human activity on fires in the late Holocene

Although fire history is determined by a variety of natural climatic and vegetation factors, the human contribution to ignitions cannot be ignored due to the rapid growth of population in the late Holocene (Klein Goldewijk et al., 2011). Although the controlled use of fire by humans can be traced back to one million years ago, the exact effects of human activity on fire regimes are still not well understood (Marlon et al., 2008, 2013; Bowman et al., 2009; Berna et al., 2012). Human influences on burning can be distinguished through the compilation of archaeological and documentary evidence (Bowman et al., 2011). In Western Sichuan Province and the southeastern TP, the beginning of a strong human influence on the landscape is represented by important archaeological evidence from the sites of Yingpanshan (5.5–4.5 cal ka BP) and Changdu Karuo (5.7–4.3 cal ka BP) (Aldenderfer, 2007; d'Alpoim Guedes, 2013), corresponding to the expansion of the Majiayao Culture. Millet cultivation was the earliest form of agriculture in Western Sichuan Province, commencing at around about 5.5 cal ka BP and shortly afterwards spreading to the TP (d'Alpoim Guedes, 2013). Many different types of worked stone implements, such as axes, adzes, and sickles, as well as kilns for pottery making, have been unearthed in archaeological sites in western Sichuan Province and the southeastern TP (d'Alpoim Guedes, 2013), indicating that primitive agriculture and pottery manufacture were well-developed in the region. This deduction is supported by large earthen-walled sites belong to the early Baodun Culture (4.7–4.1 cal ka BP) in the Chengdu Plain, as well as the contemporaneous walled settlements associated with rice agriculture in the middle Yangtze valley (d'Alpoim Guedes, 2011). The plant remains recovered from these archaeological sites suggest that the introduction of rice into the Chengdu Plain — and that a system of combined rice and millet was formed — at around 4.7 cal ka BP (Fuller and Qin, 2009; d'Alpoim Guedes, 2011, 2013). Fires are widely used to clear forests for arable land and pasture, and to produce charcoal for brick making, cooking, and heating (Thevenon et al., 2010), and these anthropogenic burning activities produce a large amount of BC, as indicated by the increased BC content of the Muge Co sediments between 5.6 and 4.6 cal ka BP (Fig. 3(a)). Thus, it can be concluded that the fire regime in the region was significantly influenced by human activity since the late Holocene.

Both the human population and the extent of agricultural land increased sharply in China during the last two millennia (Fig. 3(f), Klein Goldewijk et al., 2011). As a result of rapid population growth, Han Chinese gradually migrated to and became established in southwestern China during the last two millennia (Elvin et al., 2002), and thus the region experienced significant forest clearance for agricultural purposes. Radiocarbon and optically stimulated luminescence dating of hillslope terraces developed on loess deposits within Jiuzhaigou National Park in northern Sichuan indicate that the modern landscape was formed from 2.2 ka BP (Henck et al., 2010). Deforestation and the introduction of traditional swidden agricultural cycles caused the loess sediments to lose cohesion, in turn causing slumping and the terrace risers to retreat uphill over time (Henck et al., 2010). The paleoecological record from Lake Shayema suggests that human disturbance of the landscape intensified during the last millennium (Jarvis, 1993). Lacustrine pollen and magnetic susceptibility records from Yunnan indicate that a dramatic increase in deforestation and soil erosion occurred in the past 2 ka (Shen et al., 2006; Dearing et al., 2008; Wu et al., 2014). Thus the widespread evidence for a sharp increase in the cultivated area in southwestern China in the past two millennia implies that the intensified human activity may have led to increased biomass burning.

5.3 Comparison with other regional wildfire records

The fire history of the southeastern margin of the TP, as inferred from the BC record from Muge Co, is generally similar to that of other parts of the Asian summer monsoon region during the early and middle Holocene when human activity was limited. The record of micro-char flux indicates that wildfire activity in the Guanzhong Basin of the Chinese Loess Plateau was high between 12 and 8.5 cal ka BP, was greatly reduced between 8.5 and 3.1 cal ka BP, and then gradually increased after 3.1 cal ka BP (Fig. 3(b), Tan et al., 2013). On a broader spatial scale, syntheses of charcoal data for East Asia indicate that fire frequency decreased significantly after 8 cal ka BP and increased in the late Holocene (Fig. 3(c), Power et al., 2008). However, the micro-charcoal record from Site Liangjiayao suggests that wildfires increased more significantly during the late Holocene on the Chinese Loess Plateau than that in western Sichuan Province (Tan et al., 2013). This spatial heterogeneity in fire activity is likely to be related either to differences in the intensity of human activity or to differences in climatic variability between the Loess Plateau and southwestern China.

6 Conclusions

The combination of BC and pollen records from Muge Co with other paleoclimatic proxies and archaeological evidence provides important information about the late deglaciation and Holocene wildfire history in the southeastern margin of the TP. The variations in BC content indicate that wildfires were frequent and intense from 12.8 to 9.2 cal ka BP, were reduced from 9.2 to 5.6 cal ka BP, and then intensified in the late Holocene. The general trend of wildfire history in the region is parallel to that of Asian summer monsoon intensity. In addition, the establishment of settlement and agriculture in Western Sichuan Province and the southeastern TP at about 5.5 cal ka BP, followed by population expansion and resultant deforestation and cultivation in the last two millennia, may also have played an important role in determining the fire regime. On a broader spatial scale, the general trend of wildfire history in the southeastern margin of the TP is similar to that of the Chinese Loess Plateau and other parts of the Asian summer monsoon region.

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