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Fifty years of Quaternary palynology in the Tibetan Plateau

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Abstract Quaternary palynology in the Tibetan Plateau (TP) was initiated in the 1960s to meet the needs of economic development in western China. Pollen analysis was conducted for the first time on a 200-m long core of Quaternary lacustrine sediments taken from the main body of the TP in order to study pollen assemblages as well as vegetation and climate changes of glacial (cold)/interglacial (warm) periods. Pollen analysis of alpine snow and ice began at the first scientific expedition to the TP in the 1970s. After the 1980s, a series of international collaborative programs were carried out under Sino-French, Sino-German, Sino-Australian, and Sino-American cooperation, marking the integration of Chinese Quaternary palynology society with the international community. New methods for Quaternary palynology were gradually promoted and applied, changing the vegetational and climatic interpretation of Quaternary palynology from qualitative to quantitative. Since the 1990s, many palynologists have carried out extensive Quaternary palynological studies on fossil pollen sites of more than 60 lakes/sections and alpine glaciers in the TP to discuss the spatiotemporal vegetation changes and climatic and environmental evolution of the TP since the Pleistocene. Over the past half-century, Quaternary palynology in the TP has contributed to the establishment of the Chinese Quaternary pollen database and the study of vegetation and climate evolution since the Last Glacial Maximum (LGM) in the TP. Currently available pollen records revealed the spatial and temporal distribution of vegetation in the TP since the LGM, exhibiting expansions and shrinkages of forest, meadow, grassland and desert in different periods such as the LGM, the last deglaciation, and Holocene optimum period. The paleomonsoon reflected by paleovegetation since the LGM has undergone the changes of weak-strengthening-strong-weakening but still active-shrinking, which is mainly affected by solar insolation.

Keywords Tibetan Plateau, Lake core, Ice core, Quaternary palynology, Paleovegetation, Paleoclimate

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1. Introduction

Quaternary palynology in the Tibetan Plateau (TP) was initiated in the early 1960s in response to the needs of economic development in western China. Over the past half-century, it developed from scratch with its study objects from sedimentary sections and lake cores to ice cores and its methods from qualitative to quantitative. After it experienced

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an arduous exploration process, a certain amount of modern and fossil pollen data was accumulated to reveal the evolutional process of vegetation and climate since the LGM. It is obvious that the study of Quaternary palynology in the TP is far from finished, and more extensive studies on issues of vegetation, climate, ecology, and environment are still needed in close cooperation with other disciplines. Here at the beginning of the second comprehensive scientific expedition of the TP, and on the 40th anniversary of the establishment of China Palynology Society, we look back on the path of Quaternary palynology in the TP, review and summarize previous work, and look forward to providing experiences and lessons for later work and further improvement of Quaternary palynology in the TP.

2. A hard start: Studying glacial (cold) and interglacial (warm) pollen assemblages

Quaternary palynology originated from pollen analysis of Quaternary peat, pioneered by Swedish palynologist Lennart von Post (1916). It started relatively late in China; it was not until the end of the 1950s that Quaternary palynology was carried out (Xu, 1956; Zhou et al., 1960). It was also in the early 1960s that Quaternary palynology in the TP initiated to meet the need of economic development in western China. In 1963, Mr. Yafeng Shi organized personnel to build a palynological laboratory at Lanzhou Institute of Glaciology and Geocryology and conduct field investigations on Quaternary geology and palynology in permafrost regions from Kunlun Mountain Pass to Amdo (500 km) along the Qinghai-Tibet Highway. During this expedition, thousands of Quaternary pollen samples were obtained from the 200-m lacustrine sedimentary section in the Kunlun Mountain Pass and the 203-m Quaternary lacustrine sedimentary core drilled near the Chumaer River at the source of the three rivers (the Yangtze River, Yellow River, and Lancang River). However, it was difficult to complete the pollen analysis of these samples. At that time, the country was in a period of economic difficulty, resulting in insufficient research funds and slow construction of the palynological laboratory. Scarce references and data of Quaternary palynology in the TP and lack of pollen assemblages from different Quaternary periods in western China also delayed the completion of this work significantly. In 1965, a paper on the Quaternary pollen assemblages of the Qinghai Lake region was published in *Acta Geographica Sinica* (Yang and Jiang, 1965). It would be the earliest paper on Quaternary palynology in the TP, and provided an important reference for pollen analysis of samples from the section and core mentioned above. Under the guidance of palynologists from the Beijing Institute of Botany, such as Ren Xu, Fuxiong Wang, Yulong Zhang, Yizhen Xi, Xiangjun Sun and Zhaochen Kong, the first study of Quaternary palynology in the main body of the TP was finally completed in 1975, after nearly ten years of effort (Tang and Wang, 1976a, 1976b).

Pollen analysis of samples from the lacustrine sediment profile and core showed that pollen assemblages dominated by *Picea*, *Betula*, *Ulmus* and *Corylus* reflected forest vegetation, indicative of the warm interglacial climatic environment. Pollen assemblages dominated by Chenopodiaceae, *Artemisia*, *Ephedra* and Poaceae reflected desert and semi-desert steppe vegetation, indicative of the cold and dry glacial climatic environment (Tang and Wang, 1976a, 1976b). At that time, understanding of Quaternary glacial (cold) and interglacial (warm) pollen assemblages in China had just begun; as there was a lack of accurate chronological data, Mr. Yafeng Shi would supplement the results above with the following: "Whether the spruce layer was deposited as an interglacial or a glacial accumulation was still open to debate. A comparison of past temperature conditions needed for the growth of spruce with modern temperature at Kunlun Mountain Pass supported that the spruce layer was considered as interglacial accumulation. However, pollen assemblages overlying and underlying the spruce layer dominated by Chenopodiaceae, *Artemisia*, and *Ephedra* reflected desert grassland, a dry environment, they lacked hardy plants to indicate a dry and cold environment opposite to a warm and wet environment reflected by the spruce layer. According to the general international rules of comparing Quaternary glacial periods with the pluvial periods and the interglacial periods with the interpluvial periods, the possibility of spruce was deposited during glacial periods cannot be ruled out unless we find some special reasons to explain why the precipitation in the interglacial periods are more than that in the glacial periods in the TP" (Tang and Wang, 1976a).

The debates on the characteristics of glacial/interglacial pollen assemblages in the TP continued until the 1980s. Pollen assemblages from Wudaoliang and Tuotuohe cores in the Kunlun Mountains and Tanggula Mountains showed that vegetation was replaced by xerophytic and hardy herbs and shrubs as temperatures dropped during the glacial periods of Quaternary, while the main plants of the interglacial periods, such as spruce and pine (*Pinus*), survived in the valleys. Overall, warm and cold climatic fluctuations in the TP were reflected in the alternation of arid steppe and forest-shrub steppe (Kong et al., 1981). Pollen assemblages from the Hadawan Formation and the upper Erlangjian Formation (mid-late Middle Pleistocene) in the eastern margin of Qinghai Lake were dominated by *Picea*, indicating cold climatic conditions, whereas pollen assemblages from the lower Erlangjian Formation contained *Picea*, *Pinus*, Cupressaceae, *Salix*, *Alnus*, *Quercus*, Poaceae, Rosaceae, and *Artemisia* pollen, indicating warm and wet interglacial climatic conditions (Yang and Jiang, 1965). Pollen record from a core taken in Qinghai Lake revealed that vegetation at 11–10 ka BP (ka BP=^{14}C ka BP, uncalibrated ^{14}C age) was coniferous and broadleaved mixed forest consisting of *Picea*, *Pinus*, and *Betula*, implying warm and humid climatic conditions, and vegetation after 10 ka BP was steppe composed of Poaceae, *Artemisia*, Chenopodiaceae, and *Nitraria*, indicating cold and dry climatic conditions (Du et al., 1989). During the late Pleistocene, pollen flora of warm periods in the Qaidam Basin was coniferous and broadleaved mixed open forest and brushwood dominated by *Pinus*, whereas pollen flora of cold periods was brush-desert steppe dominated by *Ephedra* (Shen et al., 1990). In Qarhan Salt Lake, pollen spectra at 25 ka BP were dominated by Chenopodiaceae pollen, exhibiting halophytic shrub landscapes, while pollen spectra at 20–15 ka BP reflected desert vegetation consisting of *Ephedra*, Chenopodiaceae, *Artemisia*, and *Nitraria*. Both vegetation types indicated dry and cold climatic conditions (Du and Kong, 1983). Cold and dry climatic conditions appeared at 70–48 ka BP in the northern Dalijia Mountains of eastern Qinghai, dry steppe environment reflected by pollen spectra of paleosols in Xining, Guide, Xuanhua, and Linxia occurred at 23–14 ka BP, and forest-meadow suggested by pollen spectra with *Populus* and *Salix* pollen appeared at 12–8.5 ka BP in Maduo, Xinghai, and Gonghe (Pan and Xu, 1989). Pollen spectra of the last glaciation in Linxia were mainly composed of *Picea*, *Abies*, *Ulmus* (Li et al., 1988). In Xunhua of Qinghai, pollen assemblages of paleosols at 5.2 ka BP reflected dark conifer forest as well as cold and wet climatic conditions, while pollen assemblages of paleosols at 3.4 ka BP exhibited pollen features of shrub steppe with sparse trees, indicating mild and wet climatic conditions (Tang et al., 1990). In Hongyuan and Maqu of Zoige Basin and Dangxiong of Xizang, pollen spectra of the early Holocene peats were dominated by Cyperaceae, indicating alpine meadows and cold-wet climatic conditions; small pieces of brush occurred within alpine meadows during the mid-Holocene, implying warm and humid climatic conditions (Wang et al., 1981; Wang, 1987; Wang et al., 1996).

The characteristics of glacial (cold)/interglacial (warm) pollen assemblages in northeastern TP can be summarized from the above studies as follows: Glacial (cold period) pollen assemblage was Chenopodiaceae-*Artemisia*-*Ephedra* (Poaceae), which reflected cold and dry climatic conditions. Interglacial (warm period) pollen assemblage was *Betula*-*Quercus*-Rosaceae (*Ulmus*)-Poaceae (*Artemisia*), which reflected warm and wet climatic conditions. The coniferous forest dominated by spruce reflected mild and humid climatic conditions during the glacial/interglacial transitions or interstadials. Note that it was a phase understanding before the 1990s. Since the 1990s, many palynologists have carried out extensive studies on Quaternary palynology in various areas of the TP (Table 1; Figure 1), and made significant progress in the studies on the paleovegetation and paleoclimate of the TP.

It should be pointed out that the initial stage of Quaternary palynology in the TP suffered from a lack of funds and a shortage of research personnel. Relatively behindhand techniques of pollen analysis, such as disorganized sampling at large intervals, less accurate dating data, smaller pollen counting number, and using pollen percentage data mainly for qualitative interpretation instead of quantitative studies using numerical methods, resulted in unsophisticated studies and phase understandings in Quaternary palynology of the TP at this stage.

3. Trekking hand in hand: Chinese and western scientists cooperated to study paleovegetation and paleoclimate in the TP

Led by Mr. Tungsheng Liu, academician of the Chinese Academy of Sciences (CAS), and Dr. Donald Walker, professor at the Australian National University, a Sino-Australian Quaternary collaborative project was started in 1981. The collaborative findings were published in the *Journal of Biogeography* and the Proceedings of the Sino-Australian Quaternary Symposium (Walker, 1986; CAS Sino-Australian Quaternary Research Group, 1987). The project greatly promoted the studies of Quaternary palynology in the TP and its surrounding regions as well as China, marking the beginning of the integration of Chinese Quaternary palynology with the international community. In 1988, Prof. Xiangjun Sun organized a youth workshop of Quaternary palynology in Qingdao, lectured by Prof. Walker and Dr. Peter Kershaw, professor at Monash University. This workshop had a certain influence on young palynologists in China, many of whom would become the main force of later studies of Quaternary palynology in the TP. New techniques of Quaternary palynology were continuously popularized and applied, and Quaternary palynology in China gradually improved in accuracy.

In the late 1980s, Chinese and French scientists conducted a joint program on Quaternary lakes in northwest TP. Chinese scientists included research Profs. Bingyuan Li and Cixuan Huang from the Institute of Geographic Sciences and Natural Resources Research, CAS, and Prof. Fubao Wang from Nanjing University. French scientists included Dr. Elise Van Campo of the University of Paris, and Dr. Elise Van Campo from the Laboratory of Quaternary Geology, Faculte des Sciences de Luminy. The results of the joint program (e.g., Gasse et al., 1991; Van Campo and Gasse, 1993; Huang et al., 1996) brought great influence to the palynology of late Quaternary in the TP, especially the northwest of TP; A/C (*Artemisia*/Chenopodiaceae) ratio was used as a humidity/dryness proxy in the TP for the first time.

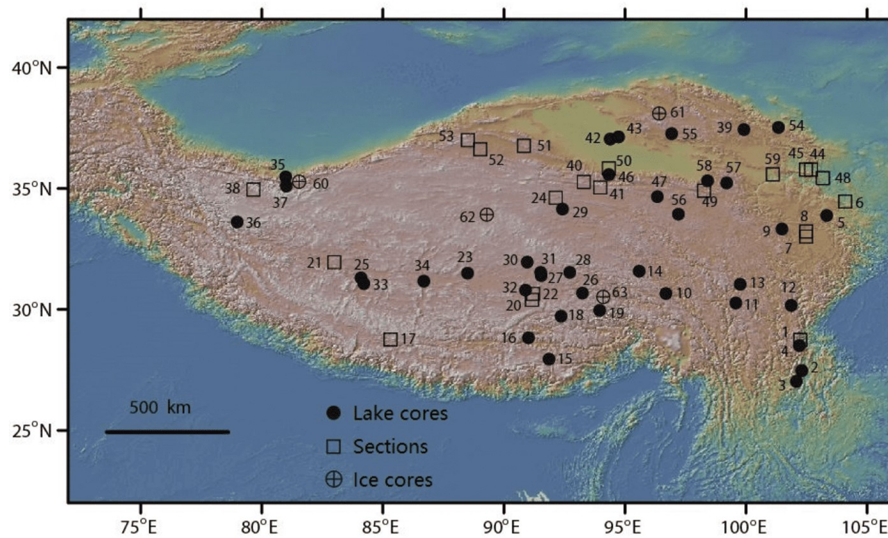

Figure 1 Location of selected sites of Quaternary palynology in the TP.

The Sino-American Quaternary collaborative project was started in 1994, by a Quaternary palynology team led by Prof. Lingyu Tang of Nanjing Institute of Geology and Paleontology, CAS, and a paleomonsoon team led by Dr. Kambiu Liu, professor of Louisiana State University, and Dr. Jonathan T. Overpeck, professor of the University of Arizona. It was supported by four projects from the National Natural Science Foundation of China and the United States. 4 visits to Tibet for the expeditions of vegetation, topsoil sample collection, and coring 9 medium-sized lakes were conducted during this cooperation more than 10 years. The vegetation history of the TP and evolutionary history of the southwest monsoon during the last deglaciation and Holocene were studied using these lake sediments (Overpeck et al., 2005), and the quantitative reconstruction of paleovegetation and paleoclimate, as well as a comprehensive study of multiple proxies, were emphasized (Shen, 2003; Tang et al., 2004, 2009b; Morrill et al., 2006; Shen et al., 2006, 2008a, 2008b).

The Sino-German Cooperation (2008–2015) was supported by the Pilot Project (Category B) of the Chinese Academy of Sciences, projects of the National Natural Science Foundation of China, and the German DFG priority program. Led by Dr. Liping Zhu, professor at the Institute of Tibetan Plateau Research, CAS, and Dr. Roland Mäusbacher, professor of Jena University, the Sino-German team consisting of members Xinmiao Lu, Qingfeng Ma, and others, made a detailed investigation of large lakes such as Nam Co and Tangra Yum Co and conducted pollen analysis of lake cores to reveal the evolution of the southwest monsoon and the history of the interaction between the monsoon and the westerlies over the TP in the past 20,000 years (Ma et al., 2014, 2019; Zhu et al., 2015).

In these cooperative studies, Quaternary palynology in the TP gradually reached international standards in the methodology, evidence, and understanding of pollen analysis. Pollen concentration, pollen influx and other techniques gradually became commonly used, and various climate proxies, such as A/C ratio and the numerical analysis of pollen data, were widely used in pollen analysis. As for the standard of evidence, the comprehensive study of multiple proxies was emphasized and awareness on the importance of modern pollen processes for the reconstruction of paleovegetation and paleoclimate was increased.

4. From qualitative to quantitative: Trekking on way to quantitatively reconstruct paleovegetation and paleoclimate

In the early 1960s, paleobotany played an important role in the studies of the uplift of the TP. Fossils of *Quercus semicarpifolia* were discovered in the lower part of the Pliocene Yepokangale group on the northern slope of Xishapangma by Mr. Yafeng Shi, Tungsheng Liu and others in 1964; they would speculate the occurrence of an uplift by at least 3000 m of the northern slope of Xishapangma since the Pliocene (Shi and Liu, 1964; Xu et al., 1973). However, a number of Chinese and foreign scholars would question this inference in the 1990s, as the usage of qualitative data as a quantitative explanation was considered unscientific. This debate incentivized Chinese palynologists to pay more attention to the development of methodology in Quaternary pollen analysis from qualitative to quantitative. The Palynological Society of China (PSC) held a workshop on the statistical analysis of Quaternary pollen data in 1988, but

Table 1 List of selected sites of Quaternary palynology in the TP

Region	Number	Site name	Latitude	Longitude	Altitude (m a.s.l.)	Time span (ka cal. BP)	No. of ^{14}C dates	Reference
			28°44′N	102°14′E	2250	4.0–6.1	5	Liu and Wang, 1984
	1	Lake Yihai	27°30′N	102°20′E	3660	0–7	1	Li and Liu, 1988
	2	Lake Dahaizi	27°05′N	102°04′E	3660	0–12	3	Li and Liu, 1988
	3	Lake Honghai	28°35′N	102°13′E	2453	0–11	5	Jarvis, 1993
	4	Lake Shayema	33°57′N	103°21′E	3400	0–1740	19	Liu et al., 1995; Shen C M et al., 2005;
	5	Zoige	33°21′N	100°24′E	4360	0–8	21	Liang et al., 2020; Zhao et al., 2020
	6	Nianbaoyuzeshan	33°05′N	102°30′E	3492	0–12	9	Schlütz and Lehmkuhl, 2009
Eastern TP	7	Hongyuan	32°46′N	102°31′E	3506	0–13.8	32	Wang et al., 1996
	8	Wasong	33°15′N	102°30′E	3490	0–30	9	Zhou et al., 2010
	9	Ximen Co	33°23′N	101°28′E	4020	0–2	0	Wang et al., 1996
	10	Ren Co	33°23′N	101°06′E	4000	0–19	24	Yang, 1996
	11	Lake Yidun	30°43′N	96°40′E	4450	0–18.8	7	Herzschuh et al., 2014
	12	Muge Co	30°18′N	99°33′E	4500	0–13.3	3	Tang et al., 1998, 2004
	13	Lalong Co	30°13′N	101°83′E	3780	0–12.2	8	Shen et al., 2006, 2008b
	14	Lake Butuo	31°06′N	99°45′E	4200	0.1–17.7	11	Ni et al., 2019
			31°36′N	95°35′E	4682	1.8–11.1	3	Kramer et al., 2010a, 2010b
								Zhang Y et al., 2015
				91°50′E	4760	ca. 2–7	2	Huang et al., 1983
	15	Nariyong Co	28°00′N	91°00′E	4450	ca. 2–8	1	Huang et al., 1983
	16	Chen Co	28°50′N	90°29′E	4420	3.2–10.7	8	Lu et al., 2011
Southern TP	17	Peiku Co	28°58′N	85°20′E	4590	5–12.5	3	Huang, 2000
	18	Lake Hidden	28°50′N	92°22′E	4980	0–13	7	Tang et al., 2000a, 2004
	19	Basong Co	29°48′N30°01′N	93°55′E	3476	0–0.9	6	Li et al., 2017
			30°31′N	91°10′E	4370	0–10	3	Wang et al., 1981
	20	Dangxiong	32°00′N	83°00′E	4400	0–5	1	Huang et al., 1983
	21	Zhalunchaka	30°40′N	91°10′E	4675	ca. 5–8	1	Huang et al., 1983
	22	Cuole	31°34′N	88°31′E	4530	0–11	4	Sun et al., 1993
	23	Selin Co	34°38′N	92°09′E	4670	0–20	2	Shan et al., 1995
	24	Goulong Co	31°21′N	84°04′E	4421	0–36	3	Xiao et al., 1996
	25	Lake Chabyer	30°45′N	93°15′E	4400	0–5	2	Tang et al., 1998
	26	Zela Co	31°31′N	91°30′E	4510	0–2800	12	Lu et al., 2001; Shen et al., 2008a
Central TP	27	Co Ngion	31°37′N	92°42′E	4580	4–9.2	52	Shen, 2003; Tang et al., 2009b
	28	Ahung Co	34°10′N	92°25′E	5200	0.4–4.2	4	Tang et al., 2009b, 2016
	29	Tanggula Mt. Pass	32°00′N	90°54′E	4560	0–10.5	5	Herzschuh et al., 2014
	30	Zigetang Co	31°57′N	90°20′E	4595	0.1–8.3	4	Shen, 2003
	31	Xuguo Co	30°50′N	90°54′E	4718	2–24	36	Li et al., 2011; Zhu et al., 2015
	32	Nam Co	30°55′N	90°53′E	4730	0–120	9	Wu et al., 2004; Herrmann et al., 2010
	33	Taro Co	31°08′N	84°13′E	4566	0–10.2	12	Ma et al., 2014
	34	Tangra Yum Co	31°14′N	86°43′E	4545	0–17.5	28	Ma et al., 2019
	35	Sumxi Co	35°30′N	81°00′E	5058	0–14.8	6	Van Campo and Gasse, 1993
Western TP	36	Bangong Co	33°40′N	79°00′E	4241	0–10.8	35	Van Campo et al., 1996
	37	Longmu Co	35°10′N	81°00′E	5008	ca. 2–5	1	Huang et al., 1996
	38	Lake Tianshuihai	35°01′N	79°40′E	4597	17–240	4	Liu G X et al., 1998
			37°28′N	99°56′E	3196		0	Yang and Jiang, 1965
	39	Lake Qinghai	36°33′N	100°47′E	3196		3	Du et al., 1989
	40	Chumaer River	36°42′N	100°36′E	3200	Pleistocene 0–11	6	Liu et al., 2002; Shen J et al., 2005
	41	Kunlun Mt. Pass	35°20′N	93°15′E	4400	0–16	0	Tang and Wang, 1976a, 1976b
	42	Qarhan Salt Lake	35°05′N	94°00′E	5000	Pleistocene	0	Tang and Wang, 1976a, 1976b
	43	Lake Biele	37°05′N	94°25′E	2680	Pleistocene 4–31	6	Du and Kong, 1983
	44	Xunhua	37°10′N	94°45′E	2680	Pleistocene ca. 1–8	0	Du and Kong, 1983
	45	Mengdashan	35°50′N	102°40′E	2530	ca. 1–4	2	Tang et al., 1990
	46	Lake Bunan	35°50′N	102°30′E	2795	Pleistocene 25–700	0	Tang et al., 1990
	47	Budongquan	35°40′N	94°20′E	4876	0–150	0	Shan et al., 1995
	48	Yuanbao	34°13′N	93°56′E	4854	0–10.4	0	Liu, 2010
Northern TP	49	Maduo	35°30′N	103°10′E	2040	0–44	0	Ma et al., 1995
	50	Xiaonanchuan	34°58′N	98°15′E	4220	ca. 5–11	2	Zhang et al., 1995
	51	Lake Xiaoshazi	35°50′N	94°21′E	4500	ca. 2–13	3	Xu et al., 1996
	52	Beilikekule	36°47′N	90°50′E	4106	ca. 4–7	2	Huang et al., 1996
	53	Aqikekule	36°40′N	89°00′E	4680	0–45	2	Huang et al., 1996
	54	Lake Luanhaizi	37°03′N	88°30′E	4250	0–12.7	1	Huang et al., 1996
	55	Lake Keluke	37°35′N	101°21′E	3200	0–14.9	10	Herzschuh et al., 2005
	56	Lake Koucha	37°17′N	96°54′E	2817	0.2–22	6	Zhao et al., 2007
	57	Lake Kuhai	34°00′N	97°12′E	4540	1.1–19	5	Herzschuh et al., 2009
	58	Donggi Cona	35°18′N	99°12′E	4150	0–10	17	Wischnewski et al., 2011
	59	Kaiyan	35°21′N	98°26′E	4090		19	Wang Y et al., 2014
			35°39′N	101°06′E	3780		11	Miao et al., 2015
	60	Guliya	35°17′N	81°29′E	6710	0–15.9		Yao, 2000
TP	61	Dunde	38°06′N	96°24′E	5325	0–11		Liu K B et al., 1998
	62	Purougangri	33°53′N	89°16′E	5900	−0.05–0.1		Yang et al., 2008; Tang et al., 2009a
	63	Ruoguo glacier	30°30′N	94°05′E	5100	Modern		Tang et al., 1983

only introduced simple techniques of data processing used by foreign scholars without any cases used by Chinese palynologists. In the winter of the same year, the PSC held a meeting in Beijing for palynologists to prepare for the establishment of the Chinese Quaternary Pollen Database. At this meeting, Mr. Tungsheng Liu, Mr. Yafeng Shi, Prof. Kam-biu Liu, and Dr. Eric Grimm (the author of Tilia software, the research professor at the Illinois State Museum) were invited to be present for guidance. At the meeting, the work of major regions in China was assigned to groups led by the Beijing Institute of Botany, Nanjing Institute of Geology and Paleontology, and Sun Yat-sen University. "Numerical Methods in Quaternary Pollen Analysis" by Birks and Gordon (1985) was translated into Chinese by Caiming Shen and Lingyu Tang and published in 1991. The book introduced pollen data types and presentation techniques, numerical methods of processing modern and fossil pollen data, and quantitative methods of fossil pollen data interpretation in Quaternary pollen analysis. On the basis of the collection of pollen data by various units, the founding meeting of China Quaternary Pollen Database (CPD) was held in Sweden in 1997. At the meeting, most of the Chinese palynologists provided available Quaternary pollen data in China; Drs. Kam-biu Liu (the United States), Sandy P. Harrison (Sweden), Rachid Cheddadi and Joel Guiot (France) were also invited as Quaternary Pollen Database experts to give guidance. After the meeting, several papers on paleovegetation reconstruction and simulation of the mid-Holocene and the LGM in China, as well as vegetation mapping at 6 ka BP, were published using CPD (e.g., Yu et al., 1998, 2000; Sun et al., 1999). This meeting marked a major step forward for the quantitative studies of Quaternary pollen analysis in China.

The early quantitative studies were conducted only in the 1980s-90s in northern China (Lu, 1989; Shen and Tang, 1992; Song et al., 1997) and the middle and lower reaches of the Yangtze River (Tang et al., 1993). Attempts were made to reconstruct paleoclimate using pollen-climate transfer functions, but the procedure was not applied to Quaternary palynology in the TP until the late 1990s and the early 21st century (Tang et al., 1999; Shen, 2003; Shen et al., 2006, 2008a; Herzschuh et al., 2010; Lu et al., 2011; Wang Y et al., 2014; Zhang, 2015; Liang et al., 2020; Zhao et al., 2020). One of the most important factors affecting quantitative reconstructions was the lack of modern pollen training databases. Modern pollen rain studies are the basis of quantitative reconstruction of paleovegetation and paleoclimate, but no such studies were done in the early stage of Quaternary palynology in the TP. Modern pollen rain studies would not appear until the 1990s (e.g., Huang et al., 1993; Weng et al., 1993; Wu and Xiao, 1995; Cour et al., 1999), and it was not until this century that relevant studies were widely carried out (e.g., Yu et al., 2001; Shen et al., 2006; Herzschuh et al., 2010; Lu et al., 2011; Wang Y et al., 2014; Liang et al., 2020).

Using 227 topsoil pollen samples in the TP, Shen et al. (2006) studied the quantitative relationship of modern pollen rain and climate in the TP, determined mean annual precipitation (MAP) and July temperature as climatic parameters controlling modern pollen rain, developed pollen-climate transfer functions, and reconstructed quantitatively paleovegetation and paleoclimate since the LGM in the catchments of Ren Co, Co Ngion, and Hidden Lake of Xizang and Lake Yidun of western Sichuan. For instance, reconstructed paleoclimate since 17.3 cal. ka BP in the catchment of Lake Yidun showed that the MAP maximum occurred between 9.0 and 7.5 cal. ka BP when MAP was 100–120 mm higher than the present, and July temperature peaked at 6.5 cal. ka BP when it was 1.0–1.2 higher than today (Tang et al., 2004; Shen et al., 2006). The modern pollen training dataset used in that study consisted of pollen samples from moss-polsters, and linear and non-linear models were used to develop transfer functions and obtain reliable quantitative reconstructions. However, uneven spatial distribution of modern pollen training data, due to the collection of modern moss samples along roads and the inconsistency in the sedimentary environment between modern and fossil pollen, raised uncertainties on the quality of the reconstructions. Herzschuh et al. (2010) developed pollen-climate transfer functions using modern pollen data of 112 lake surface sediment samples, and reconstructed quantitatively paleoclimate in the catchment of Lake Luanhaizi in the northeastern TP. Their results showed that climate during the MIS3 was similar to that of today, MAP during the LGM was 300 mm less than the present and mean annual temperature (MAT) was 2°C lower than the present, MAP at 13–7 cal. ka BP was 70 mm higher than today, and MAT was 0.5°C higher than today. Although their modern pollen training data was collected from lake sedimentary environments consistent to that of fossil pollen, the small dataset brought more uncertainties, limiting the application of quantitative reconstruction. Lu et al. (2011) analyzed a pollen dataset consisting of 1,202 topsoil samples using canonical correspondence analysis (CCA) to determine major environmental factors influencing modern pollen distribution, and quantitatively reconstructed Holocene climate in the catchment of Chen Co of southern TP. Climatic conditions in the catchment of Chen Co were warm and dry with MAT 0.8°C higher than today at 10.7–9.0 cal. ka BP, which was followed by wet climatic conditions with MAP 30 mm higher than the present at 9.0–6.1 cal. ka BP; climatic conditions became dry again at 6.1–3.2 cal. ka BP. The modern pollen training dataset used in Lu et al. (2011) was sourced from moss polsters and topsoils, so there was still inconsistency in sedimentary environments between modern and fossil pollen. However, a huge modern pollen training dataset and multiple models used in developing transfer functions improved the reliability of reconstruction. Wang Y et al. (2014) used modern pollen data from 53 lakes to quantitatively reconstruct precipitation changes since 19 cal. ka BP in the catchment of Donggi Cona of northeastern TP. The results showed that MAP was the lowest at 19–18.3 cal. ka BP and climatic conditions were the wettest with an average MAP of 334 mm at 13.1–9.5 cal. ka BP. Zhang Y et al. (2015) quantitively reconstructed Holocene MAP and MAT changes in the catchment of Lake Butuo of eastern TP. Their results indicated humid climatic conditions at 11.1–8.7, 8–6, and 5.6–1.8 cal. ka BP, as well as cold and dry climatic conditions at 8.7–8 and 6–5.6 cal. ka BP. Modern pollen training datasets used in these two studies above were relatively small and thus limited their application in quantitative reconstruction. Quantitative reconstructions of paleoclimate using many fossil pollen records and pollen-climate transfer functions showed climatic conditions characterized by the optimum early or middle Holocene and cold/dry late Holocene since the last deglaciation in the TP. Recently, an integrated study on pollen-based quantitative reconstructions of paleoclimate at 50-year resolution was carried out (Chen et al., 2020), which showed that the warmest summer temperature of the early and middle Holocene occurred in 9–5 cal. ka BP, followed by a gradual decrease in temperature. This result is consistent with the enhancement of summer solar insolation and southwest monsoon (Chen et al., 2020). Zhao Yan's team made an attempt to build a comprehensive pollen-based method framework using the Holocene quantitative temperature reconstruction on the eastern TP as a case study. Their study showed that Holocene temperature on the eastern TP was not only related to solar insolation but also solar activities (Liang et al., 2020). This attempt laid a certain foundation for the establishment of a quantitative reconstruction method system in terms of the selection of modern pollen database, training dataset, climate factors, and models. Studies of quantitative paleoclimate reconstructions so far have revealed that WA-PLS (Weighted Average-Partial Least Squares Regression) was the better model among linear and non-linear models in the TP.

It should be pointed out that multivariate statistical methods such as principal component analysis (PCA) and detrended correspondence analysis (DCA) based on linear and non-linear models were also widely used in paleovegetational and paleoclimatic interpretations of Quaternary pollen data in the TP. For example, PCA of Holocene pollen record from Lake Keluke in Qaidam Basin revealed desert-steppe dominated by *Artemisia* at 11.9–9.5 cal. ka BP, desert dominated by Chenopodiaceae at 9.5–5.5 cal. ka BP, and desert-steppe dominated by *Artemisia* and Poaceae after 5.5 cal. ka BP (Zhao et al., 2007). DCA and PCA were conducted on pollen records from Zigetang Co in central TP and Lake Koucha in northeastern TP respectively to study MAP and July temperature and recover paleovegetation (dry/cold alpine desert-steppe, semi-humid/warm steppe, and humid/cold alpine meadow) during the different periods since the last glacial in the catchments of lakes (Herzschuh et al., 2006, 2009). Additionally, as an example of the application of numerical methods in modern pollen and climate data, Lu et al. (2008) used 598 topsoil pollen samples in the TP to study the correlation of the distribution of *Abies* and *Picea* pollen to the spatial changes of vegetation, climate, and altitude. Nowadays, numerical methods are widely used in paleovegetation and paleoclimate reconstructions of pollen analysis, greatly improving the level of Quaternary palynology in the TP.

From qualitative to quantitative, there have been great leaps of progress in Quaternary palynology on the TP. The TP is the least human-disturbed region in China, and thus is an ideal region for the study of modern pollen processes. Pollen-based quantitative reconstruction of paleoclimate in the TP has accumulated a very solid foundation in the aspects of numerical methods, model selection and other techniques, and a relatively complete quantitative reconstruction system will eventually be developed with the steady accumulation of modern pollen training dataset in the TP. Due to a relative lack of studies on pollen production and modern pollen processes, such as pollen transportation and deposition, quantitative reconstruction of paleovegetation still needs to be strengthened.

5. Broadening a new field: Carrying out pollen analysis of snow/ice in alpine glaciers

Pollen analysis of snow/ice mainly studies environmental changes reflected by pollen assemblages of surface snow, snow pits, and ice cores from polar and alpine glaciers. Foreign palynologists have been applying pollen analysis to the study of modern glaciers since as early as the 1930s–1960s (e.g., Erdtman, 1936; Godwin, 1949; Ambach et al., 1966). Pollen records of ice cores were first studied as environmental and paleoclimatic proxies in polar ice core studies by European scientists (e.g., Fredskild and Wagner, 1974; McAndrews, 1984; Short and Holdsworth, 1985; Bourgeois, 1986). In the late 1980s, American scientists obtained climate-sensitive pollen records from tropical ice cores, thus marking the start of the decadal, interannual, and even seasonal pollen-based paleoclimate reconstruction of non-polar ice cores with high deposition rates (Thompson et al., 1988, 1995; Liu K B et al., 1998). Non-polar glaciers in the TP are close to pollen sources (i.e., regional vegetation) and have high pollen influx conducive to the effective reconstruction of paleovegetation and paleoclimate. Pollen analysis of snow/ice in China started during the first large-scale scientific expedition in 1975. The glacial group led by

Mr. Jijun Li (Lingyu Tang responsible for pollen analysis) took pollen samples from firn layers of snow pit (9-m thickness) and surface snow in Ruoguo glacier terminal, Xizang. Pollen was collected via evaporation technique in the Palynological Laboratory of Lanzhou Institute of Glaciology and Geocryology, CAS. The changes of pollen assemblages in late summer and winter layers and annal firn layers of Ruoguo Glacier during 1972–1975 were analyzed to study vegetation changes in different seasons around Ruoguo Glacier and the sources of avalanches in summer (Wang and Tang, 1980; Tang et al., 1983). This was the first study on the TP snow and ice pollen in China, but at that time, there was no systematic study on pollen records of ice cores to quantitatively reconstruct paleoclimate during glacial accumulation.

In the late 1980s, Dr. Tandong Yao considered a cooperation with Drs. Lonnie G. Thompson, Kam-biu Liu and other foreign scientists to conduct high-resolution pollen analysis on the ice cores of alpine glaciers from the TP. Up to now, systematic palynological studies of ice cores in the TP have been carried out, with a series of results obtained, from three glaciers: the Guliya ice core (308.6-m in length at the elevation of 6710 m) in northwestern TP, the Dunde ice core (140-m in length at the elevation of 5325 m) in northeastern TP, and the Purougangri ice core (80-m in length at the elevation of 5900 m) in central TP (Liu K B et al., 1998; Yao, 2000; Yang et al., 2008; Tang et al., 2009a).

The 30-year (1957–1986) pollen record from the Dunde ice core in northeastern TP revealed that total pollen concentration was correlated positively with summer precipitation and negatively with summer temperature in the Qilian Mountains, and its Holocene pollen record showed high pollen concentrations between 10 and 4.8 cal. ka B.P., suggesting that the summer monsoon extended beyond its present limit to reach Dunde (Liu K B et al., 1998). This was the first pollen analysis on a non-polar ice core in China.

The pollen record from the Guliya ice core revealed the history of vegetation and climate change over the past 12 ka in the northwestern TP. High percentages of Chenopodiaceae pollen reflected an arid environment before 11.5 cal. ka BP. The increase of *Artemisia* pollen at 11.5–9.5 cal. ka BP indicated a relatively humid environment. During 9.5 - 6.5 cal. ka BP, the significant increase of grass pollen implied the expansion of steppe, which might be caused by the increase of monsoonal precipitation due to the strengthening of summer monsoon. After 6.5 cal. ka BP, Poaceae pollen decreased significantly, indicating that climatic conditions returned to arid environment again. Vegetation and climate after 1.9 cal. ka BP were close to the present (Yao, 2000; Huang et al., 2019).

The pollen spectra of the Puruogangri ice core recorded the succession process of vegetational development since the 15th century, from cold and arid desert-steppe to cold and humid meadow-steppe, and then to warm and arid steppe. Pollen percentages of main pollen taxa in the pollen record were positively correlated with observational summer temperature over central TP; temperature changes for recent 150 years were thus inferred from pollen record. The 1870s, 1890s, and 1990s were high temperature periods with a temperature 1.9°C higher than the present, while the 1860s, 1880s, and 1950–70s were relatively cold periods. Over the past 100 years, the gradual warming in the late 20th century was significantly related to MAT of the whole TP, and was consistent with the glacier shrinkage recorded in the TP (Yang et al., 2008; Tang et al., 2009a).

In recent years, Shugui Hou's team has been carrying out pollen analysis of the No. 4 ice core (a bottom-penetrating ice core with 216.6-m in length located at 35°14′57″N, 81°5′28″E with elevation of 6105 m, about 30 km away from the Guliya ice core) in the Chongce Ice Cap of West Kunlun Mountains and surface snow samples of Geladaindong (Hou, 2019). The second scientific expedition to the TP will aim to produce higher level results via increased utilization of pollen analysis of snow/ice in the TP. Pollen analysis of snow/ice has not only broadened the field of Quaternary palynology in the TP, but also provided a useful method for the comprehensive study of multiple disciplines on glaciers in the TP.

6. Reconstructing paleovegetation: Studying spatiotemporal changes of vegetation in the TP since the Pleistocene

Since the large-scale scientific expedition to the TP in the 1970s, Mr. Yafeng Shi, Honglie Sun, Jijun Li and others have attached great importance to the reconstruction of paleovegetation in the TP since the Late Cenozoic. Vegetation succession as a program has been included in all major scientific research projects on the TP. For instance, Mr. Honglie Sun, the leader of the scientific expedition team to the TP, asked Lingyu Tang to introduce Quaternary pollen analysis at the team training meeting (Chengdu) in 1975; during the expedition, Mr. Jijun Li took Lingyu Tang and others to climb Ruoguo glacier and collect pollen samples. At the summary meeting (Lanzhou) of the National Climbing Program "Research on the formation and evolution, the environment change, and ecological system of the Tibetan Plateau" in 1995, the environmental evolution over the last 900 ka indicated by pollen records of RH and RM cores in the Zoige Basin was discussed. In 1996, Mr. Yafeng Shi called the national researchers who were engaged in the Quaternary palynology of the TP together, in Nanjing, to collect and summarize research results of Quaternary palynology in the TP, and a special collection of 12 papers was published in *Acta Micropalaeontologica Sinica* summarizing the spatiotemporal changes of vegetation in the TP since the late Cenozoic. Vegetation succession was included in the book "Late Cenozoic Uplift and Environmental Change of the TP", edited by Yafeng Shi, Jijun Li and Bingyuan Li, in 1998 (see Shi et al., 1998, p314–331). In 2001, a 2.8-Ma pollen record from Co Ngion in central TP revealed, for the first time, the processes of tectonic uplift and vegetational and environmental changes in the plateau interior above 4500 m since the end of the Pliocene (Lu et al., 2001). It is one of the oldest Quaternary pollen records in the main body of the TP, affirming that pollen analysis can provide continuous and reliable evidence for directly reflecting the processes of plateau uplift and vegetational and climatic changes in the TP. In 2020, Zhao Yan′s team made a breakthrough in the study of vegetation and climate over 1.74 Ma based on a long core in the Zoige Basin (Zhao et al., 2020), which further attracted the attention of the world to Quaternary palynology in the TP. However, the Quaternary palynology of the TP over the past 50 years was primarily focused on lacustrine pollen records since the late Pleistocene.

6.1 Vegetation succession since the last deglaciation in southeastern TP

Pollen records from Lakes Dahaizi and Shayema in Luoji Mountain, western Sichuan reflected vegetational changes in the southeastern margin of the TP. The coniferous and broadleaved mixed forest dominated by *Pinus* and *Quercus* occurred at 12.4–11 ka BP. Forests consisting of *Abies*, *Betula*, and deciduous *Quercus* developed at 11–9.1 ka BP in the catchment of Lake Shayema in Mianning, western Sichuan. Evergreen *Quercus* and *Tsuga* increased at 9.1–7.8 ka BP, indicating a warm and humid climate. Sclerophyllous forests expanded 7.8–4.0 ka BP, suggesting seasonal enhancement of rainfall. The pollen concentration of all plant taxa, especially *Pinus*, *Tsuga*, and sclerophyllous *Quercus*, decreased at different degrees, and was indicative of the deterioration of climate and the intensification of human activity. Since 2.0–1.0 ka BP, sclerophyllous forests have developed until now in the catchment of Lake Shayema (Li and Liu, 1988; Jarvis, 1993).

Pollen records from Lake Yidun in western Sichuan and Ren Co in southeastern Xizang reflected vegetational changes since the LGM in the southeastern TP. Desert-steppe dominated by Chenopodiaceae, *Artemisia*, Poaceae, and Cyperaceae occurred in the catchment of Lake Yidun at 20–12.4 cal. ka BP. Vegetation at 12.4–11.5 cal. ka BP was alpine forest-steppe consisting of *Artemisia*, Poaceae, Cyperaceae, *Pinus*, *Abies* and *Picea*. Vegetation changed from steppe to forest at 11.5–9.2 cal. ka BP, and then (9.2–6.8 cal. ka BP) to coniferous and broadleaved mixed forest dominated by *Betula* and *Pinus*. During 12.4–5.7 cal. ka BP, the pollen record of Ren Co was characterized by a significant decrease of Chenopodiaceae pollen and an increase *Betula* pollen, indicating alpine forest steppe landscape in the catchment of Ren Co. Forest vegetation was dominated by *Pinus* with a continuous increase of *Quercus* at 6.8–2.5 cal. ka BP, and oak forest expanded from 2.5 cal. ka BP to the present in the catchment of Lake Yidun (Tang et al., 2000a, 2004, 2009b; Shen et al., 2006, 2008b).

6.2 Vegetation succession since the last Pleistocene in southern TP

Pollen records from Lake Hidden, Nariyong Co, Chen Co, Peiku Co, and Dangxiong Section in southern TP showed that pollen percentages of *Artemisia*, Poaceae, and Cyperaceae were high at 12.4–11.4 cal. ka BP, with few *Pinus*, *Abie*s and *Picea*, reflecting alpine forest-steppe. At 11.4–9.4 cal. ka BP, *Artemisia* pollen decreased and Cyperaceae pollen increased with few *Pinus* and *Betula* pollen, showing alpine meadow vegetation or alpine shrub meadow vegetation. After 9.4 cal. ka BP, *Betula* and *Pinus* pollen increased, reflecting the gradual transition from alpine shrub meadow to coniferous and broadleaved mixed forest. At 8.0–3.0 cal. ka BP, *Betula*, *Quercus*, *Tsuga*, Rosaceae, Ericaceae pollen increased, and forest-shrub meadow landscapes appeared. From 3.0 cal. ka BP to the present, arboreal pollen decreased significantly or disappeared, while shrub pollen increased and herbaceous pollen accounted for up to 73–89%, indicating a shrub steppe vegetation. (Wang et al., 1981; Huang et al., 1983; Huang, 2000; Tang et al., 2000b, 2004, 2009b; Lu et al., 2011).

6.3 Vegetation succession since the Pleistocene in middle eastern TP

Pollen records from RM and RH cores, as well as Wasong and Hongyuan sections in the Zoige region of middle eastern TP (Liu et al., 1995; Wang et al., 1996; Shen et al., 2005), reflected vegetation succession since the middle Pleistocene; the pollen spectra of the last interglacial and interstadials of 190–18 ka BP were dominated by *Picea*, *Abies*, and *Pinus* with high pollen concentrations, reflecting the occurrence of spruce-fir forest and warm-wet climatic conditions. The pollen spectra of the LGM were composed of Chenopodiaceae, Cyperaceae, Poaceae, and *Artemisia* with very low pollen concentrations, indicating vegetation of desert-alpine screes and cold-dry climatic conditions. However, some samples contained relatively high percentages of long-distance transport arboreal pollen, such as *Pinus* and *Quercus*, which caused difficulties with the quantitative interpretation of pollen spectra. The pollen spectra of stadials were dominated by Cyperaceae and Poaceae, reflecting alpine and subalpine sedge meadow vegetation and climatic conditions of stadials between the LGM and the last interglacial. During the last deglaciation of 18–15 ka BP, subalpine spruce-fir forest reappeared. At 15–10 ka BP, the pollen of broadleaved and sclerophyllous plants such as *Betula*, *Quercus*, *Corylus*, and *Hippophae* reached a high value, implying that forest expanded and alpine meadows retreated. During 10 to 9.4 ka BP, the pollen spectra were dominated by Cyperaceae with some *Artemisia*, Asteraceae, *Abies*, *Picea* and *Betula*, indicating that meadow vegetation still developed with mosaic distribution of spruce-fir forest, and swamps widely grew in the foothills and lowlands. From 9.4 to 4.0 ka BP, the dark coniferous forest dominated by *Abies* and *Picea* spruce reached the Holocene maximum. After 4.0 ka BP, subalpine meadows and shrub meadows expanded and tended to swamping.

6.4 Holocene vegetation succession in central TP

Pollen records from lakes (Selin Co, Chabyer Lake, Zigetang Co, Ahung Co, Xuguo Co, Co Ngion, and Lake Tanggula Mt. Pass) showed that pollen spectra at 11.0–9.6 cal. ka BP contained low pollen concentrations and consisted mainly of Asteraceae, *Artemisia*, and Chenopodiaceae, reflecting alpine sparse vegetation. Cyperaceae and *Artemisia* pollen increased at 9.6–8.5 and 7.5–6.0 cal. ka BP, while more Pinus pollen and fern spores appeared at 8.5–7.5 cal. ka BP, suggesting that steppe/meadow vegetation at 9.6–6.0 cal. ka BP replaced alpine sparse vegetation at the previous phase. At 6.0–3.8 cal. ka BP, Cyperaceae and *Artemisia* pollen increased with some *Pinus* and *Abies* pollen, and pollen concentration reached its Holocene maximum, indicative of steppe vegetation. The appearance of *Picea*, *Tsuga*, and *Alnus* at 3.8–2.4 cal. ka BP and an increase in arboreal pollen, especially *Pinus*, suggested an occurrence of steppe-shrubland in the central-south of central TP (Selin Co and Chabyer Lake). In the central-north of central TP (Zigetang Co, Xuguo Co, and Lake Tanggula Mt. Pass), vegetation gradually changed from steppes to marsh meadows dominated by Cyperaceae at 4.0–3.0 cal. ka BP, and returned to steppes again after 3.0 cal. ka BP (Sun et al., 1993; Shen, 2003; Shen et al., 2008a; Herzschuh et al., 2006; Tang et al., 2009b).

6.5 Holocene vegetation succession in western TP

Pollen records from Sumxi Co, Longmu Co, and Bangong Co in northwestern TP showed that pollen spectra were dominated by Chenopodiaceae and *Ephedra* of desert components and contained the lowest Holocene pollen concentrations at 12.7–10.0 cal. ka BP, in which *Potamogeton* and Cyperaceae pollen found in sediments at 12.7–12.5 cal. ka BP reflected the beginning of marsh environment. The Younger Dryas event occurred at 11.0–9.9 cal. ka BP. The highest A/C values at the early period of 9.9–7.7 cal. ka BP indicated an increase of vegetation cover. Very low pollen concentrations, high percentages of Chenopodiaceae, monotonous plant species, and very low vegetation cover reflected desert vegetation and cold-dry climatic conditions at 9.9–9.6 cal. ka BP. Pollen concentrations and percentages of *Artemisia*, Poaceae, and Cyperaceae increased, suggesting a steppe vegetation at 9.6–7.8 cal. ka BP. Vegetation of 7.8–3.5 cal. ka BP was still a steppe. From 3.5 cal. ka BP to the present, pollen spectra were dominated by *Ceratoides latens* and *Ajania* pollen increased, implying that vegetation changed from a steppe to a desert (Van Campo and Gasse, 1993; Van Campo et al., 1996; Huang et al., 1996).

6.6 Vegetation succession since the early Pleistocene in the adjacent region of Gansu and Qinghai in northeastern TP

Vegetation succession since the early Pleistocene in the adjacent region of Gansu and Qinghai in northeastern TP was revealed by pollen records in Qaidam Basin (Du and Kong, 1983; Shen et al., 1990), Qinghai Basin (Yang and Jiang, 1965), Qinghai Lake (Liu et al., 2002; Shen J et al., 2005), Gonghe Basin (Tang and Wang, 1988), Hoh Xil (Li et al., 1994; Shan et al., 1995), and Kunlun Mt. Pass and its adjacent region (Tang and Wang, 1976a, 1976b; Xu et al., 1996; Yang, 1996). For example, the pollen record from Qinghai Lake showed high pollen percentages of *Artemisia*, the occasional appearance of *Betula* pollen, low pollen percentages of *Ephedra*, and low pollen concentration, which suggested steppe or forest-steppe vegetation in the catchment of Qinghai Lake. At 10.8–8.5 cal. ka BP, an increase in pollen concentrations, as well as *Betula* and Cyperaceae pollen, indicated a significant increase in precipitation and temperature around the lake. Coniferous plants such as *Picea* and *Abies* replaced *Betula* and became dominant pollen taxa at 8.5–7.8 cal. ka BP, reflecting cold and dry climatic conditions. At 7.8–4.5 cal. ka BP, *Pinus* and *Picea* pollen increased at the cost of *Artemisia* pollen, and regional vegetation evolved into forest-steppes. During the 10.8–4.5 cal. ka BP, regional vegetation in general consisted of forests or forest-steppes, reflecting warm and wet environment of Holocene optimum period. At 4.5–2.5 cal. ka BP, pollen concentrations decreased, *Pinus* pollen gradually declined, *Picea*, *Abies*, and *Betula* pollen appeared sporadically, *Artemisia* pollen increased dramatically, and regional environment evolved to cold and dry climatic conditions. After 2.5 cal. ka BP, pollen concentrations increased, and regional vegetation evolved into steppes dominated by *Artemisia*, Poaceae, and Cyperaceae while climate was still relatively cold and arid (Liu et al., 2002; Shen J et al., 2005).

Available studies (Figure 2) showed that steppe/desert vegetation developed in southeastern and eastern TP in the early period of the last deglaciation, and then changed to

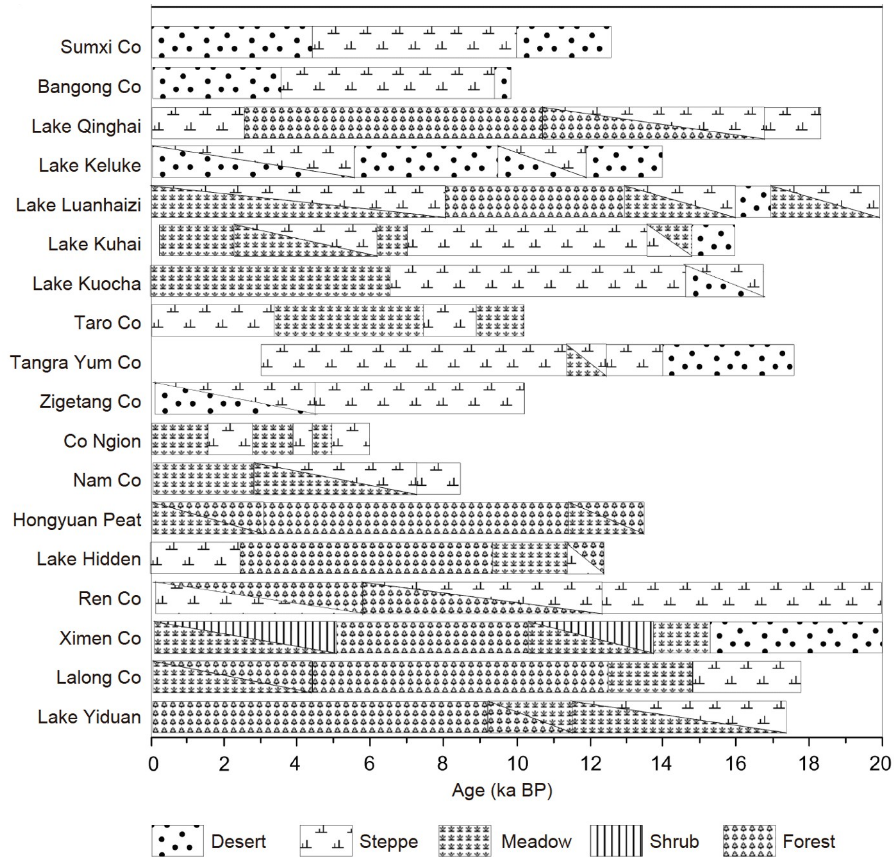

Figure 2 Schematic diagram of paleovegetation over the past 20 ka reflected by pollen records from lakes and sections along a transect from southeast to northwest in the TP.

forest vegetation in its late period. Forest vegetation expanded during the early to mid-Holocene, then retreated in the late Holocene. In central TP, desert/sparse vegetation was dominant at the beginning of the last deglaciation, then changed into steppe/meadow vegetation at its later period, while steppes developed during the Holocene. In northeastern TP, the regions with low elevations (<3500 m a.s.l.) were occupied by steppe/meadow vegetation in the early period of the last deglaciation, forest/forest-steppe in its late period, forest vegetation during the early to mid-Holocene, and steppe/meadow vegetation during the late Holocene. The regions with high elevations (>3500 m a.s.l.) in northeastern TP were covered by desert/steppe vegetation in the early period of the last deglaciation and by steppe/meadow vegetation in its late period and the Holocene. In northwestern TP, desert vegetation developed from the late period of the last deglaciation to the early Holocene, while steppe vegetation occurred during the early to mid-Holocene, and desert vegetation developed again in the late Holocene.

The spatial and temporal variation of Holocene vegetation from east to west in the TP can be revealed by pollen records from seven lakes including Lakes Shayema, Yidun, Hidden, Chabyer, Ren Co, Selin Co, and Sumxi Co (Figure 3). The horizontal distribution patterns of paleovegetation from east to west in each period of Holocene on the TP were as follows: (1) Before entering Holocene, about 12 cal. ka BP, desert-steppe vegetation developed from east to west only, with an exception of the catchment of Lake Hidden (29°55′N,92°20′E) in southeast Xizang, where steppe vegetation occurred at 14–11 cal. ka BP. (2) In the early Holocene (12–9 or 11–8 cal. ka BP), coniferous and broadleaved mixed forest or deciduous broadleaved forest existed in the southeastern part of the TP (e.g., Lake Shayema at 102°E in western Sichuan). To the west, meadow or shrub-steppe occurred in southeastern Xizang (Ren Co and Lake Hidden), while steppe vegetation appeared further west (Selin Co, Lake Chabyer, and Sumxi Co at 88°30′E–84°04′E). (3) In the mid-Holocene (9.0–3.2 or 8.0–3.0 cal. ka BP), vegetation types from east to west were coniferous and broadleaved mixed forests or sclerophyllous broadleaved forests (104°E–98°E), coniferous and broadleaved mixed forests (98°E–94°E), steppe-meadows (94°E–92°E) and steppes (92°E–80°E) in turn. (4) In the late Holocene (3.2 or 3.0 cal. ka BP to the present), vegetation types from east to west were sclerophyllous broadleaved forests (104°E–99°E), coniferous and broadleaved mixed forests (99°E–96°E), meadow-steppes (96°E–88°E), steppes (88°E–84°E), and deserts (84°E–80°E), respectively.

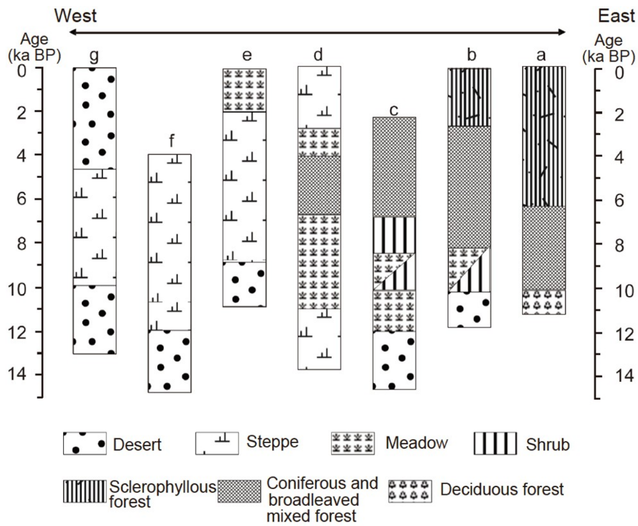

Figure 3 Schematic diagram of the Holocene paleovegetation reconstructed from pollen records of selected lakes along a transect from southeast to northwest in the TP. (a) Lake Shayema; (b) Lake Yidun; (c) Ren Co; (d) Lake Hidden; (e) Selin Co; (f) Lake Chabyer; (g) Sumxi Co.

7. Reconstructing paleoclimate: Studying the southwest monsoon-dominated plateau climate changes

The Holocene climatic history of the TP has always been the focus of geographical and Quaternary academic communities. After the reforming and opening to the outside world, studies of paleomonsoon in the TP using pollen data were carried out over the entire TP with the financial support of the National Natural Science Foundation of China. In co-operation with scientists from France, Germany, the United States, Australia and Japan, Chinese scientists, mainly researchers from the CAS, have conducted many field investigations and taken dozens of cores from lakes in the TP to study the evolutionary history of the southwest monsoon since the LGM.

In eastern TP, the Mianning and Zoige regions of western Sichuan and Lake Qinghai region of northeastern Qinghai are influenced by both the southwest monsoon and southeast monsoon. Pollen records from these regions showed that summer monsoon nonlinearly and gradually enhanced and deepened from south to north after 10 ka BP. The monsoonal rainfall maximum of the Holocene started as early as 7.8 ka BP in the Mianning region, and at 7.0 ka BP in Zoige region, and then at 6.8 ka BP in Qinghai Lake region, implying that summer monsoon reached its maximum around 6.8 ka BP. During 6.8–3.5 ka BP, precipitation generally exhibited a trend of nonlinear decrease, but maintained a high level, indicating that summer monsoon was still active. After 3.5 ka BP, precipitation decreased significantly with a small amplitude, indicating an obvious shrinkage of summer monsoon to establish a modern monsoon environment. In southeastern Xizang, NNW-NNE trending river valleys make it easy for hot and humid air masses, driven by monsoon from the Bay of Bengal, to invade the TP and inlands of northwest China, thus the climate of this region is mainly controlled by the southwest monsoon. In the catchments of Lake Hidden and Ren Co, climate was cold and dry at ca. 20–12.4 cal. ka BP, and vegetation was mainly composed of xerophytic herbaceous plants. The harsh climate and alpine desert-steppes in this region were indicative of a weak and shrinking monsoon circulation. From 11.4 to 9.4 cal. ka BP, the vegetation was dominated by steppe components with a sudden increase of birch, indicating a sudden strengthening process of the southwest monsoon and the arrival of the Holocene optimum period. For instance, July temperature was ca. 1°C lower than the present and MAP was close to the present at 10.1 cal. ka BP in the catchment of Lake Hidden. In the catchment of Chen Co in southern Xizang, climate was warm and dry with MAT of 0.8°C higher than the present during 10.7–9 cal. ka BP, then humid with MAP of 30 mm higher than the present during 9–6.1 cal. ka BP, and subsequently became drying during 6.1–3.2 cal. ka BP (Lu et al., 2011).

The Holocene optimum period occurred in 9.4–2.4 cal. ka BP in the TP. During this period, the coniferous and broadleaved mixed forest grew, and climate was warm and humid with MAT of 3°C higher than now and MAP of about 250 mm higher than now in southeastern Xizang. In the catchment of Niyanghe River of the same region, the climate during this period was also warm and humid (Sun, 1996). Many Neolithic sites with abundant large fossils and cultural relics, such as stone tools and pottery shards, were discovered in Nyingchi and Qamdo, also reflecting a warm and humid climate (Chen, 1980; Huang, 1980). Pollen records from Selin Co and Sumxi Co in central TP showed that after reaching a certain intensity around 9.5 cal. ka BP, the southwest monsoon gradually weakened to reach a valley at 8.0–7.8 cal. ka BP, then gradually strengthened to reach its maximum at 7.5–6.0 cal. ka BP, where it would subsequently shrink. All pollen records from southeast to northwest TP showed a strong southwest monsoon in the mid-Holocene. During this long period of warmth and humidity, the southwest monsoon increased from 9.4 cal. ka BP to its peak at 7.0–6.0 cal. ka BP, then gradually declined after 5.0 cal. ka BP.

After 5.0 cal. ka BP, the influence of the southwest monsoon was weakened in northwestern TP, and modern monsoon environment would be established after 4.3 cal. ka BP, whereas the southwest monsoon was still active at 5.0–4.0 cal. ka BP in central TP, where modern monsoon environment appeared at 4.0 cal. ka BP. In southeastern TP, a significant decrease of deciduous trees and an expansion of steppe implied the transition of vegetation from forest to steppe at 3.5 cal. ka BP. According to estimates from pollen-climate transfer functions, January and July temperatures decreased by 1.5 and 0.5–1°C, and MAP declined by 100–150 mm during the late Holocene.

Many data showed that warm and humid climatic conditions during the early to mid-Holocene and dry climatic conditions during the late Holocene were overall characteristics of the Holocene climate in the TP. Mid-Holocene climate exhibited a consistent pattern in temperature rise and humidity increase in most regions of the TP. Although the Holocene mode of temperature change over the TP is still controversial, the summer temperature peak that occurred in the early to mid-Holocene coincided with the strengthening of summer solar insolation and southwest summer monsoon (Chen et al., 2020). The southwest monsoon, which invaded from southeast to northwest of the TP, gradually retreated southeastward with the weakening of its intensity (Figure 4). while the southwest monsoon invaded from southeast to northwest of the TP and gradually retreated eastward with the weakening of intensity (Figure 4). Therefore, the Holocene paleomonsoon experienced a change process of strengthening, maximum, weakening but still active, and shrinking, mainly controlled by solar insolation. During the Holocene, the timing of the southwest monsoon strengthening was basically the same across the whole of the TP, but the timing of the southwest monsoon weakening varied in different regions of the TP. The southwest monsoon weakening was primarily attributed to the drying of the environment, which began at 6.0 cal. ka BP in the northwest of the TP as suggested by the decrease of A/C ratio and lake level, and at ca. 4.0 cal. ka BP in eastern and southeastern TP as suggested by pollen records. The timing of the southwest monsoon weakening exhibited a lag from northwest to southeast, indicating that the southwest monsoon retreated southeastward step by step. This phenomenon was also reflected by the establishment timing of modern environmental conditions in the TP. It was ca. 4.3 cal. ka BP in northwestern TP, ca. 4.0 cal. ka BP in central TP, and ca. 3.5 cal. ka BP in southeastern TP. Furthermore, a series of centennial-scale monsoon weakening events were superimposed on the general trend of southwest monsoon variation controlled by solar insolation. MAP estimated quantitatively by pollen records in southeastern TP showed 10 centennial-scale monsoon weakening events at 10.1, 9.2, 8.2, 7.7, 6.5, 5.8, 4.5, 3.0, 2.1, and 1.1 cal. ka BP (Shen, 2003).

In addition to the southwest monsoon, the northeastern margin of the TP is also affected by the southeast monsoon. Three patterns of the late Quaternary monsoon climate in this region were suggested by Li et al. (1988). They were (1) the glacial maximum pattern (18.0–15.0 ka BP): cold and dry climatic conditions, and steppe vegetation dominated by *Artemisia* and Chenopodiaceae; (2) the interglacial pattern (the last interglacial and Holocene): warm and humid cli-

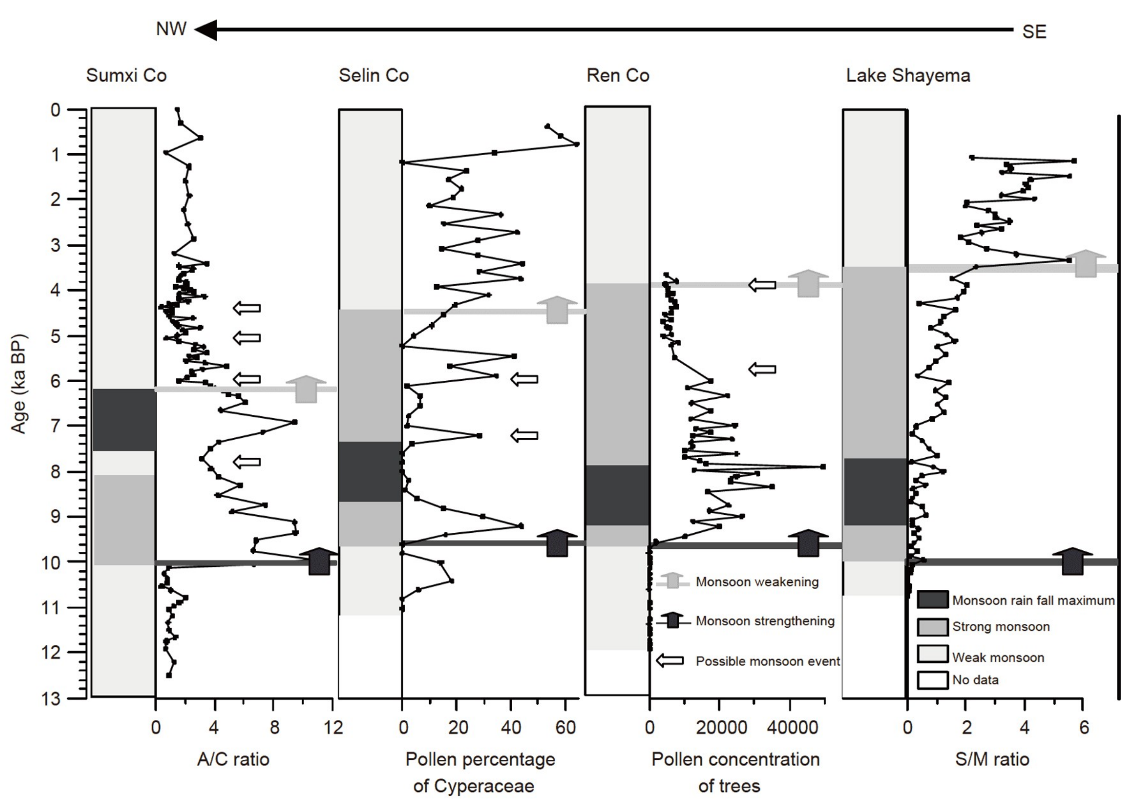

Figure 4 Spatial and temporal pattern of monsoon along a transect from southeast to northwest in the TP (S/M ratio=evergreen sclerophyllous taxa excluding evergreen oaks: mesic deciduous taxa, Jarvis, 1993; A/C ratio=*Artemisia*/Chenopodiaceae, Van Campo and Gasse, 1993).

matic conditions, and deciduous broadleaved forests dominated by *Quercus* and *Betula*; (3) transitional or interstadial pattern (50.0–23.0 ka BP): cold and wet climatic conditions, and coniferous forests dominated by *Picea* (Li et al., 1988). This study led to many later paleoclimate studies in northeastern TP and its surrounding regions. In this region, vegetation and humidity changes, observed from a high-resolution pollen record from the Zhuye Lake of the Shiyang River Basin in the northern margin of the TP, revealed southeast monsoon changes. During the Early Holocene (11.6–7.1 cal. ka BP), alpine forests composed mainly of *Sabina chinensis*, *Picea* and *Pinus* indicated that moist climatic conditions in the Shiyang River Basin coincided with the Holocene southeast monsoon maximum. During the mid-Holocene (7.1–5.0 cal. ka BP), pollen spectra consisted of *Nitraria*, Poaceae, Asteraceae, *Artemisia*, and Chenopodiaceae, reflecting desert-steppe vegetation and weak summer monsoon (Chen et al., 2006). Precipitation changes since 19 cal. ka BP in the catchment of Donggi Cona of northeastern TP reveal the evolution of the southeast monsoon since the LGM. At 19–18.3 cal. ka BP, vegetation was dominated by *Artemisia* and Chenopodiaceae, and MAP was ca. 150 mm. During 18.3–13.1 cal. ka BP, vegetation was still dominated by *Artemisia* and Chenopodiaceae, MAP rose to be 197 mm. At 13.1–9.5 cal. ka BP, and *Artemisia* dominated while Chenopodiaceae declined, suggesting a wettest period with MAP of ca. 334 mm since the LGM. *Artemisia* decreased and Chenopodiaceae increased, and MAP was 251 mm during 9.5–7.3 cal. ka BP, whereas *Artemisia* increased and Chenopodiaceae decreased, and precipitation increased to 324 mm during 7.3–4.3 cal. ka BP. At 4.3–1.1 cal. ka BP, vegetation was composed of *Artemisia*, Chenopodiaceae, Poaceae, and Cyperaceae, and MAP was 281 mm (Wang Y et al., 2014).

8. Looking ahead: A tough task

The comprehensive scientific investigation on the TP in the 1960s and 1970s gave birth to Quaternary palynology in the TP of China. The reform and opening of China forty years ago and the later knowledge innovations of the Academy of Sciences pushed palynology into a new era of pursuing new development, exploring new rules, creating new methods, and accumulating new knowledge, and integrated the development of palynology with international academic communities via the implementation of various international collaborations. Over the past 50 years, Quaternary palynology in the TP has made great contribution to the studies of vegetational and climatic evolutions since the LGM. However, as the focus of the studies on the TP shifted from the need of economic development to the mechanism of environmental change and the optimization of the ecological security barrier system, it should be noted that Quaternary palynology in the TP will play an increasingly important role in TP ecology, earth system science, and biogeography by providing a long-term overview of population dynamics and ecosystem development, as well as the fourth dimension of detailed history in ecology and biogeography, i.e., paleoecology (Birks et al., 2016).

(1) From previously unsophisticated studies to sophisticated studies: to study the rapid response of vegetation and soil (permafrost) to climate change and climatic events, and to obtain a unique and detailed insight into the paleoecology of ecosystems and the operation of past ecological processes, the time resolution of samples and inter-samples in previous studies scarcely met research needs, which required a more refined time resolution of samples and inter-samples. Naturally, such time resolution greatly increases the requirements for plateau lakes with high sedimentation rate and the workload of Quaternary palynology. As the Asian water tower, the TP has the largest lake group in China and even the world, and while lakes with high deposition rates and annually laminated sediments (Chen et al., 2016) obviously exist, they are difficult to find.

(2) From discrete point to surface studies: the temporal dynamic and spatial changes of different vegetation types in the TP reflect the response of plant groups to climate change and the competition among plant types, while also bearing great significance for studying the sensitivity of monsoon climate and global climate to the land cover changes of the TP in observational studies and paleoclimate simulations. Available vegetation landscape succession maps were roughly reconstructed from a few sites with a relatively coarse time interval (e.g., 2500 years) (e.g., Tang and Shen, 1996). However, to reconstruct the vegetation landscape map with a finer time interval (e.g., 500 years or even less) and the spatial distribution map of plant species and genera (e.g., Ren and Beug, 2002), a planned and relatively spatial even lake pollen analysis with emphasis on ecotone is required, in addition to the detailed pollen analysis of samples with high time-resolution of samples and inter-samples mentioned above (e.g., Zhao, 2018). Only vegetation landscape maps procured with the above method can reveal the Holocene, Quaternary, and Tertiary temporospatial variations of vegetation species while providing a solid historical background for explaining the geographic DNA patterns of existing tree and herb populations, as well as high precision land cover data for paleoclimate simulations. Important boundary conditions (Bibi et al., 2018), vegetation types and glacier sizes on the TP are not only critical for climate simulations (Sen et al., 2001; Zhao et al., 2011; Wang X et al., 2014), but also of great help to studies on the feedback mechanism of vegetation and carbon cycle in the TP (Hua et al., 2019; Mu et al., 2020; Wang et al., 2020; Yan et al., 2020).

(3) Studies on the modern pollen processes and pollen

production in the TP: Few studies on the modern pollen processes in the TP are available. However, pollen production, dispersal, deposition, preservation, and pollen source area, as well as pollen-vegetation and pollen-climate relationships, are the keys to the quantitative reconstruction of paleoclimate and paleovegetation (Xu et al., 2015). Since the vegetation in the TP is the least disturbed by human activity in China, it is conducive to relevant studies. Additionally, there are ecological stations in the TP that are also conducive to the targeted study of pollen-vegetation-climate relationships.

(4) Quantitative reconstruction from non-similar environment to similar environment training pollen datasets: Modern pollen data and fossil pollen records, derived from the same sedimentary environment, are the basis for reliable quantitative reconstruction (Birks et al., 2010). Since most fossil pollen records in the TP were taken from lakes, it is most ideal for modern pollen data to be taken from lake surface sediments, as the same deposition process of modern and fossil pollen can minimize the influence of factors such as pollen taphonomy, lake size, and pollen source area (Cao et al., 2018). Compared to pollen databases in North America and Europe, which consist mainly of lake surface samples (Whitmore et al., 2005; Davis et al., 2013), current modern pollen databases used for paleoclimate reconstruction in the TP are primarily based on pollen datasets and databases of topsoil and moss samples (e.g., Shen et al., 2006; Lu et al., 2011), while the only modern pollen dataset composed of lake surface samples (112 lakes) was mainly completed by European scientists (Herzschuh et al., 2010). Only pollen databases composed of lake surface samples can theoretically provide reliable quantitative reconstruction of paleoclimate for these lake fossil pollen records. The most urgent need is to establish regional modern pollen databases composed of lake surface samples. Additionally, modern pollen data composed of lake surface samples should contain as few human-disturbed vegetation types as possible, to ensure that fossil pollen spectra retain their high-quality modern analogues (Birks et al., 2010; Cao et al., 2018). The TP is the region with the least human activity in China, and has more than 1000 lakes in size more than 1 km^2 (Ma et al., 2011), as well as countless lakes with an area less than 1 km^2. This provides a unique opportunity to establish a regional modern pollen database composed of lake surface samples in a sedimentary environment like that of lake fossil pollen records.

(5) Studies of pollen records from cores longer in time and deeper in depth: The core purpose of the second comprehensive scientific expedition to the TP was to explore the mechanisms behind changes to the 'Asian Water Tower', an issue relevant to 2 billion people. To determine the future scenarios of climate change in the TP and their impacts on the ecosystem, and to address the core purpose of the second comprehensive scientific expedition to the TP, it is necessary to improve our understanding of the timing, duration and intensity of past climate change and environmental impacts, not only in the short term but also in the long-term geological time scale. Chinese scientists have obtained 201-m and 573.39-m cores in the Co Ngion of central TP and Zoige Basin of eastern TP. Their pollen records reveal the regional vegetation history, climate change and tectonic movement history of the past 2.8 Ma and 1.774 Ma in the two regions of the TP (Lu et al., 2001; Zhao et al., 2020). The time resolution of samples and inter-samples (335 pollen samples) was relatively coarse, but seven distinct changes revealed by pollen records evidenced the vegetation succession and tectonic uplift in the Co Ngion Basin (Lu et al., 2001). The pollen record from the Zoige Basin has a high inter-sample resolution (2787 pollen samples, inter-sample resolution of about 530–620 years). The vegetation changes reflected by pollen record indicated that the climate in the past 1.74 Ma presented a three-stage change feature. The gradual cooling trend in three periods was superimposed by climate changes at different orbital scales and millennial-scales. 1.74–1.54 Ma BP saw an insolation-dominated mode with strong -20,000-year cyclicity and quasi-absent millennial-scale signal. 1.54–0.62 Ma BP represents a transitional insolation-ice mode with 20,000- and 40,000-year cycles superimposed by millennial-scale oscillations. The past 0.62 Ma witnessed an ice-driven mode with 100,000-year cyclicity and less frequent millennial-scale variability (Zhao et al., 2020). Obviously, high-resolution pollen records can reveal more detailed information about vegetation succession and climate change. Over the last year, as part of the international continental scientific drilling program, the institute of Tibetan Plateau Research, Chinese Academy of Sciences, achieved a 144.79-m core in Nam Co, one of the largest and deepest lakes in the TP. It is expected to reconstruct continuous climate record of nearly 150 ka, and its high-resolution pollen record will provide new insights into the reconstruction of climatic cycles and events since the last interglacial, and the understanding of the interaction between westerlies and monsoon.

(6) Extending study field to the development of human civilization in the TP: At the beginning of this century, the earliest noodles in the world (4 ka ago) were found at the Lajia Site in Qinghai Province and identified as being made of glutinous millet (Lu et al., 2005). Recent results showed that highland barley cultivation encouraged the Tibetan people to settle on the TP 3600 years ago (Chen et al., 2015), and Denisovans lived in the TP 160 ka ago (Chen et al., 2019). In recent decades, palynologists found that certain pollen, such as *Rumex*, *Sanguisorba*, *Ulmus*, *Potentilla*-type *Humulus*, and certain species of Apiaceae, Liliaceae, Chenopodiaceae, and Fabaceae have special significance in southeastern TP (Schlütz and Lehmkuhl, 2009; Kramer et al., 2010a, 2010b; Wischnewski et al., 2011; Herzschuh et al., 2014); they are most likely to be used to indicate the in-

troduction of grazing or planting, and thus the intensity of human activity. These achievements are not only relevant to human adaptation to the plateau environment, but also to the impact of human activity on the plateau environment and, more importantly, to sustainable development and the human-environment relationship (Zhang X Z et al., 2015). Considering the above, it is clear that these studies will expand the contents of Quaternary palynology in the TP.

Palynology is an open discipline integrating the knowledge of many disciplines. In addition to the need for researchers to have a deep foundation and accumulation of knowledge, it also requires extensive cooperative exchange. We hope that the successors in the palynology field will not confine themselves to accumulating data and maintaining the status quo. Do not be satisfied by simply one's number of articles; seek to carry out influential systematic summary and theoretical improvement. Instead of being complacent with one's own expertise or playing with other people's ideas, one should also "go to the mountainous areas and the countryside" to collect first-hand data and discuss practical issues related to the evolution of the ecological environment and human activity with the integration of multiple disciplines.

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References

Ambach W, Bortenschlager S, Eisner H. 1966. Pollen-analysis investigation of a 20 m. Firn Pit on the Kesselwandferner (Ötztal Alps). J Glaciol, 6: 233–236

Bibi S, Wang L, Li X, Zhou J, Chen D, Yao T. 2018. Climatic and associated cryospheric, biospheric, and hydrological changes on the Tibetan Plateau: A review. Int J Climatol, 38: e1–e17

Birks H J B, Birks H H, Ammann B. 2016. The fourth dimension of vegetation. Science, 354: 412–413

Birks H J B, Gordon A D. 1985. Numerical Methods in Quaternary Pollen Analysis. New York: Academic Press. 317

Birks H J B, Heiri O, Seppa H, BjuneA E. 2010. Strengths and weaknesses of quantitative climate reconstructions based on late-Quaternary biological proxies. Open Ecol J, 3: 68–110

Bourgeois J C. 1986. A pollen record from the Agassiz Ice Cap, northern Ellesmere Island, Canada. Boreas, 15: 345–354

Cao X, Tian F, Ding W. 2018. Improving the quality of pollen-climate calibration-sets is the primary step for ensuring reliable climate reconstructions. Sci Bull, 63: 11–12

CAS Sino-Australian Quaternary Research Group. 1987. Proceedings of the Sino-Australian Quaternary Symposium (in Chinese). Beijing: Science Press. 1–250

Chen F H, Dong G H, Zhang D J, Liu X Y, Jia X, An C B, Ma M M, Xie Y W, Barton L, Ren X Y, Zhao Z J, Wu X H, Jones M K. 2015. Agriculture facilitated permanent human occupation of the Tibetan Plateau after 3600 B.P. Science, 347: 248–250

Chen F H, Welker F, Shen C C, Bailey S E, Bergmann I, Davis S, Xia H, Wang H, Fischer R, Freidline S E, Yu T L, Skinner M M, Stelzer S, Dong G R, Fu Q M, Dong G H, Wang J, Zhang D J, Hublin J J. 2019. A late Middle Pleistocene Denisovan mandible from the Tibetan Plateau. Nature, 569: 409–412

Chen F H, Zhang J F, Liu J B, Cao X Y, Hou J Z, Zhou L P, Xu X K, Liu X J, Wang M D, Wu D, Huang L X, Zeng T, Zhang S, Huang W, Zhang X, Yang K. 2020. Climate change, vegetation history, and landscape responses on the Tibetan Plateau during the Holocene: A comprehensive review. Quat Sci Rev, 243: 106444

Chen W Y. 1980. Late Cenozoic natural environment in Nyingchi Basin, Tibet (in Chinese). Vertebrata Palasiatica, 18: 52–61

Chen Y, Liu X Q, He L, Ye L, Chen H F, Li K. 2016. Micro-area analysis and mechanism of varves from Lake Kusai in the Hoh Xil area, northern Tibetan Plateau (in Chinese). Acta Geol Sin, 90: 1006–1015

Chen F H, Cheng B, Zhao Y, Zhu Y, Madsen D B. 2006. Holocene environmental change inferred from a high-resolution pollen record, Lake Zhuyeze, arid China. Holocene, 16: 675–684

Cour P, Zheng Z, Duzer D, Calleja M, Yao Z. 1999. Vegetational and climatic significance of modern pollen rain in northwestern Tibet. Rev Palaeobot Palynol, 104: 183–204

Davis B A S, Zanon M, Collins P, Mauri A, Bakker J, Barboni D, Barthelmes A, Beaudouin C, Bjune A E, Bozilova E, Bradshaw R H W, Brayshay B A, Brewer S, Brugiapaglia E, Bunting J, Connor S E, de Beaulieu J L, Edwards K, Ejarque A, Fall P, Florenzano A, Fyfe R, Galop D, Giardini M, Giesecke T, Grant M J, Guiot J, Jahns S, Jankovská V, Juggins S, Kahrmann M, Karpińska-Kołaczek M, Kołaczek P, Kühl N, Kuneš P, Lapteva E G, Leroy S A G, Leydet M, Guiot J, Jahns S, Jankovská V, Juggins S, Kahrmann M, Karpińska-Kołaczek M, Kołaczek P, Kühl N, Kuneš P, Lapteva E G, Leroy S A G, Leydet M, López Sáez J A, Masi A, Matthias I, Mazier F, Meltsov V, Mercuri A M, Miras Y, Mitchell F J G, Morris J L, Naughton F, Nielsen A B, Novenko E, Odgaard B, Ortu E, Overballe-Petersen M V, Pardoe H S, Peglar S M, Pidek I A, Sadori L, Seppä H, Severova E, Shaw H, Święta-Musznicka J, Theuerkauf M, Tonkov S, Veski S, van der Knaap W O, van Leeuwen J F N, Woodbridge J, Zimny M, Kaplan J O. 2013. The European Modern Pollen Database (EMPD) project. Veget Hist Archaeobot, 22: 521–530

Du N Q, Kong Z C, Shan F S. 1989. A preliminary investigation on the vegetational and climatic changes since 11 000 years in Qinghai Lake—An analysis based on palynology in core QH85-14C (in Chinese). Acta Bot Sin, 31: 803–814

Du N Q, Kong Z C. 1983. Palynoflora of the Qarhan Saline Lake and its significance in geography and botany-the sporo-pollen assemblages from CK2022 drilling core at the Bieletan (in Chinese). Acta Bot Sin, 25: 275–284

Erdtman G. 1936. New methods in pollen analysis. Svensk Bot Tidsskr, 30: 154–164

Fredskild B, Wagner P. 1974. Pollen and fragments of plant tissue in core samples from the Greenland Ice Cap. Boreas, 3: 105–108

Gasse F, Arnold M, Fontes J C, Fort M, Gibert E, Huc A, Li B, Li Y, Liu Q, Melieres F, Van Campo E, Wang F, Zhan Q. 1991. A 13,000-year climate record from western Tibet. Nature, 353: 742–745

Godwin H. 1949. Pollen analysis of glaciers in special relation to the formation of various types of glacier bands. J Glaciol, 1: 325–332

Herrmann M, Lu X, Berking J, Schütt B, Yao T, Mosbrugger V. 2010. Reconstructing Holocene vegetation and climate history of Nam Co area (Tibet), using pollen and other palynomorphs. Quat Int, 218: 45–57

Herzschuh U, Birks H J B, Mischke S, Zhang C, Böhner J. 2010. A modern pollen-climate calibration set based on lake sediments from the Tibetan Plateau and its application to a Late Quaternary pollen record from the Qilian Mountains. J Biogeogr, 37: 752–766

Herzschuh U, Borkowski J, Schewe J, Mischke S, Tian F. 2014. Moisture-advection feedback supports strong early-to-mid Holocene monsoon climate on the eastern Tibetan Plateau as inferred from a pollen-based reconstruction. Palaeogeogr Palaeoclimatol Palaeoecol, 402: 44–54

Herzschuh U, Kramer A, Mischke S, Zhang C. 2009. Quantitative climate and vegetation trends since the late glacial on the northeastern Tibetan Plateau deduced from Koucha Lake pollen spectra. Quat Res, 71: 162–171

Herzschuh U, Winter K, Wunnemann B, Li S. 2006. A general cooling trend on the central Tibetan Plateau throughout the Holocene recorded by the Lake Zigetang pollen spectra. Quat Int, 154-155: 113–121

Herzschuh U, Zhang C, Mischke S, Herzschuh R, Mohammadi F, Mingram B, Kürschner H, Riedel F. 2005. A late Quaternary lake record from the Qilian Mountains (NW China): Evolution of the primary production and the water depth reconstructed from macrofossil, pollen, biomarker, and isotope data. Glob Planet Change, 46: 361–379

Hou S G. 2019. How old are the Tibetan ice cores (in Chinese)? Chin Sci Bull, 64: 2425–2429

Hua W, Lin Z, Guo D, Fan G, Zhang Y, Yang K, Hu Q, Zhu L. 2019. Simulated long-term vegetation—Climate feedbacks in the Tibetan Plateau. Asia-Pac J Atmos Sci, 55: 41–52

Huang C X, Von Combo A, Dobreme J F. 1993. A study on pollen in surface soil from the western Xizang (in Chinese). Arid Land Geogr, 16: 75–84

Huang C X, Von Combo A, Li S K. 1996. Holocene environmental changes of western and northern Qinghai-Xizang Plateau based on pollen analysis (in Chinese). Acta Micropalaeontol Sin, 13: 423–432

Huang C X, Wang Y R, Liang Y L. 1983. On the evolution of the Holocene natural environment in central and southern Tibet from the perspective of sporopollen analysis (in Chinese). In: Comprehensive scientific expedition team of Qinghai-Tibet Plateau, CAS. eds. Quaternary Geology of Tibet. Beijing: Science Press. 179–192

Huang F. 2000. Vegetation and climate between 13 ka to 5 ka B.P. in Peiku Co, Tibet (in Chinese). Acta Palaeontol Sin, 39: 441–448

Huang R H, Hou S G, Ma C M, Liu K, Yu J H, Zhang W B, Zhao L, Pang H X, Song J. 2019. Review on palynological records in snow and ice (in Chinese). J Earth Sci Environ, 41: 362–378

Huang W P. 1980. Note on Holocene Gazo site of Changdu, Xizang (in Chinese). Vertebrata Palasiatica, 18: 163–168

Jarvis D I. 1993. Pollen evidence of changing Holocene monsoon climate in Sichuan Province, China. Quat Res, 39: 325–337

Kong Z C, Liu L S, Du N Q. 1981. Discussion on the uplift of the Qinghai-Tibet Plateau from the Neogene period and Quaternary sporopollen assemblages of the Kunlun and Tanggula Mountains (in Chinese). In: Comprehensive Scientific Expedition Team of Qinghai-Tibet Plateau, CAS, eds. On the epoch, amplitude and form of the uplift of the Qinghai-Tibet Plateau. Beijing: Science Press. 78–89

Kramer A, Herzschuh U, Mischke S, Zhang C. 2010a. Holocene treeline shifts and monsoon variability in the Hengduan Mountains (southeastern Tibetan Plateau), implications from palynological investigations. Palaeogeogr Palaeoclimatol Palaeoecol, 286: 23–41

Kramer A, Herzschuh U, Mischke S, Zhang C. 2010b. Late glacial vegetation and climate oscillations on the southeastern Tibetan Plateau inferred from the Lake Naleng pollen profile. Quat Res, 73: 324–335

Li B Y, Li Y F, Zhu L P, Li S K, Kong Z C, Shan F S. 1994. Environmental changes in the last 20, 000 years in Gouxicun area, Hoh Xil, Qinghai (in Chinese). Chin Sci Bull, 39: 1727–1728

Li J, Feng Z D, Tang L Y. 1988. Late Quaternary monsoon patterns on the Loess Plateau of China. Earth Surf Process Landf, 13: 125–135

Li K, Liu X Q, Wang Y B, Herzschuh U, Ni J, Liao M, Xiao X Y. 2017. Late Holocene vegetation and climate change on the southeastern Tibetan Plateau: Implications for the Indian Summer Monsoon and links to the Indian Ocean Dipole. Quat Sci Rev, 177: 235–245

Li Q, Lu H Y, Zhu L P, Wu N Q, Wang J B, Lu X M. 2011. Pollen-inferred climate changes and vertical shifts of alpine vegetation belts on the northern slope of the Nyainqentanglha Mountains (central Tibetan Plateau) since 8.4 kyr BP. Holocene, 21: 939–950

Li X, Liu J L. 1988. Holocene vegetational and environmental changes at Mt. Luoji, Sichuan (in Chinese). Acta Geogr Sin, 43: 44–51

Liang C, Zhao Y, Qin F, Zheng Z, Xiao X, Ma C, Li H, Zhao W. 2020. Pollen-based Holocene quantitative temperature reconstruction on the eastern Tibetan Plateau using a comprehensive method framework. Sci China Earth Sci, 63: 1144–1160

Liu G X, Shen Y P, Wang S M. 1995. Vegetation history and climatic records since 150 ka in hole RH of Zoegai Basin (in Chinese). In: Expert committee of Qinghai-Xizang Project eds. Studies on the Formation Evolution, Environment Change and Ecology Systemic of the Qinghai-Xizang Plateau. Beijing: Science Press. 199–208

Liu G X, Wang R, Li S J, Li B Y, Zhu Z Y. 1998. Palynological evidence of ecological environment change since 240 ka BP for the Tianshuihai Lake, west Kunlun Mountains (in Chinese). J Glaciol Geocryol, 20: 21–24

Liu H L, Wang D Y. 1984. A study on the remains of ancient forest in Mianning, Sichuan (in Chinese). Sci Silvae Sin, 20: 380–388

Liu K B, Yao Z J, Thompason L G. 1998. A pollen record of Holocene climatic changes from the Dunde ice cap, Qinghai-Tibetan Plateau. Geology, 26: 135–138

Liu X L. 2010. Vegetation and climate changes of middle Pleistocene in Hoh Xil area (in Chinese). Dissertation for Master's Degree, Lanzhou: Lanzhou University. 1–59

Liu X Q, Shen J, Wang S M, Yang X D, Tong G B, Zhang E L. 2002. Pollen records and paleoclimate and palaeo-environment evolution of Qinghai Lake since 16 ka (in Chinese). Chin Sci Bull, 47: 1351–1355

Lu H, Wang S, Wu N, Tong G, Yang X, Sheng C, Li S, Zhu L, Wang L. 2001. A new pollen record of the last 2.8 Ma from the Co Ngoin, central Tibetan Plateau. Sci China Ser D-Earth Sci, 44: 292–300

Lu H Y, Wu N Q, Liu K B, Zhu L P, Yang X D, Yao T D, Wang L, Li Q, Liu X Q, Shen C M, Li X Q, Tong G B, Jiang H. 2011. Modern pollen distributions in Qinghai-Tibetan Plateau and the development of transfer functions for reconstructing Holocene environmental changes. Quat Sci Rev, 30: 947–966

Lu H Y, Yang X Y, Ye M L, Liu K B, Xia Z K, Ren X Y, Cai L H, Wu N Q, Liu T S. 2005. Millet noodles in Late Neolithic China. Nature, 437: 967–968

Lu H Y, Wu N Q, Yang X D, Shen C M, Zhu L P, Wang L, Li Q, Xu D K, Tong G B, Sun X J. 2008. Spatial pattern of *Abies* and *Picea* surface pollen distribution along the elevation gradient in the Qinghai-Tibetan Plateau and Xinjiang, China. Boreas, 37: 254–262

Lu H Y. 1989. The sporo-pollen assemblages in the sediments in the southern Bohai Sea since the late Pleistocene and its palaeoen-vironmental analysis (in Chinese). J Oceanogr Huanghai Bohai Seas, 7: 11–26

Ma Q F, Zhu L P, Lü X M, Guo Y, Ju J T, Wang J B, Wang Y, Tang L Y. 2014. Pollen-inferred Holocene vegetation and climate histories in Taro Co, southwestern Tibetan Plateau. Chin Sci Bull, 59: 4101–4114

Ma Q F, Zhu L P, Lü X M, Wang J B, Ju J T, Kasper T, Daut G, Haberzettl T. 2019. Late glacial and Holocene vegetation and climate variations at Lake Tangra Yumco, central Tibetan Plateau. Glob Planet Change, 174: 16–25

Ma R H, Yang G S, Duan H T, Jiang J H, Wang S M, Feng X Z, Li A N, Kong F X, Xue B, Wu J L, Li S J. 2011. China's lakes at present: Number, area and spatial distribution. Sci China Earth Sci, 54: 283–289

Ma Y Z, Cao J X, Li J J. 1995. The development of palynological flora and climatic changes in the Yuanpu loess section of Linxia, Gansu Province during the last 150000 years (in Chinese). In: Expert committee of Qinghai-Xizang Project eds. Studies on the Formation Evolution, Environment Change and Ecology Systemic of the Qinghai-Xizang Plateau. Beijing: Science Press. 103–113

McAndrews J H. 1984. Pollen analysis of the 1973 ice core from Devon Island glacier, Canada. Quat Res, 22: 68–76

Miao Y, Jin H, Liu B, Herrmann M, Sun Z, Wang Y. 2015. Holocene climate change on the northeastern Tibetan Plateau inferred from mountain-slope pollen and non-pollen palynomorphs. Rev Palaeobot Palynol, 221: 22–31

Morrill C, Overpeck J T, Cole J E, Liu K B, Shen C M, Tang L Y. 2006. Holocene variations in the Asian monsoon inferred from the geochemistry of lake sediments in central Tibet. Quat Res, 65: 232–243

Mu C, Abbott B W, Norris A J, Mu M, Fan C, Chen X, Jia L, Yang R, Zhang T, Wang K, Peng X, Wu Q, Guggenberger G, Wu X. 2020. The status and stability of permafrost carbon on the Tibetan Plateau. Earth-Sci Rev, 211: 103433

Ni Z, Jones R, Zhang E, Chang J, Shulmeister J, Sun W, Wang Y, Ning D. 2019. Contrasting effects of winter and summer climate on Holocene montane vegetation belts evolution in southeastern Qinghai-Tibetan Plateau, China. Palaeogeogr Palaeoclimatol Palaeoecol, 533: 109232

Overpeck J T, Liu K B, Morrill C, Cole J, Shen C, Anderson D, Tang L. 2005.Holocene Environmental Change in the Himalayan-Tibetan Plateau Region: Lake Sediments and the Future. In: Huber U M, Bugmann H K M, Reasoner M A, eds. Global Change and Mountain Regions: An Overview of Current Knowledge. Dordrecht: Springer. 83–92

Pan B T, Xu S Y. 1989. Late Quaternary natural environment evolution in eastern Qinghai Plateau (in Chinese). Chin Sci Bull, 34: 534–536

Ren G, Beug H J. 2002. Mapping Holocene pollen data and vegetation of China. Quat Sci Rev, 21: 1395–1422

Schlütz F, Lehmkuhl F. 2009. Holocene climatic change and the nomadic Anthropocene in Eastern Tibet: Palynological and geomorphological results from the Nianbaoyeze Mountains. Quat Sci Rev, 28(15-16): 1449–1471

Sen O L, Bastidas L A, Shuttleworth W J, Yang Z L, Gupta H V, Sorooshian S. 2001. Impact of field-calibrated vegetation parameters on GCM climate simulations. Q J R Meteorol Soc, 127: 1199–1223

Shan F S, Kong Z C, Du N Q. 1995. Paleovegetation and environmental significance (in Chinese). In: Li B Y, eds. Natural Environment of Hoh Xil Area in Qinghai Province. Beijing: Science Press. 197-205

Shen C M, Liu K B, Morrill C, Overpeck J T, Peng J L, Tang L Y. 2008a. Meadow-steppe ecotone shift and major central-scale droughts during the mid-Holocene in the central Tibetan Plateau. Ecology, 89: 1079–1088

Shen C M, Liu K B, Tang L Y, Overpeck J T. 2008b. Numerical analysis of modern and fossil pollen data from the Tibetan Plateau. Ann Assoc Am Geogr, 98: 755–772

Shen C M, Liu K B, Tang L Y, Overpeck J T. 2006. Quantitative relationships between modern pollen rain and climate in the Tibetan Plateau. Rev Palaeobot Palynol, 140: 61–77

Shen C M, Tang L Y, Wang S M, Li C H, Liu K B. 2005. Pollen records and time scale for the RM core of the Zoige Basin, northeastern Qinghai-Tibetan Plateau. Chin Sci Bull, 50: 553–562

Shen C M, Tang L Y. 1992. Preliminary study on the Holocene climate-pollen-climate transfer function in Changbai Mountains and Xiaoxing'anling Mountains (in Chinese). In: Shi Y F, Kong Z C, eds. The climate and environment of the Holocene Mega Warm Period in China. Beijing: Ocean Press. 33-39

Shen C M. 2003. Millennial-scale variations and centennial-scale events in the southwest monsoon: Pollen evidence from Tibet. Dissertation for Doctoral Degree. Baton Rouge: Louisiana State University, USA, 286

Shen J, Liu X Q, Wang S M, Matsumoto R. 2005. Palaeoclimatic changes in the Qinghai Lake area during the last 18,000 years. Quat Int, 136: 131–140

Shen Z Q, Tong G B, Zhang J P, Yu S F, Li Y L. 1990. Geological environments since Pliocene and accumulation process of saline deposit in west Chaidamu Basin, Qinghai, China (in Chinese). Mar Geol Quat Geol, 10: 89–98

Shi Y F, Li J J, Li B Y. 1998. Late Cenozoic Uplift and Environmental Change of Qinghai-Xizang Plateau (in Chinese). Guangzhou: Guangdong Science and Technology Press. 463

Shi Y F, Liu D S. 1964. Preliminary report on scientific investigation in Shishapangma area (in Chinese). Chin Sci Bull, 15: 928–938

Short S K, Holdsworth G. 1985. Pollen, oxygen isotope content and seasonally in an ice core from the Penny Ice Cap, Baffin Island. Arctic, 38: 214–218

Song C Q, Sun X J, Lu H Y. 1997. Establishment and application of pollen-climate factor transfer functions in northern China (in Chinese). Chin Sci Bull, 42: 2182–2185

Sun H L. 1996. Formation and Evolution of the Qinghai-Xizang Plateau (in Chinese). Shanghai: Shanghai Science and Technology Press. 383

Sun X J, Du N Q, Chen Y S, Gu Z Y, Liu J Q, Yuan B Y. 1993. Holocene palynological records in Lake Selincuo, northern Xizang (in Chinese). Acta Bot Sin, 35: 943–950

Sun X J, Song C Q, Chen X D. 1999. China Quaternary pollen database (CPD) and biome 6000 project (in Chinese). Adv Earth Sci, 14: 407–411

Tang L Y, Feng Z D, Kang J C. 1990. Quaternary palynoflora and sedimentary environment in the neighbouring area of Qinghai-Xizang Plateau and Loess Plateau (in Chinese). J Glaciol Geocryol, 12: 125–140

Tang L Y, Li C H, Yu G, Shen C M. 2003. Pollen-based reconstructions of Holocene vegetation and climatic change of Tibetan Plateau. Chin J Polar Sci, 14: 99–116

Tang L Y, Mao L M, Shu J W, Li C H, Shen C M, Zhou Z Z. 2016. An Illustrated Handbook of Quaternary Pollen and Spores in China (in Chinese). Beijing: Science Press. 1–601

Tang L Y, Shen C M, Kong Z C, Wang F B, Liu K B. 1998. Pollen evidence of climate during the Last Glacial Maximum in eastern Tibetan Plateau (in Chinese). J Glaciol Geocryol, 20: 133–140

Tang L Y, Shen C M, Li C H, Peng J L, Liu H, Liu K B, Morrill C, Overpeck J T, Coel J E, Yang B. 2009b. Pollen-inferred vegetation and environmental changes in the central Tibetan Plateau since 8200 yr BP. Sci China Ser D-Earth Sci, 52: 1104–1114

Tang L Y, Shen C M, Liu K B, Overpeck J T. 2000. Changes in South Asian monsoon: New high-resolution paleoclimatic records from Tibet, China. Chin Sci Bull, 45: 87–91

Tang L Y, Shen C M, Liu K B, Overpeck J T, Yu S Y. 2000b. Climatic and hydrological changes in the southeastern Qinghai-Tibetan Plateau during the past 18 000 years (in Chinese). Acta Micropalaeontol Sin, 17: 113–124

Tang L Y, Shen C M, Liu K B, Overpeck J T. 1999. New high-resolution pollen records from two lakes in Xizang (Tibet) (in Chinese). Acta Bot Sin, 41: 896–902

Tang L Y, Shen C M, Liu K B, Overpeck J T. 2000a. Evolution of the South Asian palaeo-monsoon: A new high resolution palaeoclimate record from Tibet (in Chinese). Chin Sci Bull, 44: 2004–2007

Tang L Y, Shen C M, Liu K B, Yu S Y, Li C H. 2004. Climate change in southeast Tibet since the Last Glacial Maximum-pollen records in southeast Tibet (in Chinese). Sci China Ser D-Earth Sci, 34: 436–442

Tang L Y, Shen C M, Zhao X T, Xiao J Y, Yu G, Han H Y. 1993. Vegetation and climate in Qingfeng section, Jianhu, Jiangsu since 10,000 years ago (in Chinese). Sci China Ser B, 23: 637–643

Tang L Y, Shen C M. 1996. Holocene pollen records from the Tibetan Plateau (in Chinese). Acta Micropalaeontol Sin, 13: 407–422

Tang L Y, Wang S L. 1988. Palynoflora of Gonghe formation in Gonghe basin, Qinghai (in Chinese). Acta Palaeontol Sin, 27: 583–606

Tang L Y, Wang R, Kong Z C. 1983. Pollen analytical investigation of the Ruoguo Glacier in southeast Xizang (in Chinese). Acta Bot Sin, 25: 171–179

Tang L Y, Wang R. 1976a. Palynological assemblages of Quaternary lacustrine sediments in the Kunlun Mt. pass area, Qinghai and their significance (in Chinese). In: Lanzhou Institute of Glaciology and Geocryology and Desert, CAS, eds. Journal of Lanzhou Institute of Glaciology and Geocryology and Desert, Chinese Academy of Sciences, No. 1. Beijing: Science Press. 106–126

Tang L Y, Wang R. 1976b. Palynological assemblage and its significance in the 203 m borehole of Qingshuihe, Qingzhi Highway (in Chinese). Journal of Lanzhou University (Natural Sciences), (2): 92–104

Tang L Y, Yang B, Li C H, Shao Y J, Tao S C. 2009a. A pollen record of the 15th century climate variability archived in the Puruogangri ice cap of Tibet (in Chinese). Acta Palaeontologica Sinica, 48: 200–210

Thompson L G, Mosley-Thompson E, Davis M E, Lin P N, Dai J, Bolzan J F, Yao T. 1995. A 1000 year climate ice-core record from the Guliya ice cap, China: Its relationship to global climate variability. Ann Glaciol, 21: 175–181

Thompson L G, Wu X L, Mosley-Thompson E, Xie Z C. 1988. Climatic records from the Dunde Ice Cap, China. Ann Glaciol, 10: 178–182

Van Campo E, Gasse F. 1993. Pollen- and diatom-inferred climatic and hydrological changes in Sumxi Co Basin (Western Tibet) since 13,000 yr B.P. Quat Res, 39: 300–313

Van Campo E, Cour P, Sixuan H. 1996. Holocene environmental changes in Bangong Co basin (western Tibet). Part 2: The pollen record. Palaeogeogr Palaeoclimatol Palaeoecol, 120: 49–63

von Post L. 1916. Skogsträdpollen I sydsvenska torfmosselagerföljder. Geologiska Föreningens I Stockholm Förhandlingar, 38: 384–394

Walker D. 1986. Late Pleistocene-early Holocene vegetational and climatic changes in Yunnan Province, Southwest China. J Biogeogr, 13: 477–486

Wang F B, Han H Y, Yan G, Cao Q Y, Zhou W J, Li S F, Donahue D J. 1996. Palaeo-vegetation and paleoclimate evolution in northeastern Qinghai-Tibet Plateau since 30 ka (in Chinese). Sci China Ser D-Earth Sci, 26: 111–117

Wang M H. 1987. The spore-pollen groups of peatland on Ruoergai Plateau and Paleobotany (in Chinese). Sci Geogr Sin, 7: 147–155

Wang P F, Xia Y M, Wang M H. 1981. The study on the spore-pollen groups and the evolution of the natural environment of south Xizang Plateau in the peat of the Holocene (in Chinese). Sci Geogr Sin, 1: 144–152

Wang R, Tang L Y. 1980. Preliminary application of sporo-pollen analysis method in the division of glacial annual layer (in Chinese). J Glaciol Geocryol, 2(s1): 21–24

Wang X, Yang M, Pang G. 2014. Sensitivity of regional climate simulations to land-surface schemes on the Tibetan Plateau. Clim Res, 62: 25–43

Wang Y, Herzschuh U, Shumilovskikh L S, Mischke S, Birks H J B, Wischnewski J, Böhner J, Schlütz F, Lehmkuhl F, Diekmann B, Wünnemann B, Zhang C. 2014. Quantitative reconstruction of precipitation changes on the NE Tibetan Plateau since the Last Glacial Maximum—Extending the concept of pollen source area to pollen-based climate reconstructions from large lakes. Clim Past, 10: 21–39

Wang Z, Wu J, Niu B, He Y, Zu J, Li M, Zhang X. 2020. Vegetation expansion on the Tibetan Plateau and its relationship with climate change. Remote Sens, 12: 4150

Weng C Y, Sun X J, Chen Y S. 1993. Numerical Characteristics of pollen assemblages of surface from the west Kunlun Mountains (in Chinese). Acta Bot Sin, 35: 69–79

Whitmore J, Gajewski K, Sawada M, Williams J W, Shuman B, Bartlein P J, Minckley T, Viau A E, Webb Iii T, Shafer S, Anderson P, Brubaker L. 2005. Modern pollen data from North America and Greenland for multi-scale paleoenvironmental applications. Quat Sci Rev, 24: 1828–1848

Wischnewski J, Mischke S, Wang Y, Herzschuh U. 2011. Reconstructing climate variability on the northeastern Tibetan Plateau since the last Lateglacial—A multi-proxy, dual-site approach comparing terrestrial and aquatic signals. Quat Sci Rev, 30: 82–97

Wu Y S, Xiao J Y. 1995. A preliminary study on modern pollen rain of Zabuye Salt Lake area, Xizang (in Chinese). Acta Bot Yunnan, 17: 72–78

Wu Z H, Zhao X T, Wu Z H, Zhou C J, Yan F H, Mai X S, Zhu D G. 2004. Palaeovegetation, palaeoclimate and lake-level change since 120 ka BP in Nam Co, central Xizang (in Chinese). Acta Geol Sin, 78: 242–252

Xiao J Y, Wu Y S, Zheng M P. 1996. A preliminary study on late Quaternary flora in Chabyer Caka Salt Lake Xizang (Tibet) (in Chinese). Acta Micropalaeontol Sin, 13: 395–399

Xu Q H, Li M Y, Zhang S R, Zhang Y H, Zhang P P, Lu J Y. 2015. Modern pollen processes of China: Progress and Problems (in Chinese). Sci Sin Terrae, 58: 1661–1682

Xu Q H, Yang X L, Wang Z H, Zhang N J, Li W Q, Cui Z J. 1996. Vegetational and environmental changes of Kunlun Mt. pass area since late Pleistocene (in Chinese). Acta Micropalaeontol Sin, 13: 387–393

Xu R, Tao J R, Sun X J. 1973. On the discovery of a *Quercus semicarpifolia* bed in Mount Shisha Pangma and its significance in botany and geology (in Chinese). Acta Bot Sin, 15: 103–119

Xu R. 1956. Present situation of palynology and prospect of spore pollen analysis in China (in Chinese). Chin Sci Bull, 1: 49–52

Yan B, Chen Q, Zhou Y, Fang X, Liu X. 2020. Terpenoids in surface soils from different ecosystems on the Tibetan Plateau. Org Geochem, 150: 104125

Yang B, Tang LY, Brauning A, Davis M E, Shao J J, Liu J J. 2008. Summer temperature reconstruction on the central Tibetan Plateau during 1860–2002 derived from ice core pollen. J Geophys Res, 113: D24102

Yang H Q, Jiang D X. 1965. The spore and pollen assemblages from the Quaternary deposits of the Chinghai Lake Basin and their significance (in Chinese). Acta Geogr Sin, 31: 321–335

Yang X D. 1996. Pollen assemblage and palaeoclimate during last 2000 year in Ximencuo region, Qinghai (in Chinese). Acta Micropalaeontol Sin, 13: 437–440

Yao Z J. 2000. Ice-core pollen studies from the Dunde and Guliya Ice Caps, Qinghai-Tibetan Plateau, China. Dissertation for Doctoral Degree. Baton Rouge: Louisiana State University, USA. 209

Yu G, Chen X, Ni J, Cheddadi R, Guiot J, Han H, Harrison S P, Huang C, Ke M, Kong Z, Li S, Li W, Liew P, Liu G, Liu J, Liu Q, Liu K B, Prentice I C, Qui W, Ren G, Song C, Sugita S, Sun X, Tang L, Van Campo E, Xia Y, Xu Q, Yan S, Yang X, Zhao J, Zheng Z. 2000. Palaeovegetation of China: A pollen data-based synthesis for the mid-Holocene and last glacial maximum. J Biogeogr, 27: 635–664

Yu G, Sun X J, Qin B Q, Song C Q, Li H Y, Prentice L C, Harrison S P. 1998. Mid-Holocene vegetation distribution in China simulated by pollen vegetation (in Chinese). Sci China Ser D-Earth Sci, 28: 73–78

Yu G, Tang L, Yang X, Ke X, Harrison S P. 2001. Modern pollen samples from alpine vegetation on the Tibetan Plateau. Glob Ecol Biogeogr, 10: 503–519

Zhang X Z, Yang Y P, Piao S L, Bao W K, Wang S P, Wang G X, Sun H, Luo T X, Zhang Y J, Shi P L, Liang E Y, Shen M G, Wang J S, Gao Q Z, Zhang Y L, Ouyang H. 2015. Ecological change on the Tibetan Plateau (in Chinese). Chin Sci Bull, 60: 3048–3056

Zhang Y F, Zhang J P, Xu J M, Lin F. 1995. Paleoclimate evolution of the Yellow River source area since Holocene epoch (in Chinese). Earth Sci—J China Uni Geosci, 20: 445–449

Zhang Y, Kong Z, Zhang Q B, Yang Z. 2015. Holocene climate events inferred from modern and fossil pollen records in Butuo Lake, Eastern Qinghai-Tibetan Plateau. Clim Change, 133: 223–235

Zhao D, Wu S, Yin Y, Yin Z Y. 2011. Vegetation distribution on Tibetan Plateau under climate change scenario. Reg Environ Change, 11: 905–915

Zhao Y, Yu Z, Chen F, Ito E, Zhao C. 2007. Holocene vegetation and climate history at Hurleg Lake in the Qaidam Basin, northwest China. Rev Palaeobot Palynol, 145: 275–288

Zhao Y, Tzedakis P C, Li Q, Qin F, Cui Q Y, Liang C, Birks H J B, Liu Y L, Zhang Z Y, Ge J Y, Zhao H, Felde V A, Deng C L, Cai M T, Li H, Ren W H, Wei H C, Yang H F, Zhang J W, Yu Z C, Guo Z T. 2020. Evolution of vegetation and climate variability on the Tibetan Plateau over the past 1.74 million years. Sci Adv, 6: eaay6193

Zhao Y. 2018. Vegetation and climate reconstructions on different time scales in China: A review of Chinese palynological research. Veget Hist Archaeobot, 27: 381–392

Zhou K S, Liang X L, Ye Y Y, Wang W L. 1960. Pollen and plant residues in buried soil of old loess in Chenjiaya, Wangjiawan, Lishi, Shanxi (in Chinese). Quat Sci China, 3: 104–109

Zhou W J, Yu S Y, Burr G S, Kukla G J, Jull A J T, Xian F, Xiao J, Colman S M, Yu H, Liu Z, Kong X. 2010. Postglacial changes in the Asian summer monsoon system: A pollen record from the eastern margin of the Tibetan Plateau. Boreas, 39: 528–539

Zhu L, Lü X, Wang J, Peng P, Kasper T, Daut G, Haberzettl T, Frenzel P, Li Q, Yang R, Schwalb A, Mäusbacher R. 2015. Climate change on the Tibetan Plateau in response to shifting atmospheric circulation since the LGM. Sci Rep, 5: 13318

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