This book provides an important reference guide to pollen and spore identification for Chinese Quaternary palynological studies. Presenting and describing more than 400 color photomicrographs of pollen grains and spores retrieved from sediments in China, it offers a unique asset for researchers, graduate students, and newcomers to the field of Quaternary palynology, which constitutes a major aspect of Quaternary paleoecology, paleoclimatology, and paleogeography.
Lingyu Tang · Limi Mao · Junwu Shu · Chunhai Li · Caiming Shen · Zhongze Zhou
Editors

Atlas of Quaternary Pollen and Spores in China
Quaternary palynology is more closely related to the extant vegetation than palynological studies of other geological ages. Knowledge of the floristic composition and characters of the extant vegetation is of pivotal importance for identification of fossil pollen and spores and interpretation of the nature of palynofloras. Not only taxonomic comparisons could be easily made between similar or identical Quaternary and modern palynomorphs, but heterogeneity and polymorphism of palynomorphs may be feasibly recognized by comparison with those of the relevant extant vegetation. For interpretation of the nature and evolution of palynofloras, detailed information of the extant vegetation is also indispensable. A useful handbook for Quaternary palynological studies which fully illustrates common Quaternary palynomorphs of different areas in China, with discussion on the extant floristic composition and vegetation characters of the relevant regions as well, is a want that felt.

Since 2005, Professor L. Y. Tang and his collaborators who have engaged in Quaternary palynology for several decades, spent more than ten years to compile the comprehensive volume untitled *Atlas of Quaternary Pollen and Spores in China* based mainly on the published and unpublished data of the authors. It includes descriptions and micrographs of about thousand genera of Quaternary pollen and spores, belonging to more than 300 families. As China has a vast territory with complex vegetation types and a great variety of plants, the Quaternary pollen and spores are dealt with in five divisions, i.e. northwest, north (+ northeast), southeast, south, and southwest regions in accordance with the recent vegetation regions.

In this book, an overview of the vegetation from the recent and Quaternary in the five regions of China is made, focusing on the composition, characters of pollen and spores and the evolution history of paleovegetation and paleoclimate in different regions since the Pleistocene.

The authors describe the major types and characteristics of Quaternary pollen and spores in each region of China with a number of keys to the identification of common pollen and spores and gives detailed diagnostic descriptions and comparisons of the pollen morphology of some genera and families with regional characteristics. In total, 409 plates of light and scanning electron micrographs of pollen and spores arranged respectively in order of Algae, Pteridophytes, Gymnosperms and Angiosperms in each region are illustrated with their
familial, generic and specific or even variety names.

Although the illustrated volume published in the form of a handbook, it is in fact an all-round contribution and summary of the subject. It provides a good introduction and guide to Quaternary palynology in China as also serves as a useful atlas for identification of pollen grains and spores from Quaternary sediments. It will no doubt be greatly welcomed by graduate students, beginners as well as experienced researchers of Quaternary palynology, vegetation evolution and Geology. The book should also be of interest to palynologists and specialists who work on global environmental and climatic changes and related fields abroad.

The publication of an English translation by Science Press and Springer is to be congratulated.

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November, 2017
The flora of China is one of the richest and most diverse in the world. In addition, biogeographically China encompasses virtually all the major vegetation zones on Earth, from tropical rain forest in the south to boreal forest in the north, and from tundra at high elevations to deserts and steppes in the west. This floristic richness and biogeographic complexity poses significant challenges to palynologists, whose primary mission is to use fossil pollen and spores recovered from sedimentary archives to reconstruct the patterns and processes of vegetation changes, especially during the Quaternary Period. These challenges come from the basic need to correctly identify the fossil pollen and spores to the lowest possible taxonomic level. To overcome these challenges requires, at a minimum, a well-documented atlas of the pollen and spores produced by the most common or important plant taxa in different biogeographic regions. This book, *Atlas of Quaternary Pollen and Spores in China*, exactly fulfills this need.

This book contains 409 well-illustrated color photomicrographs of pollen and spores from more than 300 families and nearly 1,000 taxa representing the pollen flora of five different geographical regions in China. This is only a small fraction of the over 30,000 species of plants native to China, but the list includes most of the fossil pollen and spores commonly found in the Quaternary sediments from China. In addition, these photomicrographs are accompanied by detailed descriptions of their morphological characteristics, which are a helpful aid to microscopic identification. Thus, this book is an enormously useful resource to all palynologists working in China.

However, this book is much more than just a pictorial key to the common palynomorphs found in China; it is also a useful textbook on the biogeography and Quaternary paleoecology of China. Chapter 1 contains overviews of the modern vegetation and Quaternary vegetation history of five different geographical regions in China. This is a fitting opening to the book and a welcome addition to the pollen atlas and descriptions that form the bulk of Chapters 2 and 3, as it puts the regional pollen flora and assemblages in their broader biogeographic and historical contexts. In this way, this book is required reading for all biogeographers and paleoecologists interested in the Quaternary vegetation history of China.

This book distinguishes itself from some other pollen atlases in that it covers not only the pollen and spores from angiosperms, gymnosperms, pteridophytes, and bryophytes, but also some algal remains as well. Some algae, such as *Pediastrum*, are often found in palynological
preparations and they can offer useful paleoenvironmental information such as water quality and water depth. It is also remarkable that while this book focuses on the Quaternary pollen and spores, it could also be of interest to palynologists working with Tertiary palynomorphs and sediments. The modern and Quaternary vegetation of China is well-known to contain a significant number of floristic relicts, which have survived environmental changes in refugia in China since Tertiary times. These Tertiary relicts, such as *Gingko, Metasequoia,* and *Keteleeria*—just to name a few, are also components of the Quaternary pollen assemblages in certain parts of China. The correct identification of these rare pollen taxa would be a prerequisite in understanding the Quaternary history of these Tertiary relicts in the Chinese flora.

The authors of this book are renowned, active palynologists with decades of experience working on the Quaternary pollen and spores of China. The photomicrographs are mostly derived from their original research collections, and the morphological descriptions and regional overviews are based on their collective research experience in this scientific field. It is indeed important, and timely, that they share their knowledge in Quaternary Palynology with the international scientific community. This book should be on the shelf of every palynologist or biogeographer who is interested in the Quaternary vegetation history of China, or anywhere else in the world. I congratulate the authors on their contributions and accomplishments that have culminated in the publication of this seminal work in English.

Kam-biu Liu
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March 13, 2018
Spore-pollen has been identified as an essential indicator of past vegetation and climate since more than 100 years ago. Hitherto, palynological data is the most developed proxy in reconstructing past vegetation qualitatively and quantitatively. However, the reliability of reconstruction depends severely on the reliability of spore-pollen optical identification and its taxonomic resolution. China is characterized by complex climate, topography and vegetation, which possesses different biodiversities in biogeographically different regions. Hence, a high-quality illustrated handbook to cover the complexity is essential for palynological study.

Professor Lingyu Tang, an 80-years old well-known Chinese palynologist, has been working on spore-pollen identification for 55 years with samples collected across China. After retired in 2001, Prof. Tang began to train master and PhD students in spore-pollen identification who comes from many universities and institutes of Chinese Academy of Sciences, including three of my students from University of Lanzhou. He contributed greatly to Chinese palynological research.

I am very pleased that Prof. Tang, as the first author, published a Chinese atlas of Quaternary spore and pollen in 2016 named by *Atlas of Quaternary Pollen and Spores in China*. In order to popularize the atlas to foreign palynologists who are working with China and Asia spore-pollen identification, Prof. Tang and his collaborators finalized this English version. It is my pleasure to prepare this foreword to recommend this handbook internationally.

In this book, based on modern vegetation and climate conditions of China, authors introduced the generally pollen-based late Quaternary vegetation change patterns of five regions: northwest, north, southeast, south, and southwest regions. For each region, authors introduce two to four representative pollen records to illustrate the common spore-pollen taxa and their potential changes in abundances; followed by their descriptions and micrographs. In my opinion, the regional introductions of spore-pollen assemblages is quite essential because of the high plant diversity of China and the specific plant species ensemble covered by a pollen taxon among different regions.

I think this handbook is a valuable reference for spore and pollen grains identification.
from Quaternary sediments in China and adjacent regions. I congratulate Prof. Tang and other co-authors to publish this handbook.

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September, 2018
Quaternary Palynology is an important branch of Quaternary science. It concerns morphology and classification of plant pollen and spores as well as pollen analysis. Pollen analysis is a unique means for the studies on past vegetation succession, climate change, and human-induced effects on vegetation, it thus plays a key role in the studies of paleoecology and global change. Nowadays, global warming is becoming more and more obvious, most likely due to anthropogenic forcing. A better understanding of climatic and eco-environmental changes under natural and anthropogenic conditions are essential to assess the impacts of global warming on the human societies and natural ecosystems and to develop suitable adaptation and mitigation policies. Pollen analysis has played an irreplaceable role of other disciplines in past studies of global change for understanding climatic and environmental changes, revealing their dynamic mechanism, and predicting their future trends of evolution.

Pollen morphology is the basis of Quaternary palynology. In the past several decades, Fuhsiang Wang, Tsengchieng Huang, Jintan Zhang, Yizhen Xi, Yulong Zhang, and other palynologists published a series of books and papers on pollen morphology of modern plants, which provided important reference for the identification of pollen and spores in Chinese Quaternary palynological studies. Even so, the correct identification of pollen and spores is still affected by the shape deformation of some pollen grains and spores caused by various factors in their burial procedures and certain subjectivities in identification standards, which lead to their identification difficulty and even deviation. Especially for the beginners in palynology, “a simple comparison of modern pollen photomicrographs with a fossil pollen grain” easily results in wrong identification. The authors, engaging in work of Quaternary palynology for several decades, profoundly understand an atlas of pollen and spores from Quaternary sediments as an identification reference necessary for beginners as well as relevant experienced researchers in palynology. To this end, we have collected pollen data and photomicrographs from on-going studies and publications since 2005. Atlas of Quaternary Pollen and Spores in China is the result of our many years’ work.

The most of data and photomicrographs of Quaternary pollen and spores used in this book are from the authors, who accumulated these materials in their Quaternary palynological studies over many years. Only a small number of photomicrographs of fossil and modern pollen are from other palynologists. For example, Drs. Ximmiao Lü and Qinfeng Ma provided
some photomicrographs of pollen grains from Holocene lake sediments in Xizang; Drs. Anding Pan, Wenzhao Zhang, and Xuemei Chen provided some photomicrographs of pollen grains from arid and sub-arid regions. The authors completed collecting and arranging plates of photomicrographs for common pollen and spores from Quaternary strata in more than 10 years. Given China’s vast territory, complex vegetation types, a variety of plants, and pollen grains with similar morphology probably produced by different plant species in different regions, this book’s photomicrographs of pollen and spores are organized in a five-region division of China, i.e. northwest, north, southeast, south, and southwest regions.

This book includes three chapters. The first chapter is an overview of modern and Quaternary vegetation in five regions of China, focusing on regional evolution history of paleovegetation and paleoclimate since the Pleistocene. Note that the $^{14}$C dates used in this chapter are not unified, just following the original publications. They can be uncalibrated or calibrated ages, used as “ka BP” or “cal. ka BP”. The second chapter describes major types and characteristics of Quaternary pollen and spores in each region of China, and makes comparisons of identifiable keys among common types of pollen and spores in different regions of China. This chapter gives detailed diagnostic descriptions on the pollen morphology of some genera and families with regional characteristics, also makes comparisons of pollen morphology among some genera. For instance, comparisons of identifiable features and morphological descriptions are made among some arid and semi-arid plant pollen types with similar morphological characteristics [such as some genera from Zygophyllaceae, Compositae (Asteraceae), Elaeagnaceae, and Umbelliferae (Apiaceae)] in northwest region; identification keys and diagnostic descriptions of pollen morphology for genera of Betulaceae, and comparisons of fossil pollen morphological characteristics for *Pinus, Abies,* and *Picea* in north region are made; identification keys of pollen morphology for genera of Fagaceae in southeast region are listed and described; comparisons of fossil pollen morphological characteristics are made among genera of Pinaceae in southwest region; Sonneratiaceae and Rhizophoraceae of mangrove trees in south region are described. The third chapter is a collection of photomicrographs and their descriptions of pollen grains and spores from different regions of China. Since spores from bryophytes and cell parts of algae such as *Pediastrum* and *Concentricystes* are also commonly found in pollen extracts of Quaternary lacustrine sediments, some of them are also included in this chapter. Photomicrographs of pollen and spores in each region are arranged by plant classification system, i.e. in order of algae, bryophyte, pteridophyte, gymnosperm, and angiosperm. 409 plates of color photomicrographs of pollen and spores are finally illustrated. Among them, 63, 63, 108, 44, and 131 plates are for pollen and spores from northwest, north, southeast, south, and southwest regions. Below each plate, the numbers of photomicrographs for pollen and spores are followed by their family, genus or species name according to modern plant natural nomenclature for readability.

Carl Zeiss and Olympus microscopes with high optical resolution and semi-apochromatic objectives (40×, 60×, and 100×) were used in the observation of pollen and spores.
Photomicrographs for pollen and spores were taken using regular digital cameras and high pixel CCD cameras. Pollen grains were photographed using 40× or 60× lenses in most cases, and few pollen grains were done using a 100× oil immersion lens to capture clear ornamentation of the exine. The photomicrographs except of CCD images are reproduced on a scale of 8 mm to 10 micron, the scale of CCD images is directly obtained online.

The correct identification of pollen and spores depends on how much information observers obtain on the morphology of pollen and spores using microscopes. Under normal circumstances, observers would like to observe pollen grains and spores from different planes (e.g. polar and equatorial view), angles, and focus levels (e.g. upper focal, optical, and lower focal planes). Therefore, the reference books of pollen morphology attempt to show the full range of features using as many photomicrographs for the same pollen grains from different angles as possible. In this book, we provide a number of photomicrographs for the same pollen taxa to facilitate readers’ contrast and identification. The size of pollen and spores is one of reference features for pollen identification, the relative sizes of different pollen taxa are shown in the same plate using a single scale. Sometimes for typographical beauty, different scales are directly marked on the corresponding photomicrographs for some large pollen grains and spores.

To facilitate the reader to quickly search, the numbers of photomicrographs for pollen and spores on each plate are followed by their family, genus or species name according to modern plant natural nomenclature as well as fossil sites for readability. For each region, pollen taxa are arranged alphabetically according to their Latin name of family. Within the same family, the genera are also arranged alphabetically according to the first letter of their Latin name of genus. All of the photographs that have a species name are taken from modern pollen grains. And “cf” written before the species name represents related species of fossil pollen. Some fossil pollen grains cannot be identified at the genus level because of the fossil preservation and/or unclear photomicrographs, so they are designated as “unidentified family name”. In this book, most photomicrographs are optical microscope photos, a few are SEM or LCS photos, which are respectively indicated after photomicrograph. Additionally, *Quercus* of Fagaceae has a lot of species, its pollen grains cannot be distinguished into species but into two types, i.e. evergreen oak and deciduous oak, named as *Quercus* (E) and *Quercus* (D) in the book.

Many people and organizations contributed to our efforts. We thank particularly Drs. Xinmiao Lü, Qingfeng Ma, Anding Pan, Wenchao Zhang, Xuemei Chen, Deke Xu, Lu Dai for their providing us some pollen photomicrographs, Dr. Xiaoping Zhang and Jianwen Shou for their help in the classification of Compositae pollen, their helps enrich the content of this book. We acknowledge and thank Yiman Fang and Chunlei Yang for their hard work in composing photomicrographs; Chunmei Ma, Yiman Fang, Yongtai Zhao, Yongfei Li, Ning Yang, Lin Zhao, Anning Cui, Bing Li, Xiaoyi Fan, Erjun Zhuo, and Haochen Pan, for their assistance in editing work. We also thank the academician Zhiyan Zhou at the Nanjing Institute of Geology and Palaeontology, Chinese
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The authors hope that the book will be useful for graduate students, beginners as well as experienced researchers in Quaternary palynology. The authors have confidence that this book will provide a good reference for the identification of pollen grains and spores from Quaternary sediments. However, the limitations of our knowledge, cognition ability, and accumulation of past work might circumscribe the comprehensiveness of our understanding some pollen grains and spores, and the accuracy of our identifying some genera and species; the limitation of our accumulated materials on hand also gives rise to that some pollen types are not compiled into this book, especially that few photomicrographs are not as beautiful as others, even look blurred. These defects might be found somewhere in the book, we sincerely accept comments, suggestions, and criticisms from colleagues.

The authors

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July, 2018
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Overview of Modern and Quaternary Vegetation in China
A variety of vegetation types from forest to grassland and desert as well as from tropical rain forest to cool coniferous forest and alpine tundra occur in China’s vast territory. Except for the equatorial rainforest, most of the vegetation types on Earth can be found in China. Thus these vegetation types become the basis of vegetation divisions in China. In terms of latitudinal and altitudinal differences based on climate, China can be divided into a series of vegetation zones, such as cold-temperate coniferous forest, temperate mixed conifer-broadleaved forest, warm-temperate deciduous broadleaved forest, subtropical evergreen broadleaved forest, tropical monsoonal rainforest, and rainforest, as well as temperate grasslands, temperate desert, and the Tibetan Plateau high-cold vegetation zonation. On the basis of the above vegetation zones and the Quaternary pollen records we have collected from these zones over the years, we divide the whole China into five regions—northwest, north, southeast, south, and southwest—to describe modern and Quaternary vegetation, and to display pollen photomicrographs of major taxa. Among the five regions, northwest region includes Xinjiang, Qinghai, Gansu, northern Tibetan Plateau, and western Inner Mongolia; north region includes North China Plain and Northeast China; southeast region includes Fujian, Jiangsu, Zhejiang, Anhui, Hubei, Jiangxi, Hunan, and Taiwan provinces; south region includes Guangdong, Guangxi, Hainan Island, the South China Sea, and Hong Kong; and southwest region includes Sichuan, Yunnan, Guizhou, and southeast Xizang (Figure 1.1).

1.1 Northwest Region

Quaternary fossil pollen and spores in northwest region are mainly collected from the late Pleistocene strata of sites in Xinjiang, Qinghai, Gansu, western Inner Mongolia, northern Tibetan Plateau, and western Loess Plateau. Regional vegetation of these sites mainly includes Gobi Desert in intermontane basins of eastern Xinjiang,
high-cold desert in the Qaidam Basin, steppe-meadow-shrubland in the Yellow River Plateau of Qinghai, desert and steppe in Hexi Corridor, and steppe and desert-steppe in western Inner Mongolia Plateau. Oak forest, pine forest and shrubland steppe occur in the regional vegetation of western Loess Plateau, while temperate and warm-temperate deciduous broadleaved forests exist in the regional vegetation of central and southern Loess Plateau.

1.1.1 Overview of modern vegetation

1.1.1.1 Gobi Desert in eastern Xinjiang

The Gobi Desert region in the intermontane basins of eastern Xinjiang mainly includes Yanqi, Turpan, and Hami basins, where climatic conditions are dry with little rainfall, strong sunlight, and great evaporation. The water for plant growth is from seepages of upper diluvial fans and karez supplies in this region. Such severe natural conditions cause poor plant diversity and simple vegetation type. Common plant communities are *Alhagi sparasifolia*, *A. canescens + Phragmites communis + Karelinia caspia*, *Phragmites communis + Lycium ruthenicum*, *Phragmites communis + Aeluropus littoralis*, and some halophytes, such as *Halocnemum strobilaceum*, *Halostachys caspica* and *Salicornia herbacea*. In addition, there are sporadic distributions of secondary salt desert plants including *Tamarix* spp., *Nitraria sphaerocarpa*, *Glycyrrhiza uralensis*, and *Glycyrrhiza inflata*.

1.1.1.2 Extremely arid desert scrub in the Qaidam Basin

The Qaidam Basin has a harsh arid continental climate with extreme drought and dramatic change in temperature. This condition leads to the development of a special vegetation type, the desert scrub. It consists of extremely sparse salt-tolerant *Ephedra przewalskii*, *Haloxylon ammodendron*, *Reaumuria songarica*, and *Eurotia ceratooides*. Meanwhile, desert-steppe with bunch grass often appears in the area from piedmont desert to basin center. Sparse *Nitraria tangutorum*, *Leymus secalinus*, *Phragmites australis* and *Mespilus germanica* scrub communities grow in the saline desert soil of the riverbank terrace and alluvial plain. The center of the basin is occupied by irregular salt meadows composed of reeds and grasses, and salt marsh communities dominated by *Eleocharis afropurpurea*, *Scirpus pumilus*, and *Carex aterrima*.

1.1.1.3 Arid desert scrub and semi-scrub in the Hexi Corridor

In the Hexi Corridor adjacent eastern Qaidam Basin, montane desert steppes dominated by xeric scrubs and semi-scrubs of grass and *Artemisia* occupy alluvial plains in front of mountains. Vegetation communities mainly consisting of *Reaumuria songarica* and *Salsola passerina* grow in piedmont alluvial and diluvial plains. Widely occurring in piedmont diluvial plains are gravel deserts dominated by xeric scrubs and semi-scrubs including *Ephedra przewalskii*, *Calligonum mongolicum*, *Nitraria sphaerocarpa*, *Asterothamnus centrali-asiaticus*, *Reaumuria songarica*, and *Anabasis brevifolia*. In the regions near the Badain Jaran desert and Tengger desert appear psammophytes *Calligonum mongolicum*, *Zygophyllum xanthoxylon*, *Oxytropis aciphylla*, *Ammopiptanthus mongolicus*, *Pugionium cornutum*, *Agriophyllum arenarium*, *A. gobicum*, *Corispermum hyssopifolium*, *Hedysarum scoparium*, *Artemisia spaerocephala*, and *Salsola kali*.

1.1.1.4 Forest-steppe and pine-oak forest in a temperate semi-humid and semi-arid transition zone of monsoon climate in the Loess Plateau

The loess hilly region west of Liupan Mountain in the western Loess Plateau has a temperate monsoon climate transitional between semi-humid and semi-arid conditions. It is separated into southern and northern parts by the upper reaches of the Weihe River. Its southern part is occupied by forest-steppes consisting of *Pinus armandii* and *Quercus wutaishanica*, whereas its northern part by arid steppes composed of *Stipa bungeana*, *Aster altaicus* and *Artemisia*. Arid steppes in the region close to Qin’an and Jingning of Gansu have shrubs such as *Sophora vicifolia*, *Ziziphus spinosa*, *Hippophae rhamnoides*, and *Ostryopsis davidiana*. From this region
eastward to the Luohe River region occurs the Qinling flora with complicated components and distinct vertical zonation. Montane forests are characterized by deciduous broadleaved forest and *Platycladus orientalis* forest. The former is generally composed of *Salix, Populus, Ulmus, Sophora, Ailanthus altissima, Toona sinensis, Broussonetia papyrifera, Morus, Gleditsia sinensis, Euonymus alatus, Cotoneaster* sp., and *Platycladus orientalis*. At elevations of 1000–2500 m mixed forests of *Pinus armandii*, oak, and deciduous broadleaved trees occur. This mixed forest has many types of plants, including *Quercus* spp., *Carpinus turczaninowii*, *Corylus*, *Cornus macrophylla*, *Acer* spp., *Salix, Lespedeza buergeri, Campylopotropis macrocarpa, Berberis* sp., and *Spiraea salicifolia*. The vegetation types above 2500 m are birch forest and alpine coniferous forests including *Larix potaninii* forest and fir forest. Common shrubs and herbs under forest are *Rhododendron* spp., *Lonicera japonica, Euonymus alatus, Rosa* spp., and *Ribes* sp.

Central and southern Loess Plateau, mainly consisting of Weihe River basin and Luohe River drainage, is located in the transitional zone between north temperate continental monsoon climate and south subtropical humid monsoon climate, so it belongs to the warm-temperate semi-humid monsoon climate, and has obvious mountain climate characteristics due to mountainous and rolling terrains. Modern vegetation is significantly influenced by human activities. *Quercus variabilis* forest zone occurs in low mountains and hills at elevations of 600–1100 m. Its constructive species are *Quercus variabilis* and *Pinus tabuliformis*, with accompanying trees such as *Quercus aliena, Populus, Ulmus, Sophora, Ailanthus altissima, Pistacia chinensis, Paulownia, Diospyros, Juglans, Castanea*, and other deciduous broadleaved elements in temperate and warm-temperate zone. Understory shrubs include *Rhus chinensis*, *Cotinus coggygria*, *Dalbergia hupeana, Campylopotropis macrocarpa*, and *Lespedeza bicolor*, while understory herbs are *Imperata cylindrica, Artemisia gmelinii, Carex rigescens*, and *Anemone vitifoliane*. *Pinus armandii* and *Quercus aliena var. acuteserrata* forest zone occurs at elevations of 1100–1800 m. Its constructive species are *Pinus armandii, P. bungeana, Quercus aliena var. acuteserrata, Tilia* sp., and *Ailanthus altissima*, accompanied by some dominant trees such as *Pinus tabuliformis, Quercus aliena*, and *Populus davidiana*. *Cotinus coggygria*, *Campylopotropis macrocarpa*, and *Forsythia suspensa* are its major understory shrubs, and *Deyeuxia arundinacea, Dendranthema indicum, Asparagus cochinchinensis*, and *Epimedium brevicornu* are its understory herbs. Birch forest zone appears at elevations of 1800–2300 m, in which *Betula albosinensis, B. luminifera, B. utilis, B. platyphylla, Pinus armandi, Tilia* sp., *Rhus chinensis*, and *Pinus tabuliformis* are the dominant species of tree layer; *Lonicera japonica, Carpinus turczaninowii, Campylopotropis macrocarpa, Corylus heterophylla, Rhododendron* spp., and *Zanthoxylum bungeanum* are its understory shrubs, and *Carex lanceolate, Poa annua, Pyrola calliantha, Gentiana scabra*, and *Pedicularis resupinata* are its understory herbs. Fir forest occurs in Caolian Mountain above 2300 m. *Abies fargesii* and *A. chensiensis* are its constructive species. *Rhododendron* spp., *Rosa tsinglingensis*, and *Lonicera japonica* are its shrubs, and *Carex* spp., *Artemisia* spp., and *Parnassia palustris* are its herbs.

### 1.1.2 Overview of Quaternary vegetation

#### 1.1.2.1 Vegetation and environment since the early Pleistocene in Qinghai region

The earliest study of Quaternary pollen and spores in northwest region was the investigation on Quaternary pollen assemblages in Qinghai Lake basin by Yang and Jiang (1965). It was followed by pollen flora and paleoclimate studies on Quaternary sediments from QH85 core in Qinghai Lake (Du *et al.*, 1989), Gonghe basin and Kunlun Mountains Pass (Tang and Wang, 1976b; Tang and Wang, 1988), Qaidam Basin (Du and Kong, 1983), and Zoigê Basin (Liu *et al.*, 1995; Shen C M *et al.*, 2005). Later, more detailed pollen studies on Quaternary sediments from the Qinghai Lake were conducted (e.g. Liu X Q *et al.*, 2002; Shen J *et al.*, 2005a).

Pollen data indicate that Quaternary vegetation developed from warm-temperate semi-desert steppes of the late Neogene in the most of northwest region. Quaternary vegetation has distinct characteristics of
temperate vegetation zone, in which *Pinus*, *Betula*, *Quercus*, and *Juglans* are its common components. In the early Pleistocene, pollen spectra were dominated by herbaceous pollen with minor changes, and marked changes occurred in the contents of tree and shrub pollen as the global climate fluctuated. A few relict plants of Paleogene and Neogene can be found in the pollen spectra. In the pollen record from Dalangtan of the Qaidam Basin, the pollen assemblage in the early stage of early Pleistocene was dominated by herbaceous pollen *Artemisia* and *Poaceae* (ca. 80%) with a few *Pinus*, *Picea*, and aquatic plant pollen. Arboreal pollen dominated by *Pinus* together with broadleaved components such as *Betula*, *Ulms*, *Quercus*, *Corylus*, *Carpinus*, and *Fraxinus* increased, while herbaceous pollen was dominated by *Artemisia* and *Chenopodiaceae* in the middle stage. *Ephedra* and *Chenopodiaceae* largely appeared with an increase of *Poaceae* (Gramineae) and *Picea*. Meanwhile, *Ulms*, *Carpinus*, *Caryophyllaceae*, *Labiatae*, *Solanaeaceae*, and *Polygonum* were present in the late stage of early Pleistocene (Table 1.1). In the Gonghe basin, early Pleistocene pollen spectra contained some relict plants of Paleogene and Neogene, such as *Tsuga*, *Podocarpus* and *Cedrus*. Steppe, forest-steppe, and desert-steppe were major vegetation types in the early, middle, and late periods of early Pleistocene, respectively (Tang and Wang, 1988). The early Pleistocene pollen record from the Erlang section in Qinghai Lake contained some *Pinus*, *Populus*, *Cupressaceae*, *Salix*, *Betula*, *Alns*, *Quercus*, *Poaceae*, *Liliaeaceae*, *Leguminosae* (Fabaceae), *Chenopodiaceae*, *Rosaceae*, and *Artemisia* pollen, and few *Cedrus* pollen grains (Yang and Jiang, 1965; also see Table 1.2). Early Pleistocene pollen records from the Kunlun Mountains Pass and core 203 in the Qingshui River (Tang and Wang, 1976a, b) show that interglacial pollen spectra reflected spruce forest dominated by *Picea* together with *Podocarpus* and *Tsuga*, indicating cool and wet climatic conditions, whereas glacial pollen spectra reflected semi-arid steppe dominated by *Chenopodiaceae*, *Artemisia*, and *Liliaeaceae*. Additionally, early Pleistocene pollen spectra from the Sammen Formation (Li, 1983) and Yongledian Formation (Sun et al., 1980) in Weihe River of Shaanxi contained a few relict plants of Paleogene and Neogene such as *Tsuga*, *Podocarpus*, *Carya*, *Liquidambar*, *Ginkgo*, and *Magnolia*.

Pollen assemblages of early mid-Pleistocene in the Qaidam Basin were characterized by an obvious increase in arboreal pollen dominated by *Betula*, *Quercus*, *Ulms*, *Fagus*, *Salix*, *Corylus*, and *Tamarix*. Herbaceous pollen mainly included *Artemisia*, *Chenopodiaceae*, *Poaceae*, and *Polygonum*, and aquatic plants and ferns were common. Pollen assemblages of late mid-Pleistocene were characterized by a marked increase of herbaceous pollen dominated by xeric *Nitraria* and *Ephedra*. Other herbs included *Poaceae*, *Artemisia*, *Ranunculaceae*, *Umbelliferae* (Apiaceae), *Solanaceae* and *Cyperaceae*. Spruce and fir forest appeared once in the late mid-Pleistocene. In the Gonghe basin of Qinghai, the vegetation of early mid-Pleistocene was forest-steppe whereas it was replaced by steppe consisting of *Chenopodiaceae* and *Artemisia* in the late mid-Pleistocene. In the Qinghai Lake basin, mid-Pleistocene pollen record contained *Picea*, *Pinus*, *Populus*, *Salix*, *Alns*, *Quercus*, *Poaceae*, *Liliaeaceae*, *Leguminosae*, *Chenopodiaceae*, *Rosaceae*, *Compositae* (Asteraceae), and *Artemisia*. In the Qaidam Basin, late Pleistocene pollen spectra were characterized by an increase of broadleaved tree pollen including dominant trees such as *Quercus*, *Betula*, and *Corylus*, and accompanying components such as *Juglans*, *Carpinus*, and *Leguminosae*. Pollen spectra also had high percentage of *Artemisia*, and contained some pollen of *Chenopodiaceae*, *Poaceae*, *Cruciferae* (Brassicaeae), *Labiatae*, *Plantago*, and *Humulus*. Late Pleistocene pollen assemblage was dominated by *Populus*, *Salix*, *Picea*, *Artemisia*, and *Leguminosae* in the Qinghai Lake basin. After 150 ka BP, more *Pinus* and *Ephedra* occurred with some pollen of *Picea*, *Abies*, *Artemisia*, and a few wetland and aquatic plant pollen. A pollen record from the Qarhan Salt Lake in the Qaidam Basin (Du and Kong, 1983) shows that *Chenopodiaceae*-*Artemisia*-*Nitraria*-*Ephedra*-*Typha*, *Ephedra*-*Nitraria*-*Chenopodiaceae*-*Artemisia*-*Pediastrum*, *Pinus*-*Betula*-*Ephedra*-*Artemisia*-*Nitraria*, and *Ephedra*-*Artemisia*-*Nitraria*-*Chenopodiaceae* pollen assemblages occurred at 31.8–25.6 ka BP, 25.6–20.6 ka BP, 20.6–16.0 ka BP and 16.0–11.0 ka BP, respectively (Table 1.1).
Table 1.1 Quaternary pollen and vegetation in northwest region (part 1)

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Age /ka BP</th>
<th>Qinghai Lake (Liu et al., 2002)</th>
<th>Qaidam Basin (Du and Kong, 1983)</th>
<th>Gountong Co, Hoh Xil (Shan et al., 1996)</th>
<th>Sumxi Co, Xizang (Campo and Gasse, 1993)</th>
<th>Bangong Co, Xizang (Campo et al., 1996)</th>
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<tbody>
<tr>
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<td>Major pollen type</td>
<td>Vegetation</td>
<td>Major pollen type</td>
<td>Major pollen type</td>
<td>Major pollen type</td>
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<td>Steppe</td>
<td>Pinus, Artemisia, Chenopodiaceae</td>
<td>Artemisia increased, Chenopodiaceae decreased</td>
<td>Desert</td>
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<tr>
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<td>1</td>
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<td>Open forest-steppe</td>
<td>Pinus, Betula, Corylus, Abies, Ulmus,</td>
<td>Artemisia decreased</td>
<td>Poaceae, Compositae, Chenopodiaceae</td>
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<td></td>
<td>2</td>
<td>Pinus, Picea, Abies, Betula, Ulmus</td>
<td>Mixed coniferous and broadleafed forest</td>
<td>Artemisia, Nitraria, Chenopodiaceae, Poaceae</td>
<td>Chenopodiaceae increased</td>
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<td>Open forest-steppe</td>
<td>Ephedra, Artemisia, Nitraria, Chenopodiaceae, Poaceae</td>
<td>Steppe and Meadow</td>
<td>Desert</td>
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<td>Ephedra, Artemisia, Nitraria, Cyperaceae, Poaceae, Typha</td>
<td>Steppe-meadow</td>
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<td>Ephedra, Artemisia, Nitraria, Chenopodiaceae</td>
<td>Meadow and Steppe</td>
<td>Desert</td>
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<td>Desert-steppe</td>
<td>Ephedra, Artemisia, Nitraria, Chenopodiaceae</td>
<td>Meadow and Steppe</td>
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<td>Artemisia (50%), Ephedra, Artemisia (20%)</td>
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Table 1.2 Quaternary pollen and vegetation in northwest region (part 2)

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<tr>
<th>Epoch</th>
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<th>Dadawan, Gansu (Tang et al., 2007)</th>
<th>Sujianwan, Gansu (Tang et al., 2007)</th>
<th>Suancijou, Gansu (Li et al., 2006)</th>
<th>Qinghai Lake Basin (Yang and Jiang, 1965)</th>
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<td></td>
<td>Pinus, Picea, Cupressaceae, Chenopodiaceae, Cyperaceae</td>
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</tr>
</tbody>
</table>
The pollen record from Qinghai Lake (Liu X Q et al., 2002) shows that pollen spectra at 14.1–10.8 cal. ka BP (pollen zone QH-4) were characterized by low percentages of Betula and Ephedra as well as low pollen concentrations \((5 \times 10^3–10^5 \text{ grains/g})\), indicating the occurrence of a steppe or forest-steppe around the lake. Pollen spectra at 10.8–4.5 cal. ka BP (pollen zone QH-3) exhibited an increase in arboreal pollen percentages and pollen concentrations, and a distinct decrease in Artemisia percentages. They reflect warm and wet conditions. Pollen zone QH-3 can be further divided into three subzones. Subzone QH-3a (10.8–8.5 cal. ka BP) has high pollen concentrations \((41.3 \times 10^3 \text{ grains/g})\), together with an increase of Betula and Cyperaceae pollen and a distinct decline of Ephedra, indicating a marked rise in regional precipitation and temperature. Subzone QH-3b (8.5–7.8 cal. ka BP) is characterized by marked decreases in pollen concentrations and Artemisia (ca. 40%), and an increase of Abies and Picea, which replaced Betula to become dominant arboreal pollen types. Pollen spectra of this pollen subzone suggest cold and dry conditions. In subzone QH-3c (7.8–4.5 cal. ka BP), pollen spectra are dominated by Pinus, together with some Abies, Picea and Betula. Artemisia was the dominant herbaceous pollen, but its percentages reached its minimum of the past 14.1 ka. This subzone reflects a typical forest-steppe as regional vegetation. Overall, forests or forest-steppes occurred under the Holocene climate optimum in the Qinghai Lake region. In pollen zone QH-2 (4.5–2.5 cal. ka BP), pollen concentrations (less than \(5 \times 10^3 \text{ grains/g}\)) dropped, Pinus pollen gradually declined, Abies, Picea and Betula pollen sporadically appeared. Artemisia pollen rapidly increased. Pollen spectra of this zone indicate an evolution of regional environments into cold and dry conditions. After 2.5 cal. ka BP, pollen concentrations \((5 \times 10^3–10^5 \text{ grains/g})\) increased; regional vegetation was steppe dominated by Artemisia, Poaceae, and Cyperaceae, still indicating cold and dry conditions. In summary, the pollen record shows that, regional vegetation types developed from steppes at 14.1–10.8 cal. ka BP to forests or forest-steppes at 10.8–4.5 cal. ka BP, and then to forest-steppes or steppes after 4.5 cal. ka BP. The environment around the Qinghai Lake region changed from temperate-wet to warm-wet and to cold-dry climatic conditions (Figure 1.2; Table 1.1).

Figure 1.2  Pollen percentage diagram of major pollen types since 12 cal. ka BP from Qinghai Lake (modified from Liu et al., 2002)
1.1.2.2 Holocene steppe/meadow succession in the northern Tibetan Plateau

A continuous pollen record from the Co Ngoin core at an altitude of 4500 m in Nagqu of the northern Tibetan Plateau reveals vegetation changes throughout the late Neogene and Quaternary (Lü et al., 2001). Fossil pollen spectra at 2.8–2.6 Ma BP were dominated by Carya, Juglans, Quercus, Pinus, Tsuga, Picea, and Artemisia, indicating montane mixed coniferous and broadleaved forest under warm and dry climatic conditions. Alpine dark conifer forest developed under cool and wet climatic conditions at 2.6–2.5 Ma BP. Pollen spectra at 2.5–2.02 Ma BP were dominated by herbs such as Chenopodiaceae and Artemisia, showing high-cold shrub steppes as regional vegetation and cold-dry climatic conditions. During 2.02–1.15 Ma BP two cyclic vegetation successions occurred between montane dark conifer forest and shrub steppe dominated by Artemisia and Elaeagnus. Regional vegetation was Artemisia shrublands in the early period, but it changed to alpine shrub steppe and meadow dominated by Picea and Cyperaceae in the late period of 1.15–0.8 Ma BP. During 0.8–0.15 Ma BP, regional vegetation was dominated by Cyperaceae, indicating alpine meadows under cold and wet conditions. After 0.15 Ma BP, Chenopodiaceae and Artemisia replaced Cyperaceae, suggesting that regional vegetation change from meadows to steppes and climatic conditions became cold and dry.

Pollen records from Tanggula Mountain Pass Lake, Ahung Co, Xuguo Co, and Co Ngoin (Shen et al., 2008; Tang et al., 2009a) reveal mid-late Holocene vegetation changes in pollen source areas of these lakes in the central and northern Tibetan Plateau (Figures 1.3–1.5).
The period 8.5–4.0 cal. ka BP was characterized by steppes mainly consisting of *Artemisia* and Poaceae, as indicated by pollen records from Ahung Co, Xuguo Co, and Co Ngoin. Pollen spectra at 6.0–4.0 cal. ka BP from Tanggula Mountain Pass Lake reflect the same regional vegetation as steppes dominated by Poaceae and *Artemisia*. After 4.0 cal. ka BP, swamp meadows dominated by Cyperaceae developed in regions around these lakes, partially because of the drop of lake levels as suggested by the occurrence of several *Potamogeton* layers in Ahung Co and sedge residue-rich layers in Tanggula Mountain Pass Lake. Concurrently, a steady decline of total pollen influx values in these three lakes suggests a reduction of vegetation coverage.

These pollen records from the central and northern Tibetan Plateau reveal a history of vegetation changes and southwest monsoon fluctuations during the Holocene, which is summarized below.

1. As indicated by the pollen record from Co Ngoin, regional vegetation was dominated by steppe during intervals of 6.0–4.9 cal. ka BP, 4.4–3.9 cal. ka BP, and 2.8–2.4 cal. ka BP, and it changed from steppe to meadow during intervals of 4.9–4.4 cal. ka BP, 3.1–2.9 cal. ka BP, and 1.2–0.0 cal. ka BP. The reconstructed July temperature ($T_{july}$) from 6.0 cal. ka BP to 4.9 cal. ka BP, causing a decline in effective moisture and lake level and the formation of a peat layer in the lake. MAP began to increase towards the present level between 4.9 cal. ka BP and 4.4 cal. ka BP, whereas $T_{july}$ declined to 0.5°C lower than present. An abrupt decline in MAP and a marked rise in $T_{july}$ occurred around 4.2–4.0 cal. ka BP, causing a decrease in effective moisture and a remarkable drop of lake level. Consequently, the shallower lake allowed *Potamogeton* to grow at the coring site, eventually forming a peat layer that marked the culmination of another major drought. During the period of 3.9–2.8 cal. ka BP, MAP increased to the present value, and $T_{july}$ fell and fluctuated around the present value. Between 2.8 cal. ka BP and 2.4 cal. ka BP, $T_{july}$ only changed slightly, whereas MAP fell abruptly to about 30 mm below the present level, suggesting the occurrence of another major centennial-scale drought. After 2.4 cal. ka BP, the MAP gradually rose to the present level, and $T_{july}$ decreased slightly. However, $T_{july}$ dropped by ca. 0.8°C during the interval of 0.7–0.3 cal. ka BP, possibly indicating the occurrence of the Little Ice Age cooling event in the central Tibetan Plateau.

2. The records from Ahung Co and Xuguo Co suggest that strong monsoon occupied the central Tibetan Plateau during 8.5–6.5 cal. ka BP, especially
8.5–7.2 cal. ka BP. At that time, regional vegetation was still dominated by steppe, indicating that hydroclimatic conditions in the lake basin were not as humid as that of today in spite of the higher monsoonal precipitation in the region. A possible explanation is that the evapotranspiration at that time was also higher than that of the present due to the higher summer temperature as a result of high insolation during the early to middle Holocene. The high monsoon rainfall during that period was also observed in the records from Siling Co (Sun et al., 1993), Hidden Lake (Tang et al., 2000a) and Sumxi Co (Campo and Gasse, 1993; Table 1.1).

(3) Three century-scale drought events occurred during 5.8–4.9 cal. ka BP, 4.4–3.9 cal. ka BP and 2.8–2.4 cal. ka BP. The first time when the regional climate shifted to the present level was at 6.5 cal. ka BP in the central Plateau. Since 3.0 cal. ka BP, the temperature and precipitation have decreased gradually to the present level (Table 1.1).

Another pollen record from Zige Tangco on the Qiangtang Plateau (Figure 1.6) reveals pollen components similar to those from lakes mentioned above. Vegetation succession and climate change during the past 10.8 ka were reconstructed by means of Biome reconstruction (Herzschuh et al., 2006). Results show that temperate steppes mainly consisting of *Artemisia* and Poaceae were dominant during the early Holocene (10.8–4.4 cal. ka BP), and alpine steppes accompanied by desert elements (major components including Cyperaceae, Poaceae, Chenopodiaceae, and *Ephedra* etc.) dominated in the late Holocene (4.4–0 cal. ka BP). *Artemisia/Cyperaceae* value, a semi-quantitative summer temperature indicator, indicates a cooling trend throughout the Holocene. The Holocene optimum for plant growth existed in the interval of 7.3–4.4 cal. ka BP, as suggested by dense temperate steppes and the largest decrease in desert components. Severe cold events occurred at ca. 8.7–8.3 cal. ka BP and 7.4 cal. ka BP (Herzschuh et al., 2006).

A pollen record from Sumxi Co in the northwestern Tibetan Plateau (Campo and Gasse, 1993) provides a history of vegetation and climate in the past 12.7 ka. Low pollen concentrations and high percentages of Chenopodiaceae and *Ephedra* pollen at 12.7–10.0 cal. ka BP indicate a barren vegetation and dry climate. The pollen spectra also suggest a general trend of increasing moisture interrupted by a short Younger Dryas-chron reversal to colder and drier conditions ca. 11.0–10.5 ka BP. At 9.9 cal. ka BP, an abrupt rise in *Artemisia* and drop in Chenopodiaceae (i.e., high A/C value) signal a sudden change to a relatively warm and wet steppe climate, i.e., the strengthening of the monsoon (Campo and Gasse, 1993). This general condition persisted for ca. 3700 years from 9.9 cal. ka BP to 6.2 cal. ka BP although there was a short reversal at ca. 8.0–7.7 cal. ka BP as indicated by the increases in Chenopodiaceae. High A/C values associated with high amounts of planktonic diatoms during 7.7–6.2 cal. ka BP indicate warm humid climate and highest lake levels, implying the strongest summer monsoon at that time (Campo and Gasse, 1993). This period was followed by a dry period at 6.2 cal. ka BP, as indicated by a dramatic decline in the A/C values. The lowest A/C value at ca. 4.3 cal. ka BP indicates an extreme arid phase, which seems to have been the driest time for the entire Holocene, consistent with the lowest lake level (Campo and Gasse, 1993). After that, the modern environmental condition was established, and only minor changes happened except for a short arid pulse ca. 0.4 cal. ka BP (Table 1.1).

1.1.2.3 Vegetation and environment since the late Pleistocene in the Loess Plateau

Pollen studies since the late Pleistocene in the western Loess Plateau have been extensively conducted, e.g., pollen records from sections in Linxia (Chen et al., 1996), Jingning (Li et al., 2006), Tongwei (Tang et al., 1991b), Qin’an (An et al., 2003; Feng et al., 2004; Tang et al., 2007), Lanzhou (Li et al., 1988; Liu et al., 1994; Chen et al., 1996; Lü et al., 1999, 2003a), Maxian Mountains (Wang and Xu, 1988; Wang et al., 1991), Hezheng and Xifeng (Hu, 1994), Pingliang (Liu and Su, 1994), and Tianshui (Ju and Chen, 1998) in Gansu, as well as Qingshui River (Li, 1997) in Ningxia. In the Suancigou section of Jingning, pollen spectra (Figure 1.7) from 47 ka BP to 11 ka BP show a vegetation succession of forest-steppe→coniferous forest→forest-
Figure 1.6  Pollen percentage diagram of major taxa from Zigê Tangco in central Xizang (modified from Herzschuh et al., 2006)
Figure 1.7  Pollen diagram of late MIS3–MIS2 from the Suancigou section in Jingning, Gansu (modified from Li et al., 2006)
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steppe→ coniferous forest→ forest-steppe→ steppe→ forest-steppe→ steppe→ coniferous forest→ steppe. The development of forest indicates high precipitation, whereas high Chenopodiaceae pollen reflects arid conditions, and thus the intensity of the Asian monsoon. This pollen record hints at the occurrence of Heinrich events and provides evidence for the occurrence of Dansgaard/Oeschger (D/O) cycles in the Loess Plateau. Pollen spectra at ca. 35 ka BP from the Huajialiang section of Tongwei show dark coniferous forests dominated by spruce (Tang et al., 1991b). Pollen records from the Dadiwan and Sujiawan sections reveal a history of the Holocene vegetation and climate (Figure 1.8) (An et al., 2003). Pollen spectra between 12 ka BP and 9 ka BP dominated by Artemisia, Poaceae, and Compositae reflect a regional vegetation of steppe under cold and dry conditions. Pollen spectra between 9.0 ka BP and 7.5 ka BP are characterized by an increase in arboreal pollen, especially pine pollen and a decrease in Artemisia and Poaceae, implying a gradual rise in humidity and temperature. The coniferous and broadleaved mixed forest, consisting of Pinus, Picea, Abies, Ulmus, Betula, and Quercus together with some aquatic and hygrophytic pollen, occurred from 7.5 ka BP to 5.5 ka BP, indicating warm and wet climatic conditions. Regional vegetation changed from forests into forest-steppes implying relatively dry conditions between 5.5 ka BP and 3.8 ka BP, and then into steppes under dry conditions during 3.8–3.3 ka BP. Forest-steppes appeared again at 3.3–2.5 ka BP indicating an increase in humidity. After 2.5 ka BP, regional vegetation became steppes, suggesting cold and dry climatic conditions (Table 1.2).

Pollen records are concentrated in the drainage basin of the Shiyang River in the Hexi Corridor (Zhu et al., 2001a, b, c; Chen et al., 2006b). From ancient Zhuyeze Lake in this basin, a high-resolution pollen record reveals a history of vegetation and climate. In the early Holocene (11.6–7.2 cal. ka BP), pollen spectra were dominated by Sabina, Picea, and Pinus pollen (50%–90%), indicating the monsoonal precipitation maximum. More desert and steppe components represented by Nitraria, Poaceae, Compositae, and Artemisia appeared in the mid-Holocene (7.1–3.8 cal. ka BP), implying arid climatic conditions. After 3.8 cal. ka BP, pollen from alpine coniferous forest became common, but pollen spectra still contained relatively high herbaceous pollen from desert and steppe elements, suggesting relatively warm and wet conditions.

The central and southern Loess Plateau is chiefly located in Shaanxi. Holocene pollen records from this region mainly come from sections in the Weihe River basin and lower reaches of Luohe River, e.g. Yangguozhen (Sun et al., 1995, 1996) and Xinzhuang (Li et al., 1983) in Weinan, Baoji (Lü et al., 1999, 2003a) and Qilipu in Xianyang (Xue et al., 1999), Duanjiapo (Lin et al., 1992) and Banpo (Sun J Z et al., 1991) in Xi’an, Dongcheng in Lantian, and Yaozun in Fuping (Sun J Z et al., 1991). The Yangguozhen section in Weinan contains sediments above S1, the last interglacial paleosoil layer 1) with the thickness of 12 m. Fossil pollen spectra can be divided into 8 pollen zones, among which only the uppermost zone (zone 8) belongs to the Holocene. This zone (ca. 11.8–3.0 ka BP) is dominated by Artemisia with an average percentage of ca. 45%. It also contains some arboreal pollen such as Pinus, Picea, Tsuga, Betula, Ulmus, Juglans, and Quercus. Arboreal pollen increased between 8.8 ka BP and 5.6 ka BP implying a warmer climate (Figure 1.9). Overall, regional vegetation was dominated by steppes in the Holocene. This conclusion is supported by phytolith results. Phytolith analysis on the Holocene soil samples from Weinan shows steppe and forest-steppe as regional vegetation. Few arboreal phytoliths were found in the mid-Holocene, suggesting that regional vegetation was steppe dominated by Poaceae instead of deciduous broadleaved forest during the Holocene climatic optimum.

1.1.2.4 Vegetation and environment since the early Pleistocene in Xinjiang

Quaternary vegetation development in Xinjiang was characterized by the formation of deserts and the intensification of drought. Regional vegetation in Xinjiang during the Paleogene was tropical-subtropical arid steppe or forest-steppe. Quaternary vegetation changed into arid desert/steppe as a result of the uplift of the Tibetan Plateau in the Neogene and global cooling.
Figure 1.8  Holocene pollen percentage diagram of major taxa from the Dadiwan section in Qin’an, Gansu (modified from An et al., 2003)
Figure 1.9  Pollen diagram of Loess section at Jiangcun reservoir in Yangguozhen, Weinan (modified from Sun et al., 1995)
in the Quaternary. Vegetation communities have xeric ecological characteristics, and they are mainly composed of Chenopodiaceae, Haloxylon ammodendron, Anabasis, Salsola collina, Nitraria tangutorum, Zygophyllum xanthoxylon, Tamarix chinensis, Calligonum mongolicum, Artemisia, Saussurea japonica, Ephedra, and components of Poaceae.

Quaternary pollen records were mainly reported in the 1990s on sections from Chaiwopu and Barkol basins, and lacustrine sediments from Bosten Lake and Manas Lake (Li et al., 1990; Han and Yuan, 1990; Han, 1992; Sun et al., 1994; Pan, 1993; Yan, 1991; Zhong and Xiong, 1998; Xu, 1999). Pollen studies in this century include those from Ulungur Lake (Xiao et al., 2006a), Zhuyez Lake (Chen et al., 2006b), Bosten Lake (Huang et al., 2009), and Manas Lake (Tao et al., 2010a, b, 2013a, b). Pollen data show that the plains were occupied by deserts and desert steppes, and river valleys by bottomland forests, whereas forests and forest-steppes or forest-meadows occurred in mountains from the late Pliocene to early Quaternary as the interior became increasingly arid in Xinjiang. The forests and forest-steppes were dominated by trees such as Picea, Pinus, Abies, Larix, Betula, and Salix, shrubs and herbs such as Poaceae, Compositae, Ranunculaceae, Cyperaceae, Caryophyllaceae, Umbelliferae, Epilobium, Polygonum, Ephedra, Rosaceae, Caragana, and Hippophae. Stepps were dominated by shrubs and herbaceous plants, which include Poaceae, Cruciferae, Ranunculaceae, Compositae, Caryophyllaceae, Polygonum, Chenopodiaceae, Artemisia, Rosaceae, Lonicera, Caragana, Ephedra and others. The bottomland forests in plains consisted of trees such as birch, elm, alder, oak, poplar, and willow, shrubs and herbs such as Poaceae, Compositae, Chenopodiaceae, Leguminasae, Umbelliferae, Artemisia, Typha, they also contained few Tamarix, Reaumuria, Ephedra, and Nitraria. Desert steppes were dominated by Artemisia and Chenopodiaceae, together with other shrubs and herbs such as Poaceae, Ephedra, Cruciferae, Reaumuria, Compositae, Liliaceae, Leguminasae, Taraxacum, Caragana, Ranunculaceae, and Nitraria. Subalpine meadows were mainly composed of Cyperaceae, Artemisia, Poaceae, Caryophyllaceae, Potentilla, Ranunculaceae, Thalictrum, Compositae, Saussurea, and Polygonum etc. Meadows in low mountains consisted of Artemisia, Chenopodiaceae, Poaceae, Cyperaceae, Carex, Nitraria, Alhagi, Tamarix, Compositae, Taraxacum, Iris, and Typha.

The Neogene in the south Tianshan Mountains contained abundant pollen of pine, spruce, hemlock, podocarpus, walnut, elm, linden, birch, hornbeam, oak, maple, and honeysuckle. Most of them disappeared after the late Neogene and Quaternary glacial periods. Only montane coniferous forests were found in mountainous areas, and deciduous broadleaved forests in the Ili River valley. The grassland in the Tianshan Mountains has been existing since the Pleistocene, it developed from sparse steppes and meadows of the Tertiary after it experienced low temperature effect in the Pleistocene glacial. The Altay region has experienced aridification since the Quaternary, but its vegetation, a coniferous and deciduous broadleaved mixed forest, has not changed much. In northern Xinjiang, vegetation from 27.3 ka BP to 11 ka BP experienced a succession of meadow steppe→desert steppe→shrub steppe (Pan, 1993). Pollen records are dominated by Chenopodiaceae, and the reconstructed vegetation types depended on the accompanying shrub and herb pollen taxa. In the Barkol Basin, pollen spectra between 35 ka BP and 12 ka BP were dominated by trees such as spruce, pine, larch, fir, willow, and birch, and shrubs and herbs such as Nitraria, Poaceae, and Typha, indicating cold and wet climatic conditions. Pollen spectra after 12 ka BP were dominated by herbaceous pollen. They contained more Artemisia and Chenopodiaceae pollen and less arboreal and aquatic pollen, implying warm and dry climatic conditions during the Holocene (Han, 1992).

Holocene pollen records from Barkol Lake and Tuolekule Lake consist of major pollen types including Artemisia, Chenopodiaceae, Ephedra, Poaceae, Compositae and Betula, indicating that the regional vegetation types were gravel desert, desert, and desert-steppe. Pollen spectra at 11.6–7.9 cal. ka BP were dominated by Chenopodiaceae and Compositae, reflecting a desert arid environment. However, Artemisia and Poaceae pollen increased distinctly while
Figure 1.10  Pollen percentage and concentration diagram since 16.7 cal. ka BP from Barkol Lake in Xinjiang (modified from Tao et al., 2010)
Compositae pollen decreased dramatically at 9.4 cal. ka BP, suggesting a transitional period when regional vegetation changed from desert to desert-steppe and the environment changed from dry to warm-wet conditions. Birch pollen increased significantly and Artemisia pollen continued to increase at 7.9–4.2 cal. ka BP, indicating typical grassland developed around lakes and the warmest and wettest climatic conditions throughout the Holocene. Pollen spectra at 4.2–3.8 cal. ka BP were characterized by an abrupt decrease in Betula and Artemisia pollen and a rapid increase in Chenopodiaceae pollen, implying the expansion of desert and possibly a centennial-scale drought. After 3.8 cal. ka BP, an increase in Artemisia and Cyperaceae pollen and a decrease in Chenopodiaceae pollen suggest a desert vegetation, implying that the environment during the late Holocene was drier than the middle Holocene, but more moist than the early Holocene (Tao et al., 2009, 2010a, b; Figure 1.10; Table 1.3).

The pollen record from Bosten Lake is characterized by the predominance of desert and steppe components with little arboreal pollen since 8.4 cal. ka BP (Huang et al., 2009). Specifically, pollen spectra at 8.4–7.8 cal. ka BP have relatively high Ephedra, Artemisia, Chenopodiaceae, and Poaceae pollen percentages, and low pollen concentrations. These pollen spectra indicate that desert occurred extensively around the lake under arid environments. Pollen spectra at 7.8–6.0 cal. ka BP are characterized by a slight increase in A/C values (ca. 0.82) and a distinct rise in pollen concentrations, suggesting an increase in the vegetation cover, an expansion of desert-steppe, and a rise in effective humidity. Pollen spectra from 6.0 cal. ka BP to 3.9 cal. ka BP have more Artemisia pollen, and thus higher A/C values, and less Ephedra pollen than in the previous period, indicating a further increase in regional effective humidity and thus warm-wet climatic conditions. Pollen spectra at 3.9–1.3 cal. ka BP are characterized by a significant increase in Typha pollen and relatively high pollen concentrations, suggesting an expansion of marsh wetland and a rise in lake level. Between 1.3 cal. ka BP and 0.5 cal. ka BP, a gradual increase in Chenopodiaceae pollen at the expense of Artemisia pollen reflects the expansion of desert in the regional vegetation and the shrinking of marsh wetland, and thus a decrease in effective humidity and a drier environment. After 0.5 cal. ka BP, a drop in Chenopodiaceae and Poaceae pollen and a rise in Artemisia indicate denser regional vegetation and wetter climatic conditions than those of the previous period (Figure 1.11; Table 1.3).

Figure 1.11  Pollen percentage diagram from Bosten Lake in Xinjiang (modified from Huang et al., 2006)
Epoch

Holocene

Late

Middle

Early

Atlas of Quaternary Pollen and Spores in China

Middle/Late Pleistocene

20

Early
Pleistocene

1670
1870

100

30
70

27

24

16

15

14

13

12

11

10

9

8

7

6

5

4

3

2

1

Age
/ka BP

Desert
steppe

Steppe

Drier

Much drier

Drier

Warm-wet

Drying

Weting

Cool-wet

Artemisia, Chenopodiaceae,
Poaceae, Ephedra, Picea

Desert steppe

Chenopodiaceae, Artemisia,
Desert steppe Warm-wet
Poaceae, Compositae
Chenopodiaceae, Artemisia Arid desert Extremely dry
Chenopodiaceae, Artemisia,
Arid desert
Poaceae, Tamaricaceae
Cold-wet to
Chenopodiaceae, Artemisia Desert steppe warm-wet

Chenopidiaceae, Artemisia,
Desert
Ephedra, Poaceae
Chenopodiaceae, Artemisia, Desert steppe
Ephedra, Aster, Cyperaceae
Chenopodiaceae, Artemisia
Desert
Pinus, Betula, Ulmus, Salix, Desert steppe
Artemisia, Chenopodiaceae
Chenopodiaceae, Artemisia
Desert

Chenopodiaceae,
Artemisia,
Poaceae, Ephedra,
Compositae, Typha

Ephedra, Artemisia,
Chenopodiaceae,
Hippophae, Picea,
Polypodiaceae

Warm-wet

Cool-wet

Steppe/
Desert
steppe

Steppe

Picea, Salix, Populus,
Betula, Artemisia,
Cyperaceae

Warm-dry

Warm-dry

Desert

Ephedra, Nitraria,
Reaumuria

Cool-wet

Warm-dry

Desert

Steppe

Betula, Picea,
Salix, Artemisia,
Cyperaceae

Chenopodiaceae,
Ephedra, Nitraria,
Reaumuria
Picea, Salix, Artemisia,
Chenopodiaceae,
Ephedra, Hippophae,
Poaceae, Cyperaceae

Desert
steppe

Vegetation Climate

Chenopodiaceae,
Artemisia,
Ephedra,
Poaceae,
Cyperceae

Major pollen type

Chaiwopu Basin, Xinjiang
(Li et al., 1990)

Chenopodiaceae,
Compositae, Artemisia,
Poaceae, Ephedra

Poaceae,
Chenopodiaceae,
Compositae, Ephedra,
Thalictrum, Betula

Betula, Artemisia,
Chenopodiaceae,
Cyperaceae,
Thalictrum

Chenopodiaceae,
Poaceae, Artemisia,
Ephedra

Artemisia,
Cyperceae,
Chenopodiaceae,
Poaceae

Barkol Lake
(Tao et al., 2009)

Compositae,
Ephedra,
Caryophyllaceae

Compositae,
Poaceae,
Artemisia,
Cyperaceae

Compositae, Artemisia

Chenopodiaceae,
Artemisia, Poaceae,
Compositae,
Cyperaceae

Tuolekule Lake
(Tao et al.,
2013a,b)

Northern
Xinjiang
(Pan, 1993)
Ebinur Lake
(Wu et al.,
1996)
Manas Lake
(Sun et al., 1994)

Ephedra, Poaceae

Poaceae, Ephedra

Chenopodiaceae,
Poaceae, Artemisia,
Cyperaceae

Shrub steppe to meadow
steppe (Chenopodiaceae,
Rosaceae, Poaceae)

Desert steppe
to desert

Shrub steppe to
meadow steppe

Shrub steppe
Artemisia,
to desert steppe
(Chenopodiaceae, Chenopidaceae,
Ephedra,
Tamaricaceae,
(Desert steppe)
Salix)

Chenopodiaceae,
Artemisia,
Poaceae, Ephedra,
Hippophae, Nitraria

Artemisia,
Poaceae
Artemisia,
Chenopodiaceae,
Poaceae,
Umbelliferae,
Compositae

Artemisia,
Ephedra,
Chenopodiaceae Steppe

Chenopodiaceae,
Artemisia, Forest
Ephedra

Juglans,
Phragmites,
Sparganium

Betula,
Cupressaceae,
Artemisia,
Chenopodiaceae,
Pediastrum

Artemisia,
Forest
steppe Chenopodiaceae,
few Pediastrum

Artemisia,
Chenopodiaceae,
many Pediastrum

Aquatic
reed
plant
community

Desert
steppe

Desert
steppe and
meadow

Vegetation
Desert
steppe

Ulungur Lake
(Xiao et al., 1996)

Major pollen type Vegetation Major pollen type

Hotan Nur Lake
(Ruddya, 2009)

Desert steppe
Artemisia,
to desert
Chenopodiaceae,
(Chenopodiaceae,
Poaceae,
Artemisia,
Cruciferae
Artemisia,
(Desert steppe) Chenopodiaceae, Chenopodiaceae,
Ephedra,
Picea
Compositae)
Artemisia, Ephedra,
Cyperaceae, Typha,
Umbelliferae,
Artemisia, Poaceae,
Betula, Pinus
Chenopodiaceae
Artemisia,
Shrub steppe
Artemisia,
Chenopodiaceae,
to desert steppe Chenopodiaceae,
Chenopodiaceae,
Anabasis,
Typha,
Poaceae
Nanophyton,
Aquatic plants Artemisia, Poaceae
Chenopodiaceae, Desert to extremely
(Warm-wet
Artemisia,
dry desert
steppe)
Picea,
Chenopodiaceae,

Artemisia, Poaceae
Chenopodiaceae

Major pollen type/Vegetation

Bosten Lake
(Huang et al.,
2006)

Table 1.3 Quaternary pollen and vegetation in Xinjiang

Chapter 1 Overview of Modern and Quaternary Vegetation in China

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Pollen records in Xinjiang reveal different timing of the Holocene climatic optimum. It started at 8.0 cal. ka BP in Ebinur Lake (Wu et al., 1996), Barkol Lake (Tao et al., 2009), and Tuolekule Lake, whereas it began at 7.0 cal. ka BP in Ulungur Lake (Xiao et al., 2006a) and at 6.0 cal. ka BP in Bosten Lake (Huang et al., 2009). This is probably caused by the difference in regional environments of lake location and uncertainties in dating. Overall, arid, wet, and dry climatic conditions occurred in the early Holocene (before 8.0 cal. ka BP), mid-Holocene (8.0–4.0 cal. ka BP) and late Holocene (after 4.0 cal. ka BP), respectively. Pollen records also indicate an abrupt centennial climate event at ca. 4.2 cal. ka BP (Table 1.3).

1.2 North Region

1.2.1 Overview of modern vegetation

Pollen records and pollen photomicrographs in north region collected in this book are mainly from the Quaternary strata of the Sanjiang Plain, Changbai Mountain, Jilin, and other places in Northeast China, as well as the Beijing and Baiyangdian areas of the North China Plain. Modern vegetation in Northeast China mainly includes temperate coniferous and broadleaved mixed forest, forest meadow, forest grassland, swamp, and mixed woodland. Oak forest, Pinus tabulaeformis forest, and shrub steppe are major vegetation types in north region.

1.2.1.1 Temperate coniferous and broadleaved mixed forest and meadow steppe in Northeast China

There are three major zones in Northeast China. They are meadow, marsh, and mixed woodland in the Sanjiang Plain, the coniferous and broadleaved mixed forest in the mountainous area of its eastern part, and forest, meadow, and steppe in the piedmont, hilly or plain areas of its northeastern part.

The Sanjiang Plain mainly refers to the delta region formed by the Songhua River, Heilong River, and Wusuli River, where the low-lying terrain, frequent floods, and long-term impoundment of water have led to the formation of a large area of wetlands and swamps. Vegetation communities there are dominated by hygrophilous meadow and swamp herbs, whereas shrubs and deciduous broadleaved forests occupy the upper hills. Three vegetation types can be found in the Sanjiang Plain: ① wet meadow in swamps, dominated by aquatic plants such as Nymphaea tetragona, Polygonum amphibium, Potamogeton sp., Schoenoplectus tabernaemontani, and Phragmites communis together with some mosses; ② wet meadow in low-lying wetlands, dominated by Calamagrostis hirsute, together with Sium suave, Lythrum salicaria, Polygonum nodosum, Lysimachia dahurica and other hygrophilous plants, along with trees and shrubs such as Salix brachypoda, S. mongolica, Corylus heterophylla, and Lespedeza bicolor, as well as herbs including Spodiopogon sibiricus, Patrinia scabiosaefolia, Potentilla fragarioides, Thalictrum squarrosum, Campanula glomratoides, Lilium pumilum, Dictamnus dasycarpus, Platycodon grandiflorum, and Stipa baicalensis; ③ woodlands in hilly areas, dominated by Corylus heterophylla and Xylosma racemosum, together with trees and shrubs such as Lespedeza bicolor, Salix floderusii, Rosa davurica, Malus baccata, Populus davidiana, and Tilia manshurica, and herbs such as Artemisia, Convallaria majalis, Dianthus amurensis, Clematis manshurica, and others.

The coniferous and broadleaved mixed forest zone in the eastern part of Northeast China includes Xiao Hinggan Mountains and Changbai Mountain areas. The high landform in mountains results in a cold and humid climate, which is suitable for mixed development of temperate montane coniferous and broadleaved mixed forest. Coniferous forests are dominated by Pinus koraiensis and Larix gmelinii or L. olgensis, with some deciduous broadleaved tress such as Betula platyphylla and Populus tomentosaas in successional communities after deforestation. In Xiao Hinggan Mountains, the mixed forests are dominated by dense Pinus koraiensis, whereas Larix gmelinii just grows in swamps. In Changbai Mountain area, Pinus koraiensisis scattered in coniferous and
broadleaved mixed forests, and *Larix olgensis* appears in swamps. Most of the plant species in this vegetation zone belong to the Changbai flora. There are some plants in the high mountains that migrated from Siberia during glacial periods and survived here after glacial periods, such as *Populus tomentosa*, *Juglans mandshurica*, *Phellodendron amurense*, *Tilia mandshurica*, *Fraxinus chinensis* subsp. *rhynchophylla*. Endemic plants include *Aristolochia manshuriensis*, *Adlumia asiatica*, *Brachybotrys paridiformis*, *Schizopepon bryoniaefolius*, *Acer barbinerve*, *Bupleurum euphurbicides*, *Galium verum*, whereas typical elements of steppe in high mountains that migrated from Siberia during glacial periods and survived here after glacial periods, are *Acer mono*, *Acer ginnala*, *Corylus* spp., *Juniperus sibirica*, and *Pinus pumila*. Herbs include *Syringa amurensis*, *Prunus davidiana*, *Tilia mandshurica*, *Populus maximowiczii*, *Betula costata*, *Carpinus cordata*, *Ulmus pumila*, and *Acer ginnala*, occur scarcely. The *Lonicera japonica*, *Chloranthus japonicus*, *Linnaea borealis*, and *A. nephrolepis* are also common in tessellated meadows, forming a brilliant and eye-catching landscape.

The forest, meadow, and steppe zone in plains and hills occurs in the northeastern part of Northeast China. A transition zone from montane forests in Changbai Mountains and Xiao Hinggan Mountains to steppes in Songnen Plain occurs in the piedmont hills of these two mountains, where forest, meadow, and steppe grow. Forests are mostly distributed in moist valleys and slopes, which are mainly composed of *Ulmus*, *Prunus*, *Tilia*, *Morus*, *Fraxinus manschurica*, *Populus tomentosa*, *Quercus mongolica*, *Acer mono*, and other trees. Understory or scattered shrubs in forests include *Acanthopanax sessiliflorum*, *Corylus*, *Lespedeza*, *Securinega suffruticosa*, *Salix mongolica*, and *Schisandra chinensis*. Typical components of meadow in the plain are *Metaplexis japonica*, *Thalictrum simplex*, and *Galium verum*, whereas typical elements of steppe in the plain are *Stipa baicalensis*, *Allium senescens*, *Lilium tenuifolium*, *Linaria vulgaris* subsp. *sinensis*, *Veronica linariifolia*, *Tanacetum sibiricum*, and *Aster altaicus*. Most of the meadow steppes here have a large variety of weeds, and they grow well and flourish. In addition to the above-mentioned plants, *Poa sphyndyloides*, *Arundinella hirta* var. *ciliata*, *Calamagrostis epigeios*, *Carex rubigera*, *Polygonum divaricatum*, *Artemisia latifolia*, *Sanguisorba officinalis*, *Stachys riederi*, *Carex parva*, *Paenion albiglora*, and *Trollius ledebouri* are also common in tessellated meadows, forming a brilliant and eye-catching landscape.

In low-lying Songnen Plain, large tracts of herbaceous plants grow, and no trees are found. Only three shrubs, i.e., *Salix mongolica*, *Armeniaca sibirica*, *Securinega suffruticosa*, occur scarcely. The dominant species of steppe in the whole plain are *Stipa baicalensis*, *Tanacetum sibiricum*, and *Leymus chinensis*, and they are xerophytes or mesoxerophytes.

### Table 1.4 Vertical zonation of alpine vegetation in Changbai Mountains

<table>
<thead>
<tr>
<th>Vegetation zone</th>
<th>Elevation/m</th>
<th>Major plants</th>
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</thead>
<tbody>
<tr>
<td>Alpine shrub meadow</td>
<td>above 2000</td>
<td><em>Dryas octopetala</em> var. <em>asiatica</em> community with small patches of <em>rhododendron</em> and willow communities. Shrubs also include <em>Ledum palustre</em>, <em>Vaccinium vitis-idaea</em>, <em>Rhododendron lutescens</em>, <em>Salix nummularia</em> and <em>Juniperus communis</em>. Herbs include <em>Polygonum viviparum</em>, <em>Genista algeria</em>, <em>Phleum alpinum</em>, <em>Agrostis vinales</em>, <em>Carex spp.</em></td>
</tr>
<tr>
<td>Betula ermanii forest and subalpine meadow</td>
<td>1800–2100</td>
<td><em>Betula ermanii</em>, accompanied by <em>Sorbus amurensis</em>, <em>Ainslia mandshurica</em>, <em>Vaccinium uliginosum</em>, <em>Juniperus sibirica</em>, and <em>Pinus pumila</em>. Herbs include <em>Syringa dehoides</em>, <em>Plectodon grandiflorus</em>, and <em>Thalictrum aquilegifo</em>.</td>
</tr>
<tr>
<td>Coniferous forest</td>
<td>1000–1800</td>
<td><em>Pinus koraiensis</em>, <em>Abies holophylla</em>, <em>A. nephrolepsis</em>, <em>Betula costata</em>, <em>Acer tschonoskii</em>, <em>A. t. segmentosum</em>, <em>Sorbus pohuashanensis</em>, <em>Quercus mongolica</em>, <em>Juglans mandshurica</em>, <em>Phellodendron amurense</em>, and <em>Ulmus propinqua</em>. Herbs include <em>Lonicera mandshurica</em>, <em>Circaea alpina</em>, <em>Mitella nuda</em>, <em>Clintonia udensis</em>, and <em>Daphne koreana</em>.</td>
</tr>
<tr>
<td>Mixed coniferous and broadleaved forest</td>
<td>500–1000</td>
<td><em>Pinus koraiensis</em>, <em>Abies holophylla</em>, <em>Quercus mongolica</em>, <em>Populus davidiana</em>, <em>Tilia mandshurica</em>, <em>Phellodendron amurense</em>, <em>Acer ginnala</em>, <em>Juglans mandshurica</em>, <em>Populus maximowiczii</em>, <em>Betula costata</em>, <em>Carpinus cordata</em>, <em>Ulmus spp.</em> and <em>Acer spp.</em> Shrubs are <em>Corylus mandshurica</em>, <em>Eleutherococcus senticosus</em>, <em>Berberis amurensis</em>, <em>Philadelphus incanus</em>, <em>Ribes</em>, <em>Eumonymus</em>, <em>Syringa</em>, and <em>Lonicera</em></td>
</tr>
<tr>
<td>Deciduous broadleaved forest</td>
<td>250–500</td>
<td><em>Quercus mongolica</em>, <em>Tilia mandshurica</em>, <em>Maackia amurensis</em>, <em>Acer ginnala</em>, <em>Craataragus pinnatifidis</em>, <em>Juniperus mandshurica</em>, <em>Corylus heterophylla</em>, <em>Populus maximowiczii</em>, <em>Lespedeza bicolor</em>, <em>Syringa amurensis</em>, <em>Vitis amurensis</em>, <em>Schisandra chinensis</em>. Herbs include <em>Aristolochis chinensis</em>, <em>Chloranthus japonicus</em>, <em>Brachybotrys paridiformis</em>, <em>Convallaria majalis</em>, and <em>Polygonatum odoratum</em></td>
</tr>
</tbody>
</table>
The weed meadow steppe grows in the lowlands with wet and/or waterlogged soil. It is mainly composed of *Medicago ruthenica*, *Sangiusorba officinalis*, *Artemisia japonica*, *A. subulata*, *Thalictrum simplex*, and *Potentilla amurensis*. The West Liaohae Plain mainly consists of sand dune belts. Sand-stabilizing plants *Artemisia holodendron*, *Agriophyllum arenarium*, *Polygonum divaricatum*, *Salix flavida*, and *Calamagrostis epigeios* grow there, together with some shrubs such as *Hedysarum fruticosum*, *Agropyron cristatum*, *Pennisetum flaccidum*, *Bassia dasyphylla*, *Linaria vulgaris* subsp. *sinensis*, *Prunus sibirica*, *P. humilis*, *Rhamnus davurica*, and *Caragana microphylla*, as well as a few trees such as *Quercus mongolica* and *Morus alba*. Plant communities composed of *Lytthrum salicaria*, *Linaria vulgaris* subsp. *sinensis*, and *Veronica linariifolia* flourish in the wind-eroded lowlands. Some plant communities, consisting of *Praegmites communis*, *Suada glauca*, *Ixeris japonica*, *Clinopodium polyccephalum*, *Saussurea glomerata*, *Puccinellia distans*, and *Calamagrostis epigeios* grow well in saline or wet places. These communities constitute the rich pasture resources in this area. Most of plants present in this area belong to the Mongolian flora.

1.2.1.2 Valley oak forest, *Pinus tabulaeformis* forest, and shrub steppe in Liaohe River Plain, North China Plain, South Shanxi Plain, and Central Shaanxi Plain

The zonal vegetation in these vast plains is semi-arid deciduous broadleaf forest. Due to a long history of reclamation, however, no original vegetation occurs in the plains except in some mountainous areas with fragmented remnants of forest, most of which belongs to secondary vegetation. Forest in this area is dominated by oaks as its predominant species and widespread *Pinus tabulaeformis* as its characteristic species. It develops well in humid mountains. Coastal beaches and inland sandy fields are occupied by dune plants, whereas saline lands are covered with Chenopodiaceae plants. The lower reaches of the Liaohe River are dominated by *Pinus tabulaeformis*, together with *Quercus mongolica*, *Q. liaotungensis*, *Q. aliena*, *Rhus chinensis*, *Ostryopsis davidiana*, *Celtis bungeana*, as well as mountainous species such as *Fraxinus chinensis* subsp. *rhynchophylla*, *F. mandshurica*, *Juglans mandshurica*, *Betula platyphylla*, *Tilia amurensis*, and *Ulmus macrocarpa*. The Carex kobomugi-Calystegia sepium-*Ixeris polyccephala* community grows in coastal areas.

The Haihe River Plain is a representative area of the North China Plain. There are some remaining small and sparse forests only in the lower part of mountains or in foothills and valleys, whereas shrub steppes occur in the vast plains. Major forest components are deciduous oaks, which are mixed with other broadleaved and coniferous trees, such as *Quercus mongolica*, *Q. liaotungensis*, *Q. aliena*, and *Pinus tabulaeformis*. Common shrubs include *Sophora japonica*, *Morus alba*, *Fraxinus chinensis* subsp. *rhynchophylla*, *Alanthus altissima*, *Pistacia chinensis*, *Paulownia*, *Broussonetia papyrifera*, *Ulmus*, *Catalpa bungei*, *Acer*, *Carya*, *Koelreuteria paniculata*, *Rhamnus* spp., *Elaeagnus umbellata*, and *Periploca sepium*. The most common herbs are *Themed japonica*, *Bothriochloa ischaemum*, *Arundinella anomala*, and *Spodiopogon sibiricus*. Other common herbs include *Radix astragali*, *Lespedeza dahurica*, *Oxypopsis hirta*, and *Artemisia* spp. Saline soils develop along the coasts of the North China Plain and the Yellow River, and in other low-lying areas. These areas are covered by communities of *Carex kobomugi*, *Glehnia littoralis*, *Calystegia soldanella*, *Ixeris repens*, *I. japonica*, *Salicornia herbacea*, *Suada ussurienis*, *S. glauca*, *Aeluropus sinesis*, *Limonium bicolor*, *Artemisia anethoides*, *Astragalus adscigerus*, *Agriophyllum squarrosum*, and *Trifolium terrestre*.

Like in the Haihe River Plain, no forest or steppe occurs in the Huanghai Plain. Only scattered deciduous broadleaved trees such as *Populus tomentosa*, *P. davidiana*, *P. nigra* var. *italica*, *Salix matsudana*, *S. integra*, *Pterocarya stenoptera*, *Ulmus pumila*, *Sophora japonica*, *Sophora japonica*, and *Diospyros lotus* occur. Herbs are weed species such as *Cynodon dactylon*, *Digitaria sanguinalis*, *Imperata cylindrica*, *Setaria viridis*, *Chenopodium album*, *Calystegia sepium*, *Taraxacum mongolicum*, *Xanthium sibiricum*, and *Solanum nigrum* etc. Aquatic plants such as *Praegmites*...
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australis and Euryale ferox are common in shallow lakes. Carex kobomugi, Atriplex patens, Chenopodium serotinum, Nitraria tangutorum, Glehnia littoralis, Atriplex sibirica, and Scorzonera mongolica can be found in saline and alkaline lands.

The mountains of central Shandong include Taishan Mountain, Zulai Mountain, Lushan Mountain, and Yimeng Mountain. The relative height of each mountain ranges from 650 m to 800 m. Vertical zonation is not obvious. The dominant tree species are Pinus tabuliformis and various oaks such as Quercus variabilis, Q. acutissima, and Q. aliena var. acuteserrata. The coverage of forest understory is about 50%. Major plants include Lespedeza inschanica, Bupleurum chinense, Saussurea ussuriensis, Miscanthus sinensis, Roegneria kamoji, Melica scabrosa and Zoysia japonica. Deciduous broadleaved trees seldom occur as a forest, but are generally scattered on hillsides. Major components include Eurya japonica, Tilia mongolica, Ailanthus altissima, Juglans cathayensis, Carpinus turczaninowii, Celtis bungeana, Pteroceltis tatarinowii, Broussonetia, Betula chinensis, Juglans ginnala, Pistacia chinensis and etc. Subtropical components such as Albizia julibrissin, Dalbergia hupeana are also present. Herbs are dominated by Poaceae, Themed japonica, and Bothriochloa ischaemum.

The South Shanxi Plain and Central Shaanxi Plain in the upper reaches of the Weihe River are located in a transition zone from pine and oak forest to the forest-steppe in the Loess Plateau. It is distinguished from the North China Plain by the growth of Pinus armandii. Due to a long history of intensive agriculture, natural vegetation is rarely seen there. Only xerophytic shrubs and herbs occur on the edge of the Loess Plateau, with remnants of forests on the northern slopes of the Qinling Mountains. The latter are dominated by pines such as Pinus tabulaeformis and P. armandi, and oaks are common in the North China Plain. In the Xiaolongshan of the Liupan Mountains (1000−2600 m), mixed oak woodlands develop well along with pure forests of Picea asperata and P. neoveitchii. In forests, shrubs include Gleditsia japonica, Sophora uicifolia, Hippophae rhamnoides, and Tamarix juniperina; herbs are dominated by Poaceae species such as Leymus secalinus, Bothriochloa ischaemum, Pennisetum flaccidum and Ergagrostis spp., together with some drought-tolerant species such as Dicranostigma leptopus, Incarvillea sinensis, and Sphaerophysa salsula. Most plant species in the area belong to the North China flora, as represented by Pinus tabulaeformis, Juniperus formosana, and Quercus spp. Only Ulmus macrocarpa, Fraxinus mandshurica, Juglans mandshurica, Phellodendron amurense, and Tilia amurense belong to the Northeast China flora. Plants of the Mongolian flora include Nitraria tangutorum, Lepidium latifolium, and others occurring on sandy beaches. Orychophragmus violaceus, Glycyrrhiza pallidiflora, Incarvillea sinensis, Myrropois dioica, Saxifraga bijiangensis, and Oresitrophe rupifraga are typical endemic plants.

A zone of oak forest-Pinus tabulaeformis forest-subalpine coniferous forest occupies mountains in northern Hebei in the northern part of North China Plain. It is a mountainous area, including the Yanshan Mountains, Taihang Mountains, Xiaowutai Mountains, Baihuashan Mountains, and Wulüshan Mountains. It has lower temperature and higher rainfall and humidity than the plain, so it has more favorable climatic conditions for plant growth. The coniferous forest zone generally occurs at 1800−2700 m a.s.l., above which the subalpine meadow is, and below which the mixed coniferous and deciduous forest and the deciduous broadleaved forest steppe in central North China Plain to the south, and to arid shrub steppe on the edge of the Mongolian Plateau to the north. Table 1.5 shows the vertical distribution of vegetation in Xiaowutai Mountains.

In addition, the shrub meadow and secondary forest developed on hillsides of the Xishan Mountains in Beijing after the original forest was destroyed. The secondary forest developing on shady slopes is dominated by Betula-Populus juvenile community with Fraxinus chinensis, Acer spp., Carpinus turczaninowii, and Xanthoceras sorbifolia, whereas it is dominated by oaks on sunny slopes. The shrub meadow is generally dominated by Vitex chinensis-Carex lanceolata community on shady slopes, and by Spiraea pubescens-Carex lanceolata-Selaginella
Betula chinensis and Polygonum viviparum). Major endemic species are Sorbus discolor, S. pohuashanensis, Ostrya liana, Hydrangea bretschneideri, Evodia daniellii, and others.

### 1.2.2 Overview of Quaternary vegetation

Paleoenvironmental evidence has shown that many sub-tropical and temperate elements are widely distributed throughout China, such as Inner Mongolia, and the North China Plain. As many geological events happened in the Neogene, these events gradually caused temperature to decline and rainfall to decrease, leading to a dry and cool climate. The climatic conditions resulted in a decrease in the temperate forest vegetation components and an increase in Pinus and herbaceous plants, resulting in the formation of the temperate-warm temperate broadleaved forest, coniferous forest, coniferous and broadleaved mixed forest zone in Shandong, Hebei, eastern Liaoning and the Weihe River basin. The main trees of these forests were Betula, Tilia, Acer, Celtis, Catalpa, Ulmus, Juglans, Fagus, Populus, and Salix. By the late Pliocene, the climate in the North China Plain and the Weihe River basin further dried up, causing the development of steppe landscape and mixed forest dominated by pine and oak with very few other deciduous broadleaved elements. This led to the formation of the early Quaternary vegetation zone, i.e., the temperate coniferous and broadleaved mixed forest and forest meadow zone. In the early Pleistocene, coniferous and broadleaved mixed forest was common in the North China Plain, however, it changed to forest-steppe in the mid-Pleistocene as a result of the cyclical changes of Quaternary glacial-interglacial climate. For example, the southern Shanxi and central Shaanxi areas were occupied by forests consisting of Pinus, Quercus, Carpinus, Fagus, Ulmus, and Rhus in the early Pleistocene; however, they were occupied by more steppes and less forests in the mid-Pleistocene. Although coniferous forest and deciduous broadleaved forest mixed forest composed of Picea, Pinus, Quercus, Ulmus, and Acer still occurred in the mid-Pleistocene, they had obvious characteristics of vertical vegetation zonation. In the plains, the vegetation changed to forest-steppe dominated by trees such as Ulmus, Morus,

### Table 1.5 Vertical zonation of vegetation in Xiaowutai Mountains

<table>
<thead>
<tr>
<th>Vegetation zone</th>
<th>Elevation/m</th>
<th>Major plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subalpine meadow</td>
<td>~2500</td>
<td>Weeds</td>
</tr>
<tr>
<td>Larix principis-rupprechiti forest</td>
<td>2100−2500</td>
<td>Larix principis-rupprechiti, Picea, and Betula</td>
</tr>
<tr>
<td>Coniferous forest</td>
<td>1600−2100</td>
<td>Picea wilsonii, Larix principis-rupprechiti, and Abies accompanied by Betula dahurica, B. albo-sinensis, B. platyphylla, and Salix sp.</td>
</tr>
<tr>
<td>Mixed linden and birch forest</td>
<td>1100−1400 (1600)</td>
<td>Betula fruticosa, B. platyphylla, Tilia mongolica, T. mandshurica, Populus davidiana, Sorbus pohuashanensis, and Ostryopsis davidiana</td>
</tr>
<tr>
<td>Deciduous broadleaved forest dominated by oaks</td>
<td>400−1100 (1400)</td>
<td>Quercus acutissima, O. liaotungensis, Pinus tabulaeformis, Fraxinus chinensis, Carpinus turczaninowii, Acer mono, Tilia mongolica, Pistacia chinensis, Ulmus macrocarpa, Diospyros kaki, Betula fruticosa, Evodia daniellii, Hovenia acerba, Chionanthus retusus, Piceas quassioides, Lespedeza bicolor, Corylus heterophylla, Populus sinensis community on sunny slopes. The humid areas are occupied by communities consisting of Deutzia grandiflora, Myriopnos dioica, Leptodermis oblonga, Arundinella anomala, and Deyeuxia arundinacea, whereas the arid areas are occupied by communities composed of Lespedeza davurica, Stemmacantha uniflora, Elsholtzia ciliata, Artemisia japonica, and Bothriochloa ischaemum. The natural vegetation in the Taihang Mountains has been destroyed heavily; it is generally replaced by secondary vegetation characterized by the sparse semi-arid oak forest and shrub steppe. The sunny slopes are dominated by Quercus variabilis, and shady slopes by Quercus aliena, together with Ailanthus altissima, Pistacia chinensis, Acer elegantuluum, and Pinus tabulaeformis. Shrubs are common in the North China Plain, including Lespedeza, Vitex negundo var. heterophylla, Ziziphus jujuba var. spinosa, Gleditsia japonica, Rhamnus parvifolia, and Periplaca septum. Plant communities above 1000 m are composed of Carpinus turczaninowii, Ulmus laciniata, U. davidiana, Betula chinensis, Acer, Morus, Chionanthus retusus, and Actinidia arguta. The plant species in this area mainly belong to the North China flora, but a few species are components of the Northeast China flora (such as Tilia and Corylus), the Mongolian flora (such as Hippophae rhamnoides, and Ostryopsis davidiana), and even the Old Arctic flora (such as Papaver nudicaule and Polygonum viviparum). Major endemic species are Sorbus discolor, S. pohuashanensis, Ostrya liana, Hydrangea bretschneideri, Evodia daniellii, and others.</td>
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</tbody>
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1.2.2.1 Vegetation and environment since the early Pleistocene in the North China Plain

Quaternary palynological studies in the North China Plain began earlier because of clear division of Quaternary strata, i.e., Nihewan Formation of the early-Pleistocene, Zhoukoudian Formation of the mid-Pleistocene, and Salawusu Formation and Malan Formation of the late-Pleistocene. These formations had been discussed in great details and have been recognized as standard stratigraphic sections (i.e., stratotypes). The early-Pleistocene pollen assemblages are characterized by high percentages of cold-tolerant coniferous forest trees such as spruce, fir, and pine, and the appearance of a small number of Paleo-Neogene relict plants. Pollen spectra from the Nihewan Formation at the Hutouliang section in the Hebei Plain contain coniferous pollen up to 95%, including 40%–80% of Pinus pollen and 18%–45% of Picea pollen. Some pollen of Abies are also present, together with Neogene relic elements such as Podocarpus, Cedrus, and Tsuga, and a few pollen of broadleaved trees and herbaceous plants, reflecting cold climatic conditions in the early Pleistocene (Liu, 1980). Similarly, pollen zone III in the Datong Basin, pollen zone I in the Yangyuan Basin, and pollen zone II in the Yuxian Basin of Hebei Province (Tang and Liu, 1984) as well as pollen zone III in the Zhangcun section of Shanxi Province (Tang, 1991), are dominated by pollen of conifers such as Picea, Abies, Pinus, and Cupressaceae. They only contain a small amount of pollen of broadleaved trees such as Tilia, Ulmus, and Quercus, and fewer herbs such as Artemisia, Chenopodiaceae, Poaceae, and Compositae. It is worth noting that they also contain a little pollen of Neogene relic plants such as Podocarpus, Cedrus, Tsuga, Carya, Liquidambar, Gingko, and Magnolia.

The characteristics of pollen assemblages of the mid-Pleistocene in the North China Plain are: ①the Paleogene and Neogene plant relicts disappeared; ②pollen spectra have the same amount of arboreal and non-arboreal pollen, and their pollen components significantly increased, reflecting a forest-steppe or steppe as the regional vegetation; ③the fossil pollen taxa are dominated by common species of the modern vegetation in this area, and the pollen assemblages show obvious dry/wet and cold/warm climate fluctuations.

The pollen record of the mid-Pleistocene in the North China Plain is represented by the pollen assemblages of Zhoukoudian Formation (Sun, 1965). Arboreal pollen taxa include Abies, Pinus, Cupressaceae, Betula, Celtis, Ulmus, Salix, Carpinus, Ostryopsis, Caragana, Deutzia, and Rhamnaceae. Poaceae, Cyperaceae, Liliaceae, Leguminasae, Potamogeton, Polypodiaceae, and Selaginella are common herbaceous plants. The relict elements of Neogene vegetation had disappeared. Pollen zone IV in the Datong Basin and pollen zone V in the Yuxian Basin (Tang and Liu, 1984), as well as the pollen assemblages of Lishi Loess in Shanxi (Zhou et al., 1960), are dominated by herbaceous plants such as Artemisia, Chenopodiaceae, and Poaceae, together with some woody plants such as Pinus, Betula, and Carpinus, reflecting semi-arid climatic conditions. In the mid-Pleistocene, pollen spectra of the Zhoukoudian Formation show a vegetation succession indicating many cycles of warm and cold climate. Pollen spectra in cold periods were dominated by Picea pollen and accompanied by Pinus pollen, so they reflected dark coniferous forests; pollen spectra in warm periods contained pollen and spores of warm-wet broadleaved plants and herbs such as Juglans, Nymphaea, and Selaginella, indicating coniferous and broadleaved mixed forests and steppes.

As the earth entered the late Pleistocene, the temperature dropped and fluctuated more widely. The climate was characterized by a warm period in its early period from 120 ka BP to 70 ka BP and a cooling trend in its late period from 70 ka BP to 11 ka BP. For example, the pollen record from the cave sediments of Zhoukoudian contained Quercus, Celtis, and other broadleaved plants favoring warm conditions; pollen spectra from the top of the Xiaodukou section were dominated by Artemisia and Chenopodiaceae; and a pollen record from the peak of Taibaishan Mountains
in Shaanxi contained 35% Tsuga and 5% Picea, indicating warm conditions. These pollen records in the early period of the late Pleistocene showed relatively warm climatic conditions. In the late period of the late Pleistocene, pollen records in Tianjin, Huanghua, and other places were dominated by Picea pollen, indicating an increase in dark spruce forest, and cold climate with temperature presumably 12°C lower than the present (Luo et al., 1982). Especially, a marked temperature drop by 3–4°C and even 10–12°C occurred during the Last Glaciation (70–10 ka BP). The Salawusu Formation in Inner Mongolia consists of a set of fluvial and lacustrine sediments (a 14C date at the 5th layer of its upper unit is 27.94 ka BP). Its pollen spectra are almost completely composed of conifer pollen such as Pinus, Picea, and Abies. They indicated the occurrence of pure fir and spruce forests, and thus cold and wet climatic conditions (Yuan, 1978; Zhou et al., 1982; Ke et al., 1992; Table 1.6). Pollen records from Yanqing, Miyun, Huairou, and Tongzhou in Beijing (Kong and Du, 1980) show that coniferous forests of fir and spruce once flourished in the hills and plains at 30 ka BP, which were then replaced by steppes consisting of Artemisia, Chenopodiaceae and Poaceae by 22 ka BP. At 13 ka BP, the subalpine coniferous forests, dominated by spruce, fir, and larch, once again extended to the hills and plains of Beijing. Fir and spruce forests that usually grow at an altitude of 1600–2000 m today shifted downhill to Zhaitang and the urban areas of Beijing at 430–450 m a.s.l. during the late-glacial time. After 12 ka BP, the coniferous forest retreated to higher elevations in the mountain areas, as warm-temperate deciduous broadleaved forest represented by Tilia expanded, and swamps developed, indicating a warming climate. At about 11 ka BP, temperate mixed coniferous and broadleaved forests composed of Pinus, Tilia, and Quercus decreased again, whereas steppes consisting of Artemisia and Chenopodiaceae increased. The steppes continued to grow together with pine forests until 10 ka BP.

Pollen records from Qasq (Wang and Sun, 1997), Daihai (Xiao J L et al., 2004), and Diaojuehaizi (Song et al., 1996) in Inner Mongolia and from Beijing (Kong et al., 1982) show steppes dominated by Artemisia and Chenopodiaceae at 10–9.0 ka BP (Table 1.6; Figure 1.12). Temperate coniferous forests developed in the Dongshan Mountains, Beijing at 10–9.0 ka BP, indicating dry and cold climatic conditions. At 7.0 ka BP, coniferous forest decreased, and deciduous broadleaved forest consisting of oak, birch, and linden increased on the plains, reflecting a rise in temperature. There was a short reversal of temperature around 5.6 ka BP, when spruce and fir forests expanded. The period 5.0–3.0 ka BP marks the Holocene climate optimum in Beijing. The main components of temperate deciduous broadleaved and coniferous-broadleaved mixed forests were oak, linden, birch, elm, mulberry, and hazelnut in this period. Meanwhile, swamps developed under warm and humid climatic conditions, resulting in the accumulation of peat. At 2.0–1.0 ka BP, forest-steppes represented by pine appeared and lakes shrank, indicating cool and dry climatic conditions (Table 1.7).

1.2.2.2 Vegetation and environment since the early Pleistocene in Northeast China

During the Neogene, Qian’an in the Songnen Plain of Northeast China was influenced by a maritime climate, thus it had warm and humid climatic conditions and its vegetation had transitional features from temperate to subtropical vegetation (Jia et al., 1989). The lowlands were occupied by deciduous broadleaved forests mainly consisting of Quercus, Ulmus, Fagus, Juglans, Liquidambar, Carya, and Betula together with some evergreen broadleaved trees such as Castanopsis, whereas the mountains were covered with coniferous forests composed of Pinus, Picea, Abies, Tsuga, and other species of Pinaceae. Ceratopteris, a subtropical fern, grew around warm lakes. Some meso-xerophytic herbaceous plants expanded due to global cooling after the Neogene. As the climate became much cooler and drier by the end of the Neogene, the steppe area expanded. The earth entered the Quaternary period two million years ago, and the global temperature and sea level dropped and lakes shrank. As a result of global cooling, the subtropical evergreen and deciduous broadleaved elements such as Castanopsis, Liquidambar, Carya, Fagus, and Hamamelis, which once were the
### Table 1.6  Pollen and vegetation since the Pleistocene in Inner Mongolia

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Major pollen type</th>
<th>Vegetation</th>
<th>Climate &amp; environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.8-12.8</td>
<td>Artemisia, Chenopodiaceae</td>
<td>Steppe</td>
<td>Cold and dry, sparse vegetation, no forests</td>
</tr>
<tr>
<td>12.8-15.3</td>
<td>Pinus, Quercus, Chenopodiaceae</td>
<td>Forest steppe</td>
<td>Warm and wet, the reappearance of the lake</td>
</tr>
<tr>
<td>15.3-20.9</td>
<td>Cupressaceae, Pinus</td>
<td>Sylvosteppe</td>
<td>Cool and dry, sparse vegetation, no forests</td>
</tr>
<tr>
<td>20.9-23</td>
<td>Artemisia, Chenopodiaceae</td>
<td>Steppe</td>
<td>Warm and wet, the reappearance of the lake</td>
</tr>
<tr>
<td>23-28</td>
<td>Pinus, Quercus, Chenopodiaceae</td>
<td>Forest steppe</td>
<td>Cool and dry, sparse vegetation, no forests</td>
</tr>
<tr>
<td>28-30</td>
<td>Cupressaceae, Pinus, Quercus</td>
<td>Sylvosteppe</td>
<td>Warm and wet, the reappearance of the lake</td>
</tr>
<tr>
<td>30-38</td>
<td>Artemisia, Chenopodiaceae, Cupressaceae</td>
<td>Steppe</td>
<td>Cold and dry, sparse vegetation, no forests</td>
</tr>
<tr>
<td>38-42</td>
<td>Pinus, Quercus, Chenopodiaceae</td>
<td>Forest steppe</td>
<td>Warm and wet, the reappearance of the lake</td>
</tr>
<tr>
<td>42-110</td>
<td>Cupressaceae, Pinus, Quercus</td>
<td>Sylvosteppe</td>
<td>Warm and wet, the reappearance of the lake</td>
</tr>
<tr>
<td>110-130</td>
<td>Artemisia, Chenopodiaceae</td>
<td>Steppe</td>
<td>Cold and dry, sparse vegetation, no forests</td>
</tr>
</tbody>
</table>

*DSGW: Dishaogouwan; SLWS: Salawusu; DBF: deciduous broadleaved forest; MCBF: mixed coniferous and broadleaved forest
Figure 1.12  Holocene pollen percentage diagram of major taxa from Daihai Lake (modified from Xiao et al., 2004).
dominant components of the Neogene flora in the Da Hinggan Mountains and Songliao Plain, gradually disappeared, and only a few cold-resistant components such as *Pinus*, *Betula*, and *Ulmus* left. Temperate steppes composed of *Artemisia*, Chenopodiaceae, and Poaceae expanded. In the early period of the early Pleistocene, the Songnen region was covered by temperate mixed forests consisting of *Pinus* and *Ulmus* as dominants and some broadleaved elements such as *Quercus*, *Alnus*, and *Juglans* as accompanying species. During the glacial of the early Pleistocene (1.8−1.2 Ma BP), the climate in the western Songnen Plain became cold and dry, making it unsuitable for the growth of spruce and fir, but suitable for the development of forest-steppes dominated by *Artemisia* and Chenopodiaceae. At the late phase of the early Pleistocene, the climate on the Northeast Plains was warming, trees such as *Betula*, *Ulmus*, *Quercus*, and other broadleaved species increased, and aquatic plants such as *Myriophyllum*, *Typha*, *Potamogeton*, *Zygnema*, and *Pediastrum* adapted to warm climate also appeared, while lakes developed. The Songnen Plain was occupied by forest-steppes composed of pine, birch, oak, and sagebrush. In the early mid-Pleistocene (about 0.7 Ma BP), pine increased again, and dark coniferous forests composed of spruce and fir then extended to the Hulan Ergi hills and plains of the Heilongjiang Province, indicating cold and wet climatic conditions. The dark coniferous forest elements disappeared and herbs increased with climate warming in the middle mid-Pleistocene, whereas mesophytic Poaceae, hygrophyllous Cyperaceae, and helobious *Typha* increased to form steppes and/or meadows in the late mid-Pleistocene. In the early phase of the late Pleistocene, herbaceous plants increased again and arboreal plants decreased relatively to form steppes composed of *Artemisia*, Chenopodiaceae, and Poaceae with the shrinkage or disappearance of lakes. As the climate became dry and cold, steppes or meadow steppes were widely distributed in Hulan Ergi and other areas. A large number of pollen records show that herbaceous pollen percentages in the late-Pleistocene reached their maxima in the Quaternary, indicating a cold climate (Liu et al., 1990; Kong and Du, 1984; Chen et al., 1965).

A pollen record from Moon Lake in the middle Da Hinggan Mountains (Zalantun City, Inner Mongolia) revealed paleovegetation and paleoclimatic changes during the late period of the last glaciation (Wu and Liu, 2012) (Figure 1.13; Table 1.8). Steppes developed at 20.9−18.0 cal. ka BP under cold and dry climatic conditions, and meadow steppe prevailed at

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Age/ka BP</th>
<th>Beijing Plain</th>
<th>North Hebei Plain</th>
<th>EPPTM*</th>
<th>Baiyangdian</th>
<th>Heilonggang</th>
<th>Tianjin</th>
<th>Cangzhou</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late</td>
<td>1</td>
<td><em>Pinus-Quercus</em>-Poaceae</td>
<td><em>Pinus</em></td>
<td><em>Pinus-Artemisia</em>-Chenopodiaceae-<em>Myriophyllum</em></td>
<td><em>Pinus-Artemisia</em>-Chenopodiaceae</td>
<td><em>Pinus-Artemisia</em>-Chenopodiaceae</td>
<td><em>Pinus-Artemisia</em>-Chenopodiaceae</td>
<td><em>Pinus-Artemisia</em>-Chenopodiaceae</td>
</tr>
<tr>
<td>Late</td>
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<td><em>Pinus-Ulmus-Betula-via</em>-Morus-Betula-Quercus*</td>
<td><em>Pinus-Quercus-Artemisia</em></td>
<td><em>Pinus-Quercus-Betula-Ailanthus-Poaceae</em></td>
<td><em>Pinus-Quercus-Betula-Ailanthus-Poaceae</em></td>
<td><em>Pinus-Quercus-Betula-Ailanthus-Poaceae</em></td>
<td><em>Pinus-Quercus-Betula-Ailanthus-Poaceae</em></td>
<td><em>Pinus-Ulmus</em></td>
</tr>
<tr>
<td>Late</td>
<td>3</td>
<td><em>Pinus-Betula-aquatic plants-Ceratopteris</em></td>
<td><em>Ulmus-Betula-aquatic plants</em></td>
<td><em>Pinus-Quercus-Betula-aquatic plants</em></td>
<td><em>Pinus-Quercus-Betula-aquatic plants</em></td>
<td><em>Pinus-Quercus-Betula-aquatic plants</em></td>
<td><em>Pinus-Quercus-Betula-aquatic plants</em></td>
<td><em>Pinus-Quercus-Betula-aquatic plants</em></td>
</tr>
<tr>
<td>Middle</td>
<td>4</td>
<td><em>Typha-Pinus-Picea-Abies</em></td>
<td><em>Artemisia-Chenopodiaceae-Pinus-Betula</em></td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
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<td>Middle</td>
<td>5</td>
<td><em>Typha-Pinus-Picea-Abies</em></td>
<td><em>Artemisia-Chenopodiaceae-Pinus-Betula</em></td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
</tr>
<tr>
<td>Early</td>
<td>6</td>
<td><em>Tilia-Betula-Quercus-Pinus</em></td>
<td><em>Artemisia-Chenopodiaceae</em></td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
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<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
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<tr>
<td>Holocene</td>
<td>7</td>
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<td><em>Artemisia-Chenopodiaceae</em></td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
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<td>Holocene</td>
<td>8</td>
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<td><em>Artemisia-Chenopodiaceae</em></td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
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<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
<td><em>Pinus-Betula-Picea-Artemisia-Chenopodiaceae</em>-Cyperaceae</td>
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*EPPTM: Eastern Piedmont Plain of Taihang Mountains*
Figure 1.13  Pollen diagram from Moon Lake in central Da Hinggan Mountains (modified from Wu and Liu, 2012)
**Table 1.8 Holocene vegetation and climate in Northeast China**

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<td>Vegetation</td>
<td>Climate</td>
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<td></td>
<td>Pinus koraiensis forest</td>
<td>1−2°C lower than present</td>
<td>MCBF*</td>
<td>Cooling</td>
<td>Oak-birch forest</td>
<td>Pinus, Betula, Quercus, Ulmus</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cooling</td>
<td>MCBF*</td>
<td>MCBF*</td>
<td>Cool &amp; wet</td>
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<td>MCBF*</td>
<td>Cool + wet</td>
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<td></td>
<td></td>
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<td>Megathermal period</td>
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<td>MCBF*</td>
<td>Warm</td>
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<td></td>
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<td>Deciduous broadleaf forest</td>
<td>Warmer + drier than present</td>
<td>Deciduous broadleaf forest</td>
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<td>Dark coniferous forest</td>
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<td>Artemisia, Betula, Ulmus, Quercus, Corylus</td>
</tr>
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<td></td>
<td>15.3</td>
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<td></td>
<td></td>
<td>Warm + wet</td>
<td></td>
<td>Artemisia, Betula, Ulmus, Quercus, Corylus</td>
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<td>18</td>
<td></td>
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<td></td>
<td>Warm + wet</td>
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<td>Artemisia, Betula, Ulmus, Quercus, Corylus</td>
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<td></td>
<td>20.9</td>
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<td></td>
<td>Warm + wet</td>
<td></td>
<td>Artemisia, Betula, Ulmus, Quercus, Corylus</td>
</tr>
</tbody>
</table>

*HLJ: Heilongjiang; MCBF: Mixed coniferous and broadleaved forest*
Figure 1.14 A composite diagram of pollen percentage and influx, TOC, and varve thickness from the Marr lake in Sihailongwan, Jilin (modified from Stebich et al., 2009)
Figure 1.15 A comparison of pollen record from the Marr lake in Sihailongwan, Jilin with oxygen isotope record of GRIP ice core (modified from Stebich et al., 2009)
Figure 1.16 Holocene pollen record from Jingpo Lake in Heilongjiang (modified from Li C H et al., 2011)
of 18.0−15.3 cal. ka BP when the climate was cold and humid. At 15.3−14.0 cal. ka BP, trees began to appear with a distinct increase in birch, suggesting that the vegetation changed from meadow steppe to forest as the climate changed from cold and humid to warm and humid. Forest expanded and steppe shrunk as the climate became warm at 14.0−12.8 cal. ka BP; and then a cold period was indicated by the expansion of steppe at 12.8−11.8 cal. ka BP. This cold period probably suggests the occurrence of the Younger Dryas (YD) event in Northeast China. The occurrence of this cold event between 12.7 cal. ka BP and 11.7 cal. ka BP was also detected in the pollen record from Sihailongwan Maar Lake, Jilin (Stebich et al., 2009; Figures 1.14, 1.15; Table 1.8). Pollen records from peat sections and lake cores in the Sanjiang Plain of Heilongjiang (Xia, 1988), as well as in Huinan and Jingyu areas of Jilin (Liu, 1989; Yuan and Sun, 1990; Sun et al., 1991; Li C H et al., 2011; Table 1.8), show sparse vegetation and cold climates at 13.0 ka BP. The hills were occupied by birch shrubs or tundra shrub meadow, indicating a colder climate with temperatures about 3−6°C lower than today. A pollen record from Moon Lake also shows that steppes expanded and shrunk many times, suggesting that the climate became colder and several cooling events occurred from 11.8 cal. ka BP to 0.8 cal. ka BP. In Jilin and the Sanjiang Plain, deciduous broadleaved Ulmus and Quercus increased, indicating an early Holocene (10−8.0 cal. ka BP) warming. The hypsithermal interval occurred from 8.0 cal. ka BP to 4.0 (3.0) cal. ka BP, when deciduous broadleaved forests consisting of oak, walnut, and elm developed in the areas of Jingpo Lake in Heilongjiang (Li C H et al., 2011; Figure 1.16; Table 1.8), and Changbai Mountain, Huinan and Jingyu in Jilin. In the Sanjiang Plain, the vegetation was dominated by Quercus mongolica forest first, and then by coniferous and broadleaved mixed forest. The Sanjiang Plain experienced two cold events in the period of 4.0−2.5 cal. ka BP, followed by a cooling trend in the late Holocene. The coniferous and broadleaved mixed forest generally developed in the regions mentioned above during the late Holocene. However, the Sanjiang Plain was dominated by Korean pine forest, indicating a much lower temperature (Table 1.8).

1.3 Southeast Region

1.3.1 Overview of modern vegetation

Southeast region is located in subtropical China, a region characterized by a vast territory, east-west and north-south oriented mountain ranges, as well as intertwined valley plains. It not only has the richest plant resources and the greatest diversity of plants, but also has complex vegetation types in East Asia. It has an ancient flora that has persisted since pre-Quaternary times. Due to the small influence of continental glaciers on subtropical China during the Quaternary period, many relic plant species have survived there from the Paleogene-Neogene to today, such as Ginkgo biloba, Cathaya argyrophylla, Pseudolarix amabilis, Glyptostrobus pensilis, Metasequoia glyptostroboides, Davidia involucrata, Liriiodendron chinensis, among others (Wu, 1980).

The zonal vegetation in subtropical China is the Subtropical Evergreen Broadleaved Forest (SEBF). It can be further divided into the eastern humid and western semi-humid evergreen broadleaved forest subregions in terms of its ecological features and the associated moisture conditions. Southeast region belongs to the eastern humid subregion, including the northern and middle subtropical parts. Geographically, it lies between 23.5°N−34°N and 102.5°E−122°E, covering Central China, East China, and most of South China, roughly equal to the region bounded by the Huaihe River-Qinling line, the Tropic of Cancer, the southeast coastline, and the east slope of the Tibetan Plateau on its northern, southern, eastern, and western sides, respectively. Administratively, it covers the whole provinces of Zhejiang, Fujian, Jiangxi, and Hunan; most of Guizhou, Jiangsu, Anhui, Hubei, and Sichuan; northern Guangdong and Guangxi; southern Henan, Shaanxi, and Gansu. Topographically, it includes the northeastern part of the Yunnan-Guizhou Plateau, the Sichuan Basin, the Sichuan-Hubei Mountains, the northern part of the Nanling Mountains, the Jianghuai
hills, the Dabie Mountains, the mountainous areas of Fujian and Zhejiang, and the plains of the middle and lower Yangtze River. Altitudinally, plains, hills, and hilly mountains generally have elevations of less than 50 m, 200−500 m, and 1000−2000 m a.s.l., respectively, whereas mountains in its western and northwestern areas can reach elevations of >3000 m a.s.l.

The zonal vegetation in this region is predominantly characterized by the SEBF. This forest type has the most typical feature and the largest area in the middle subtropical zone; however, it is replaced by the mixed evergreen and deciduous broadleaved forest in the northern subtropical zone. The floristic composition is dominated by the floristic elements of subtropical humid forest in southern China, a subregion of the China-Japan flora. This flora is characterized by plants of Fagaceae, Lauraceae, Magnoliaceae, and Theaceae as constructive and dominant species. The tree layer of the evergreen broadleaved forest is dominated by Castanopsis, Cyclobalanopsis, Lithocarpus, Machilus, and Schima, followed by species of Lauraceae, Theaceae, Hamamelidaceae, Magnoliaceae, Elaeocarpaceae, Aquifoliaceae, and Symplocaceae. The shrub layer is mainly composed of Eurya, Symplocos and Rhododendron. According to the natural heat and water conditions and the differentiation of vegetation, this zone can be further divided into four vegetation areas from east to west, i.e., cultivated and aquatic vegetation in the Jianghuai Plain; forests of deciduous oaks, Castanopsis, and Pinus massoniana in Jianghuai hills; forests of deciduous oaks and Cyclobalanopsis in the mountainous and hilly area of Tongbai Mountain and Dabie Mountain; and forests of oaks, Pinus henryi, and Pinus armandii in the mountainous and hilly areas of Qinling Mountains and Bashan Mountains (Table 1.9).

(2) The subtropical evergreen broadleaved forest (laurel forest) zone has typical features of SEBF and the most extensive distribution in China. Its area spans ca. 7 degrees of latitude and ca. 10 degrees of longitude. It covers plateau and mountain areas (e.g., the western Sichuan marginal mountains with an elevation of 1000−3000 m, Guizhou-Hubei mountains) in its western part, Jiangnan hilly lands (e.g., Huangshan Mountain, Tianmu Mountain, Jiuling Mountain, Wugong Mountain) in its middle part, the open plain of the middle and lower reaches of the Yangtze River in its eastern part, and the Nanling mountainous area with an elevation of about 1000 m in its southern part. The dominants in the tree layer are Cyclobalanopsis, Castanopsis, and Lithocarpus of Fagaceae, Schima of Theaceae, Altingia of Hamamelidaceae, and Machilus, Phoebe and Cinnamomum of Lauraceae. In addition, the tree layer is also often mixed with Elaeocarpus and Sloanea of Elaeocarpaceae, Michelia of Magnoliaceae, Symplocos of Symplocaceae, Daphniphyllum of Daphniphyllaceae,
### Table 1.9 Vegetation zonation and their climatic conditions in southeast region

<table>
<thead>
<tr>
<th>Vegetation zone</th>
<th>Sub-zone</th>
<th>Vegetation region</th>
<th>Mean annual temperature/℃</th>
<th>≥ 10℃ Accumulated temperature/℃</th>
<th>Annual temperature in January/℃</th>
<th>Mean annual Precipitation/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>North subzone</td>
<td>1. North subtropical mixed evergreen and deciduous broadleaved forest (represented by deciduous Quercus, Castanopsis sclerophylla, and Cyclobalanopsis glauca, etc.)</td>
<td>North subtropical mixed evergreen and deciduous broadleaved forest</td>
<td>13.5−16</td>
<td>4500−5100</td>
<td>0−3</td>
<td>800−1200</td>
</tr>
<tr>
<td></td>
<td>1.1 Yangtze River and Huahei River plains, cultivated vegetation, and aquatic vegetation</td>
<td>Yangtze River and Huahei River plains, cultivated vegetation, and aquatic vegetation</td>
<td>13.5−15.5</td>
<td>4500−5000</td>
<td>−1−2.5</td>
<td>900−1200</td>
</tr>
<tr>
<td></td>
<td>1.2 Yangtze River and Huahei River hilly areas, deciduous Quercus, Castanopsis sclerophylla, and Pinus massoniana forests</td>
<td>Yangtze River and Huahei River hilly areas, deciduous Quercus, Castanopsis sclerophylla, and Pinus massoniana forests</td>
<td>14.5−16.1</td>
<td>4800−5000</td>
<td>1−2.6</td>
<td>800−1200</td>
</tr>
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<td></td>
<td>1.3 Tongbai and Dabieshan Mountains and hills, deciduous Quercus and Cyclobalanopsis forests</td>
<td>Tongbai and Dabieshan Mountains and hills, deciduous Quercus and Cyclobalanopsis forests</td>
<td>14.7−16.0</td>
<td>4500−5200</td>
<td>0.9−3.5</td>
<td>800−1200</td>
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<td></td>
<td>1.4 Qinling-Bashan mountains and hills, oaks, Pinus hembryi, and Pinus armandii forests</td>
<td>Qinling-Bashan mountains and hills, oaks, Pinus hembryi, and Pinus armandii forests</td>
<td>14.0−16.0</td>
<td>4500−4800</td>
<td>0</td>
<td>800−900</td>
</tr>
<tr>
<td>South subzone</td>
<td>2. Central subtropical evergreen broad-leaved forest (represented by Castanopsis, Schima, Altingia, Machilus, etc.)</td>
<td>Central Subtropical evergreen broad-leaved forest</td>
<td>16.0−21.0</td>
<td>4000−6500</td>
<td>5−12</td>
<td>1000−1200</td>
</tr>
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<td></td>
<td>2.1 Zhejiang-Anhui mountains and hills, Cyclobalanopsis glauca and Castanopsis sclerophylla forest</td>
<td>Zhejiang-Anhui mountains and hills, Cyclobalanopsis glauca and Castanopsis sclerophylla forest</td>
<td>15.5−17.0</td>
<td>4500−5200</td>
<td>5−12</td>
<td>1100−1800</td>
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<td></td>
<td>2.2 Zhejiang-Fujian mountains, Castanopsis eyrie and Schima superba forest</td>
<td>Zhejiang-Fujian mountains, Castanopsis eyrie and Schima superba forest</td>
<td>16.0−19.0</td>
<td>5500</td>
<td>5−8.3</td>
<td>1200−2000</td>
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<tr>
<td></td>
<td>2.3 Taihu and Chushan plains, cultivated vegetation, and aquatic vegetation</td>
<td>Taihu and Chushan plains, cultivated vegetation, and aquatic vegetation</td>
<td>16.0−18.0</td>
<td>5100</td>
<td>3.5−5.5</td>
<td>1100−1700</td>
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<td></td>
<td>2.4 Hunan-Zhejiang hills, Cyclobalanopsis and Castanopsis Forest</td>
<td>Hunan-Zhejiang hills, Cyclobalanopsis and Castanopsis Forest</td>
<td>16.0−18.0</td>
<td>4300−5600</td>
<td>4−5</td>
<td>1300−1900</td>
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<td></td>
<td>2.5 The Three Gorges-Wuling mountains, Castanopsis and Machilus forest</td>
<td>The Three Gorges-Wuling mountains, Castanopsis and Machilus forest</td>
<td>16.0−17.5</td>
<td>4500−5300</td>
<td>3.5−5</td>
<td>1200−1800</td>
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<td></td>
<td>2.6 Sichuan Basin, Machilus and Cyclobalanopsis forest</td>
<td>Sichuan Basin, Machilus and Cyclobalanopsis forest</td>
<td>16.0−18.0</td>
<td>−</td>
<td>−</td>
<td>900−1200</td>
</tr>
<tr>
<td>South subzone</td>
<td>2.7 South Zhejiang-Central Fujian mountains and hills, Castanopsis and Altingia gracilipes forest</td>
<td>South Zhejiang-Central Fujian mountains and hills, Castanopsis and Altingia gracilipes forest</td>
<td>18.0−20.0</td>
<td>5300−6000</td>
<td>5−12</td>
<td>1600−1800</td>
</tr>
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<td></td>
<td>2.8 Nanling mountains, Castanopsis and Altingia forest</td>
<td>Nanling mountains, Castanopsis and Altingia forest</td>
<td>18.0−21.1</td>
<td>5300−6800</td>
<td>8−10</td>
<td>1400−2000</td>
</tr>
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<td></td>
<td>2.9 Mountains in three river drainages, Castanopsis and Schima forest</td>
<td>Mountains in three river drainages, Castanopsis and Schima forest</td>
<td>16.0−20.0</td>
<td>−</td>
<td>5−10</td>
<td>1000−1900</td>
</tr>
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<td></td>
<td>2.10 Guizhou Plateau, Castanopsis and Cyclobalanopsis forest, and limestone vegetation</td>
<td>Guizhou Plateau, Castanopsis and Cyclobalanopsis forest, and limestone vegetation</td>
<td>13.5−16.0</td>
<td>4300−5600</td>
<td>3.5−6</td>
<td>900−1300</td>
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<td></td>
<td>2.11 Sichuan, Yunnan and Guizhou mountains and hills, Castanopsis and Schima forest</td>
<td>Sichuan, Yunnan and Guizhou mountains and hills, Castanopsis and Schima forest</td>
<td>17.0−18.0</td>
<td>4300−5600</td>
<td>3.5−6</td>
<td>1000−1200</td>
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</table>
and *Padus* of Rosaceae; this composition of tree layer is distinctly different from that of the northern subtropical mixed evergreen and deciduous broadleaved forest. In this region, the mid-montane mixed evergreen and deciduous broadleaved forests occur in the mountainous areas of 1000–1500 m a.s.l. The trees are cold-resistant evergreen species of Fagaceae such as *Castanopsis sclerophylla*, *Cyclobalanopsis oxyodon*, *Lithocarpus cleistocarpus*, *L. henryi*, and deciduous *Fagus*. There are significant differences in the compositions of natural vegetation types between the northern and southern parts of this zone, so it can be divided into the northern subtropical mixed evergreen and deciduous broadleaved forest subzone and southern subtropical evergreen broadleaved forest subzone. Each subzone can be further subdivided into several districts, as detailed in Table 1.9.

### 1.3.2 Overview of Quaternary vegetation

#### 1.3.2.1 Vegetation succession since the mid-Pleistocene in Hubei

A pollen record from the peat bogs of Dajiuhu Basin is the most detailed in Shennongjia region (Zheng Q F *et al.*, 2014). Its major arboreal pollen types are *Cyclobalanopsis*, *Quercus*, *Fagus*, Rosaceae, *Ulmus*, *Carpinus*, *Betula*, and other broadleaved species, as well as *Pinus*, *Tsuga*, *Picea*, *Abies*, and other conifer species. Herbaceous pollen taxa are dominated by Poaceae, *Artemisia*, Compositae, Ranunculaceae, and Cyperaceae. Monolete spores are common and *Sphagnum* spores reach its high percentages at some levels of this pollen record. The pollen assemblages from this pollen record reflect six stages of vegetation succession and paleoclimate evolution since the late mid-Pleistocene (Figure 1.17):

I. Late MIS 8 (275–245 ka BP), cold-temperate coniferous forest and alpine meadow, cold and dry climatic conditions;

II. MIS 7, mixed evergreen and deciduous broadleaved forest, warm and humid climatic conditions;

III. MIS 6, cold-temperate coniferous forest and then alpine meadow, cold and dry climatic conditions;

IV. MIS 5, warm temperate deciduous broadleaved forest, warm and humid climatic conditions;

V. 71.8–15.0 ka BP, interval development of cold-temperate coniferous forest and alpine meadow, cold and dry climatic conditions;

VI. 15.0–1.0 ka BP, subtropical mixed evergreen and deciduous broadleaved forest, warm and humid climatic conditions.

Another pollen record from Dajiuhu Basin (Li J *et al.*, 2013a, 2013b) shows that forest-steppe and alpine meadow-meadow developed at ca. 42–39 ka BP and 39–31 ka BP. Desert steppe occurred in the MIS 2 (ca. 24–12 ka BP), when vertical vegetation zone had an average drop of 1400 m and the temperature decreased by 7°C. One more pollen record from Dajiuhu (Hao, 2008) shows that the temperate mixed coniferous and broadleaved forest developed in the MIS 4; forest shrank and marshland developed in the MIS 3; and then the temperate mixed coniferous and broadleaved forest developed again at the Last Glacial Maximum (LGM). The significant difference in reconstructed vegetation during the MIS 3 between the two pollen records has been attributed to the high percentages of Cyperaceae pollen. Pollen spectra with average pollen percentages of Cyperaceae exceeding 25% are similar to those from modern alpine steppe-meadow under high and cold conditions in Xizang (Li J *et al.*, 2013a). However, most Cyperaceae plants are hygrophytes generally growing in basin swamps and plain wetlands. They are closely related to local precipitation, groundwater, and runoff system rather than regional climate. Therefore, it is particularly crucial to distinguish the ecotypes of Cyperaceae for the reconstruction of vegetation types during the glacial stages using pollen data.

Modern pollen studies were conducted on topsoil samples from the bottom to the top of Shennongjia Mountains (Liu *et al.*, 1993; Liu *et al.*, 2001; Fang *et al.*, 2015). The results of these studies show the phenomenon of vertical vegetation zones in the spatial distribution of modern pollen rains.
2. Vegetation since the LGM in the Jianghan Plain

A pollen record from Longquan Lake shows that cold-temperate coniferous forest dominated by *Abies* developed in the LGM, and mixed evergreen and deciduous broadleaved forest consisting of *Quercus*, *Cyclobalanopsis*, and *Pinus* occurred in the Holocene (Liu, 1991, 1993). Another pollen record from a core in Liuhe Farm of Jiangling (Li W Y, 1993) reveals that the vegetation during the last glacial and Holocene was dominated by *Pinus*, with a small amount of *Picea*, *Abies* and *Tsuga*. Pollen records from a section in Jiangbei Farm of Jiangling (Xie, 2004; Xie et al., 2006) and the M1 core in Hecheng town of Xiantao (Yang et al., 1998a) show that the Holocene was dominated by the evergreen and deciduous broadleaved forest. A 4500-year pollen record from the core ZK2 in the Meijiazhou of Poyang Lake reveals vegetation dominated by *Microlepia* (Wu et al., 1997). pollen records from the east and west lakes in Wuhan show five episodes of the Holocene vegetation development and succession, i.e., temperate coniferous forest → pine-dominated mixed coniferous and broadleaved forest → mixed evergreen and deciduous broadleaved and coniferous forest → mixed coniferous and broadleaved forest → coniferous forest, mixed evergreen and deciduous broadleaved forests (Yang and Yao, 1992).

Pollen records from some archaeological sites in Hubei provide a broad picture of vegetation succession and human activities during the middle and late Holocene. A pollen record from the Qujiyalong site shows mixed evergreen and deciduous broadleaved forests around the site at 5.4−4.2 ka BP. A large number of Poaceae and *Pinus* pollen as well as charcoal in the pollen record indicate intense human activities and warm-humid climatic conditions during this interval (Li Y Y et al., 2009). Pollen records from the cultural layers in the Zhongqiao and Tanjialing sites show subtropical
swamp meadow with sparse pines under mild and wet conditions at 4.6–4.4 ka BP. This vegetation was then replaced by subtropical wetland and grassland with sparse deciduous broadleafed trees at 4.4–4.2 ka BP (Li Y Y et al., 2010; Li B et al., 2013; Wu, 2013). At 4.2–2.2 ka BP, a significant decrease of Cyperaceae pollen and Ceratopteris spores as well as the development of Artemisia and Chenopodiaceae tussock reflect the aridification of the habitat around sites, which is attributed partly to dry climatic conditions, and partly to intense human activities. Pollen records also show the occurrence of secondary vegetation at 4.2–3.9 ka BP. Since 2.2 ka BP, especially since the Ming and Qing dynasties, natural vegetation has been strongly disturbed by human activities, as indicated by a large amount of Poaceae pollen and high concentrations of charcoal.

1.3.2.2 Vegetation and environment since the late Pleistocene in the lower valley of the Yangtze River

1. Holocene vegetation and human activities in Shanghai-Hangzhou region

Quaternary pollen analysis in the lower reaches of the Yangtze River was initially developed as early as the 1970s. Since then, a great deal of work has been done in this region. Geochronologically, the most extensively studied intervals are the late Pleistocene and Holocene. Geographically, pollen records are from Shanghai area (Wang et al., 1978, 1982, 1984; Chen et al., 2005; Tao et al., 2006; Qin et al., 2008), Taihu region (Xu X M et al., 1996; Shu, 2007; Shu et al., 2007), estuarine delta (Liu et al., 1992; Yi et al., 2003, 2006; Zhang Y L et al., 2004; Jia and Zhang, 2006; Mao et al., 2012), the plain of Northern Zhejiang (Sun et al., 1981; Zong et al., 2007; Liu et al., 2014), Nanjing-Zhenjiang region (Xu and Zhu, 1984; Zhang, 1985; Xu, 1992; Yang et al., 1996; Han et al., 2000), and Jianhu of northern Jiangsu (Tang et al., 1993). These pollen records provide abundant data for the reconstruction of vegetation and climate; however, some questions are still being debated due to the lack of effective and reliable dating control in the early studies. For example, did the strata of Taihu Lake record the Younger Dryas cold event? How to recognize and define the timing of the Holocene Hypsithermal Interval? Issues related to paleomonsoon changes are less emphasized in the previous studies. Additionally, the Shanghai-Hangzhou region is located in the delta zone, an open and dynamic sedimentary system. The development of the Holocene strata is significantly controlled by many factors such as sea-level fluctuation, topographic and landform changes, floods, human activities, and so on. These factors made the stratigraphic pollen records more susceptible to disturbance or interruption. Therefore, pollen records from different cores contain complicated pollen information, and they are likely to exhibit the feature of “simultaneous heterogeneity”. Overall, the region of Taihu Lake experiences frequent climate changes, intense human activities, and diverse sedimentary systems during the Holocene, thus making the sedimentary pollen records more likely to be disturbed by various factors and to become more complicated and discontinuous.

In this section, we selected 10 relatively high-resolution pollen records as representatives to establish a comprehensive pollen sequence since 15.0 ka BP. These pollen records are from the region centered on the Taihu Basin, including the northern modern estuarine delta, the western Gucheng Lake, the central Taihu Lake, and the eastern Qingpu area. They are used to synthesize the Holocene vegetation succession, climatic change, and environmental evolution in this region (Figure 1.18).

15.0–11.0 ka BP: coexistence of mixed evergreen and deciduous broadleaved forest and grassland. Pollen spectra are represented by those from the Gucheng Lake core (15.0–11.3 ka BP), Zhenjiang core (15.0–10.8 ka BP) and Qidong core (12.0–11.0 ka BP). Pollen assemblages were dominated by Artemisia, Poaceae, and Chenopodiaceae. Arboreal pollen was common, including Quercus, Pinus and some evergreen components such as Cyclobalanopsis and Castanopsis. Pollen concentrations were low in this period.

11.0 (10.8)–10.3 (10.0) ka BP: a transitional period of vegetation and climate. Pollen spectra were still dominated by Artemisia, Poaceae, and other upland herbaceous pollen. Pollen percentages of warm
temperate elements gradually increased at the expense of the middle subtropical plants. Pollen spectra indicated slightly cooler and drier climatic conditions than those of the previous period.

10.0−8.5 (8.0) ka BP: subtropical mixed evergreen and deciduous broadleaved forest with a few conifers under climatic conditions similar to today. Pollen spectra were dominated by arboREAL pollen, including Quercus, Pinus, Liquidambar, and other warm temperate deciduous elements such as Ulmus, Betula, and Corylus. Pollen of evergreen elements such as Cyclobalanopsis and Castanopsis/Lithocarpus increased significantly, their pollen percentages were equivalent to those of deciduous arboreal plants or slightly lower.

8.5 (8.0)−4 (3.5) ka BP: evergreen broadleaved forest and warm-humid climatic conditions. Pollen percentages of evergreen broadleaved components were generally more than 5% and even up to 60% in pollen spectra. Pollen spectra also contained a certain amount of Pinus and deciduous oaks. During this period, the study area was occupied by the most stable evergreen broadleaved forest since the late glacial period. A great development of evergreen trees indicated warm and humid climatic conditions. This period corresponds with the Holocene Hypsithermal Interval.

3.5 ka BP−present: a decrease in subtropical evergreen broadleaved components and an intensification of human activities. Pollen spectra are characterized by a gradual decrease in subtropical evergreen components. They contain some pollen of deciduous broadleaved components such as deciduous oaks, Juglans, Salix, and Ulmus/Zelkova. Upland herbaceous pollen such as Poaceae, Cruciferae, and Artemisia as well as Pinus pollen increased. The vegetation changes during this period reflect cool-dry climatic conditions and an intensification of human activities.

The issue about the background of primitive rice planting in the lower reaches of the Yangtze River has been extensively studied in terms of pollen data (Xiao, 1991; Xiao J Y et al., 2003, 2004; Itzstein-Davey et al., 2007a, b; Atahan et al., 2008; Ma and Tian, 2010; Shu et al., 2010, 2012; Qin et al., 2011; Zhao L et al., 2013;
Shu and Jiang, 2014). Zong et al. (2007) proposed a background hypothesis of original rice planting in the lower reaches of the Yangtze River. It is hypothesized that the “slash-and-burn” cultivation of wetland jungle dominated by *Alnus* promoted the formation of the earliest rice planting in the coastal plain, Xiaoshan in Zhejiang about 7,700 years ago. This hypothesis remains contentious. Shu et al. (2010, 2012) resampled at the same archaeological site, and compared the pollen record of this site with other records from nearby natural sites. They found that *Alnus* pollen appears in limited quantities throughout the lower reaches of the Yangtze River. This implies that the primitive rice planting is not because of a massive implementation of “slash-and-burn” but because of the direct use of wetlands as local resources to cultivate rice (Figure 1.19).

2. Holocene vegetation in Wuhu and Chaohu areas

Pollen records in Chaohu area (Chen et al., 2005; Wang X Y et al., 2008a, b; Wu et al., 2008; Chen et al., 2009) show five phases of vegetation and climate changes in the Holocene.

9.87–6.04 cal. ka BP: the vegetation was mixed evergreen and deciduous broadleaved forest dominated by the deciduous and evergreen species of Fagaceae. It reflected mild and slightly dry climate. Limited ancient human activities probably appeared before 8.0 ka BP, and intensified after 6.8 ka BP.

6.04–4.86 cal. ka BP: the vegetation was mixed evergreen and deciduous broadleaved forest dominated by deciduous oaks, *Castanea, Cyclobalanopsis*, and *Castanopsis/Lithocarpus*. The vegetation indicated that the climate changed from mild and slightly dry in
Figure 1.20  Pollen percentage diagram of core CH-1 in Chaohu Lake (modified from Wu et al., 2008)
the previous phase to warm and humid in this phase, corresponding to the Holocene climatic optimum.

4.86−2.17 cal. ka BP: the vegetation was mixed evergreen and deciduous broadleaved forest dominated by deciduous oaks, implying a gradual decrease of temperature and humidity, and thus mild and dry climate.

2.17−1.04 cal. ka BP: the whole environment exhibited a drying trend. Forest areas shrank. Mixed evergreen and deciduous broadleaved forest was rapidly destroyed, and it was replaced by grassland which was dominated by Poaceae. The climate was mild and humid.

After 1.04 cal. ka BP, the vegetation was a secondary forest dominated by *Pinus* under the influence of human activities (Figure 1.20).

Wuhu-Jiangyin area is located in the transitional zone among the middle and lower reaches of the Yangtze River, the Nanjing-Zhenjiang Mountains, and the Yangtze River delta plain. A vegetation history since 30 ka BP for this area was reconstructed from pollen records (Xu and Zhu, 1984; Xu et al., 1987). Mixed coniferous and broadleaved forest occurred under cold and wet climatic conditions during 30−18 ka BP. This vegetation changed to sparse steppe under cold and dry climatic conditions during 18−15 ka BP. The sparse grassland was replaced by mixed coniferous and broadleaved forest dominated by *Quercus* and *Pinus* during 15−13.7 ka BP, implying cool and dry climatic conditions. The forest was replaced by sparse steppe or arid steppe once again during 13.7−11 ka BP, indicating cold and dry climatic conditions. Mixed coniferous and broadleaved forest mainly composed of *Pinus* and *Quercus* occurred under cool and dry climatic conditions during 11.0−9.0 ka BP. Deciduous oak forest, mixed pine and oak forest, evergreen and deciduous broadleaved forest successively appeared from 9.0 ka BP to 4.0 ka BP, indicating warm and wet climatic conditions. After 4.0 ka BP, temperate or warm temperature forest-steppe occurred under cool and dry climatic conditions.

3. Vegetation since the MIS 19 in the North Jiangsu Plain

A pollen record from a long core in Xinghua revealed a history of vegetation changes from MIS 19 to MIS 6 (Wang, 2005). The vegetation succession in this locality is deciduous broadleaved forest with evergreen broadleaved species → sparse vegetation zone → forest-steppe → sparse vegetation zone → evergreen broadleaved forest with deciduous broadleaved species → sparse vegetation zone → deciduous broadleaved forest with evergreen broadleaved species → sparse vegetation zone → deciduous broadleaved forest with evergreen broadleaved species → sparse vegetation zone. Pollen data also show the vegetation succession since the MIS 5 as follows: evergreen broadleaved forest with deciduous broadleaved species → forest → forest-steppe → deciduous broadleaved forest with evergreen species → forest-steppe → mixed evergreen and deciduous broadleaved forest → sparse vegetation zone → evergreen broadleaved forest with deciduous broadleaved species → deciduous broadleaved forest with evergreen broadleaved species → mixed evergreen and deciduous broadleaved forest → evergreen broadleaved forest (Guo, 2004). A pollen record from the Jianhu section in northern Jiangsu (Tang et al., 1993) revealed the succession of Holocene vegetation, as follows: deciduous broadleaved forest from 10.1 ka BP to 9.2 ka BP → mixed evergreen and deciduous broadleaved forest from 9.2 ka BP to 6.6 ka BP → warm pine forest from 6.6 ka BP to 6.4 ka BP → mixed evergreen and deciduous broadleaved forest during 6.4−2.4 ka BP → deciduous broadleaved forest during 2.4−1.0 ka BP. Temperature estimated quantitatively using pollen data was about 1.3−1.7°C higher than the present during the intervals of 8.5−8.0 ka BP, 7.7−6.6 ka BP, and 6.1−3.7 ka BP.

1.3.2.3 Forest succession since the last glaciation in the coastal region of Fujian

A pollen record from a peat core in Pingnan, Fujian revealed the cyclic changes of forest vegetation during the last glacial period in the eastern subtropical region (Figure 1.21) (Yue et al., 2012). The subtropical mixed evergreen and deciduous broadleaved forest dominated by *Cyclobalanopsis* favoring relatively warm and humid
Figure 1.21  Pollen percentage diagram for the past 50 ka in Gantang of Pingnan, Fujian (modified from Yue et al., 2012)
climate developed in this region during the MIS 3. During the LGM (24−16 ka BP), Cyclobalanopsis, Alnus, and Ericaceae increased, reflecting the northern subtropical mixed evergreen and deciduous broadleaved forest. An increase of Pterocarya at the YD chronozone probably marks the occurrence of the YD cold event in this region. The evergreen broadleaved forest dominated by Cyclobalanopsis developed during 8.2−4 ka BP, the Holocene hypsithermal interval. After 4 ka BP, the monsoon became weak; and herbaceous plants and Ericaceae increased distinctly. Since 2 ka BP, the forest vegetation has been significantly influenced by human activities. Other Holocene pollen studies in Daiyunshan Mountains and the coastal region of Fujian (Yang, 1992; Lu, 1994a, b; Wang et al., 1995; Xiao et al., 1998, 2000; Zheng et al., 2004) support this conclusion. Human activities have had a great impact on vegetation.

Pollen records of three cores (Cores LHZK1, DSZK2, and XPZK3 in Longhai, Dongshan, and Xiamu, respectively) reveal the vegetation and climate since the late Pleistocene in southern Fujian (Li, 2014). Among these pollen records, major pollen types include the subtropical trees such as evergreen Quercus, Altingia/Liquidambar, Cyclobalanopsis, Castanopsis, and Lithocarpus, as well as warm temperate trees such as deciduous Quercus, Juglans, Castanea, Acer, Ulmus, Celtis, Betula, Alnus, and Pterocarya. The pollen ratio between subtropical and warm temperate trees in each pollen spectrum was used as temperature proxy in Li's study. The late Pleistocene sediments of three cores were discontinuous, so the pollen record from core DSZK2 in Dongshan was selected as a representative to elucidate the vegetation and climate changes in this region.

26.2−24.5 ka BP: the arboreal plants were dominated by Cyclobalanopsis, Castanopsis/Lithocarpus, Hamamelidaceae, and Rosaceae. Herbaceous plants mainly included Poaceae, Artemisia, and Labiatae. Pollen percentages of subtropical and warm temperate trees are 14%−23.8% and 40.1%−36.1%, respectively, implying that vegetation was dominated by warm temperate deciduous broadleaved forest, suggesting a mild climate.

10.0−8.0 ka BP: pollen spectra were dominated by Cyclobalanopsis, Hamamelidaceae, Labiatae, and Poaceae. The arboreal pollen was still dominated by warm temperate components, but the temperature proxy showed a rising trend.

8.0−3.5 ka BP: pollen spectra were mainly composed of evergreen oak, Cyclobalanopsis, Castanopsis, deciduous Quercus, Hamamelidaceae, Rosaceae and Cyperaceae. The ratio of subtropical/warm temperate trees reached its highest level throughout the past 26 ka, reflecting a hot climate in the mid-Holocene. However, the low values of subtropical components at 7.5−6.8 ka BP and 6.3−4.5 ka BP showed climate fluctuations.

3.5−1.5 ka BP: pollen spectra were dominated by Pinus and Poaceae pollen as well as fern spores. Ratio of subtropical/warm temperate trees decreased, probably implying climatic cooling in the late Holocene.

1.5−1.0 ka BP: the ratio of subtropical/warm temperate trees increased, indicating a rebound of temperature in this time interval corresponding to the Medieval Warm Period.

1.0−0.5 ka BP: the ratio dropped again, probably reflecting the onset of the Little Ice Age.

1.3.2.4 Vegetation and environment since the late Pleistocene in central Taiwan Island

(1) A pollen record from the core in the peat bog of Toushe basin, central Taiwan Island (Figure 1.22) reveals vegetation history and climatic changes since the last glacial period (Liew et al., 2006a, b).

95.2−80.5 ka BP (equivalent to MIS 5c-b): the pollen assemblage was characterized by high content of Castanopsis. It had a few Cyperaceae pollen and few spores. Pollen spectra reflect a vegetation type similar to subtropical-warm temperate Schima-Castanopsis forest at 500−1500 m in modern Taiwan Island. The climate was moister than that of today’s Schima-Castanopsis forest.

80.5−73.9 ka BP (equivalent to MIS 5a): Castanopsis significantly decreased, while Alnus, Salix, and Ilex increased. Pollen spectra indicate cool and dry climate.

73.9−59.0 ka BP (equivalent to MIS 4): Alnus increased to >60%, and Cyperaceae decreased, showing
Figure 1.22  Pollen percentage diagram of major trees and shrubs from Toushe Basin, central Taiwan Island (modified from Liew et al., 2006a)
the characteristics of temperate deciduous broadleaved forest, approximately equivalent to deciduous forest belt occurring at 2250−2500 m in central Taiwan today. The climate was cold and dry.

59.0−27.9 ka BP (equivalent to MIS 3): Alnus and Cyperaceae predominated alternately. More Cyperaceae indicates an increase of humidity. The increase of Ilex and Cyclobalanopsis reflects climate warming at 42.2−37.0 ka BP. Pollen spectra indicate warm temperate climatic conditions.

27.9−16.7 ka BP (equivalent to MIS 2): herbaceous plant pollen predominated, and the vegetation was temperate forest or forest-steppe. High Poaceae and Artemisia pollen reflect relative dry and cold conditions at 23.2−16.7 ka BP.

16.7−11.0 ka BP (the late glacial stage): arboreal pollen increased. Pollen spectra were dominated by Cyclobalanopsis, Ilex, Symlocos and Salix, reflecting the development of temperate mixed broadleaved and coniferous forests. The climate was drier and cooler than the present, but warmer and moister than the previous stage.

11.0−1.8 ka BP: a peak of Salix pollen occurred in 11.0 ka BP. This happened just before the onset of a moist period beginning at 10.7 ka BP, as reflected by significant increase in monolete spores. Castanopsis also increased. Pollen spectra indicate that the climate became subtropical with warm and humid conditions. Remarkably, warmer conditions occurred at 7.3−6.8 ka BP and 6.2−5.8 ka BP, as indicated by the increase in Mallotus and Glochidion, respectively. However, Salix peaks reflect the prevailing deciduous forest and less warm conditions, indicating the occurrence of centennial cooling events at ca. 11.0 ka BP, 9.6−9.4 ka BP, 9 ka BP, 7.9 ka BP, 7.5 ka BP, 7.2−7.1 ka BP, 5.2−5.0 ka BP, 4.0 ka BP, and 3.7 ka BP.

(2) Pollen records of two cores from Jih Tan (“Tan”, a Chinese word meaning “lake”) (altitude 745.5 m) and Tashuiku Tan (altitude 620 m) in central Taiwan Island show several drastic vegetational changes and climatic variations during the late Pleistocene and Holocene (Figure 1.23) (Tsukada, 1967).

Pollen spectra prior to 60 ka BP in the core of Jih Tan were dominated by Symlocos, Tsuga, and Pinus, reflecting warm-temperate zone vegetation. It was estimated that the temperature was 5.0−9.0°C lower than that at present, implying that a warm- to cool-temperate climate prevailed. A large number of aquatic plants appeared in the Tashuiku Tan core and formed the peat layers, indicating relatively dry conditions in summer during this period. Pollen spectra from 60 ka BP to 47 ka BP were characterized by an increase of the boreal elements (such as Abies, Picea, and Tsuga) and Pinus (reaching more than 80% altogether), as well as aquatic plants (Nuphar, Polygonum, and Trapa). The appearance of plentiful boreal species in the lowlands suggested a remarkable reduction of annual temperature, which was estimated to be 8.0−11.0°C lower than at present. The lake depth was probably less than 2.0 m during this period presumably due to somewhat decreased precipitation. From 47 ka BP to 10 ka BP, the subalpine conifers almost disappeared in the source area of Jih Tan. Pollen spectra were dominated by cold temperate trees such as Quercus, Cunninghamia, Carpinus, and Ulmus/Zelkova, indicating that the climate was still colder than today. Between 35 ka BP and 15 ka BP in this period, the climatic environment was extremely stable, for almost no extensive secondary forest was present.

Pollen spectra after 10 ka BP were characterized by a distinct decrease of cold temperate species such as Quercus, Carpinus, and Cunninghamia, and an increase of subtropical and warm temperate species such as Mallotus, Trema, Liquidambar, Castanopsis, and Podocarpus, indicating warm climate. Additionally, pollen spectra after 4.0 ka BP from Jih Tan and Tashuiku Tan cores also show evidence of increased human population and enhanced agricultural activities.

(3) A pollen record from Dongyuan Lake in southern Taiwan Island (Figure 1.24; Lee and Liew, 2010; Lee et al., 2010) reveals vegetation and climate changes since 22 cal. ka BP.

22−16 cal. ka BP: pollen spectra are mainly composed of Tsuga, Pinus, Carpinus, Ligustrum, Deutzia, Hydrangea, Cyclobalanopsis, and Quercus, reflecting temperate mixed deciduous broadleaved and coniferous forest. This vegetation suggests that climate
### Figure 1.23
Pollen diagram for a 12.79 m core from Jih Tan, central Taiwan Island (modified from Tsukada, 1967)

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<th>Age (ka BP)</th>
<th>Depth (cm)</th>
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<th>Boreal Components</th>
<th>Temperate Forest Trees &amp; Secondary Forest Elements</th>
<th>Shrubs</th>
<th>Herbs</th>
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**Table:**
- **Age (a BP):** 0, 0.03, 4, 7, 10, 12-10.5, 8.5, 14, 20, 30, 35, 40, 50, 60, 30, 20, 10, 5, 0
- **Depth (cm):** 0, 10, 20, 30, 40, 50, 60
- **Older age:** 4200 ± 60, 12300 ± 160, 35500 ± 1500, 47000

**Legend:**
- **Age/ka BP:** 0, 0.03, 4, 7, 10, 12-10.5, 8.5, 14, 20, 30, 35, 40, 50, 60
- **Depth/cm:** 0, 10, 20, 30, 40, 50, 60
- **Legend colors:**
  - Green: Boreal Components
  - Black: Temperate Forest Trees & Secondary Forest Elements
  - Blue: Shrubs
  - Yellow: Herbs
  - Red: Ferns
  - Orange: Abies
  - Pink: Picea
  - Yellow-Green: Tsuga
  - Dark Blue: Juglans
  - Purple: Cunninghamia
  - Brown: Carpinus
  - Cyan: Keteleeria
  - Green-Blue: Podocarpus
  - Light Brown: Castanopsis
  - Blue-Black: Quercus
  - Light Black: Mallotus
  - Grey: Ulmus & Zelkova
  - Grey-Blue: Salix
  - Grey-Orange: Ilex
  - Grey-Red: Symplocos
  - Grey-Yellow: Umbelliferae
  - Grey-White: Trema
  - Grey-Brown: Chenopodiaceae
  - Grey-Cyan: Compositae
  - Grey-Purple: Poaceae
Figure 1.24  Pollen percentage diagram from Dongyuan Lake, southern Taiwan (modified from Lee et al., 2010)
Overview of Modern and Quaternary Vegetation in China

Chapter 1

1.4 South Region

1.4.1 Overview of modern vegetation

1.4.1.1 Vegetation in the southern zone of middle subtropical evergreen broadleaved forests

Middle subtropical evergreen broadleaved forests occur along the northern limit of south region, including Guilin in Guangxi, Shaoquan, Huiyang, and northern Meixian in Guangdong (Wu, 1980), with average annual temperature of 18–21.1°C, average January temperature of 8–10°C, extreme lowest temperature of −2–6°C, and average July temperature of 28–30°C. Nanling blocks cold air current from north China, thus forming a climatic boundary between the north and south. In the north of Nanling, it snows in winter, but in the middle and south of Nanling, there’s no snow normally, which makes “Lingnan landscape” with well-developed evergreen broadleaved forests and richer tropical flora. The annual precipitation is 1400–2000 mm, with rainy spring and summer seasons that correspond with the growing season, thus favoring the development of subtropical evergreen forests. Regional vegetation mainly consists of evergreen broadleaved forest, but coniferous forest (Pinaceae-Taxodiaceae) and bamboo forest are also common.

Evergreen broadleaved forest occurs on mountain slopes or hills under 1200 m above sea level (a.s.l.). This forest is dominated by Castanopsis (Castanopsis fordii, C. Tibetana, C. carlesii, and C. eyrei), Altingia chinensis, Machilus thunbergii, Schima superba, and various species from Lauraceae, such as Cryptocarya, Beilschmiedia, Cinnamomum, Phoebe, Machilus, followed by Theaceae (Anneslea fragrans, Brassica juncea var. megarrhiza, Tutcheria championi, Hartia sinensis) and Magnoliaceae (Manglietia fordiana, Magnolia dawsoniana, Michelia maudiae), as well as endemic species from Hamamelidaceae (Rhodoleia championii and Exbucklandia tonkinensis), the latter including many tropical elements. Understory shrubs are mainly composed of Theaceae, Rubiaceae, Melastomataceae, Ericaceae, and bamboo (Fargesia spathacea and Indocalamus tessellates). Herbaceous species are dominated by ferns (Woodwardia japonica, Plagiogyria adnata) and other herbs (Carex, Alpinia japonica, and Lophatherum gracile). In the valley, there are tropical species such as Uvaria macrophylla and Fissistigma oldhamii (Annonaceae), along with ferns such as Cibotium barometz, Osmunda vachellii, and Blechnum orientale (Wu, 1980).

conditions were considerably colder during the LGM and early deglacial period. The annual mean temperature of the LGM was at least 7°C lower than today.

16–11.4 cal. ka BP: major pollen types are Deutzia, Hydrangea, Ligustrum, Carpinus, Ardisia, Castanopsis, Schefflera, and Ilex. Pollen spectra show a vegetation type transitional between a temperate mixed coniferous-deciduous broadleaved forest and a warm temperate evergreen broadleaved forest, indicating the gradually warming climate conditions of the late-glacial period.

11.4–8.2 cal. ka BP: pollen spectra are mainly composed of Maesa, Ardisia, Cyclobalanopsis, Quercus, Deutzia, Hydrangea, Agleia, and Ilex, reflecting a vegetation dominated by warm temperate evergreen broadleaved forest elements. The study area experienced further warming, but the temperature was still lower than today.

8.2–4.1 cal. ka BP: pollen spectra are dominated by Agleia, Phoenix, Calamus, Glochidion, Schefflera, Ilex, and Castanopsis, indicating that a subtropical evergreen forest prevailed in the study area and the climate was warmer than that of previous periods. In particular, the tropical evergreen forest appeared at ca. 6.1 cal. ka BP, marking the mid-Holocene Thermal Optimum with annual mean temperature at least 2°C higher than today.

4.1–2.1 cal. ka BP: pollen spectra consist mainly of Stewartia, Ardisia, Castanopsis, Deutzia, Hydrangea, and Ligustrum, reflecting a warm temperate evergreen broadleaved forest. The study area experienced cool climatic conditions, similar to those of the early Holocene.

2.1 cal. ka BP till now: pollen spectra are mainly composed of Agleia, Phoenix, Arenga, Bischofia, Glochidion, and Melanolepis, reflecting a reemergence of the subtropical evergreen broadleaved forest under climatic conditions similar to the present.
Above 1200 m a.s.l., there are some conifers within the evergreen broadleaved forests, such as *Taxus wallichiana* var. *mairei*, *Tsuga longibracteata*, *Podocarpus neriifolius*, *Betula luminifera*, *B. insignis*, *Pterostyrax corymbosus*, *Sassafras tzumu*, *Rehderodendron macrocarpum*, *Carpinus viminea*, *Tilia tuan*, forming conifer-broadleaf mixed or deciduous broadleaved mixed forests (Wu, 1980).

1.4.1.2 Vegetation in the southern subtropical monsoonal evergreen broadleaved forest zone

The central areas of south region include Guangdong and western Guangxi, where the regional vegetation is southern subtropical monsoonal evergreen broadleaved forest. The climate is distinctive tropical monsoonal, with high annual temperature but high interannual variability, high annual precipitation with strong seasonality marked by distinct dry and wet seasons. Controlled by the southeast monsoon in summer, as well as high impacts from Pacific typhoons, there is a distinct wet season with high temperature and rainfall. Affected by cold air from the north, the winter is relatively short but mild and dry. The seasonal vegetation contrast is more distinct than that of the middle subtropical region. Due to strong maritime influence, temperature extremes are uncommon—seldom over 37°C in the summer and rarely below 0°C in the winter, although extreme lows of −2°C or −3°C have been recorded. The composition of vegetation is relatively complex. The region is floristically diverse, with a flora mainly affiliated with the “South-China Province”, although elements of the Malaysia flora become more prominent in the west and those of the central-south China flora are more prominent the east. The predominant species are from the Fagaceae and Lauraceae families (mainly tropical genera and species), as well as Hamamelidaceae and Theaceae. Moreover, there are communities consisting of Guttiferae, Annonaceae, Myrtaceae, Euphorbiaceae, Moraceae, Rubiaceae, Myrsinaceae, Apocynaceae, Arecaceae, Rhizophoraceae and Subfamily Bambusoideae. These elements normally are not dominants in the forests, but are consisting of co-edificato or common species that can become dominant in special habitats such as plain and limestone areas, forming semi-evergreen seasonal rainforest. Important genera from Fagaceae are *Castanopsis* and *Cyclobalanopsis*, with key species *Castanopsis hystrix*, *C. chinensis*, *C. concinna* and *C. eyrei* from *Castanopsis*. Key genera from Lauraceae are *Cryptocarya*, *Machilus*, and *Litsea*. Secondary forests are dominated by *Pinus massoniana* communities, with largest area; most of them are artificial forest. Understory of forests is largely composed of tropical species, especially in the south-facing slopes of valleys. Also occurring in the understory of valley rainforest are tropical species such as *Musa* sp., *Alocasia macrorrhiza*, *Alsophila spinulosa*, *Caryota ochlandra*, and xyloid epiphytes *Calamus tetradactylus*, *Entada phaseoloides*, *Fissis tigma oldhamii*, *Ecdysanthera utilis*, and *Sindechites chinensis* (Wu, 1980).

1.4.1.3 Tropical semi-evergreen monsoonal forest and tropical monsoonal forest

Tropical semi-evergreen monsoonal forest and tropical monsoonal forest are the southernmost vegetation units in south region, mainly in Leizhou Peninsula and Hainan Island, with heterogeneous geographical landscapes, diverse flora, and varied vegetation types. Radially arranged mountains in the central-southern Hainan Island have many peaks above 1000 m a.s.l., among which the highest peak is Wuzhishan with the elevation of 1879 m a.s.l. In Hainan Island, most of the mountains have elevations of 500−800 m a.s.l., which are surrounded by hills and highlands with elevations of 10−200 m a.s.l. It is thought that Hainan Island was shaped by tectonical faulting from the depressed rift valley forming Qiongzhou Strait during the Quaternary, resulting in isolation from the Chinese mainland. Consequently, vegetation types in Leizhou Peninsula are similar to those in the northern Hainan Island. The climate in this region is controlled by the summer monsoon, with abundant rainfall. Mean annual temperature is 20−22°C, which is higher in the south (25−26°C). The lowest average temperature occurs in January, generally around 12−15°C. There
is big difference in precipitation between the east and west of Hainan Island, with 3000–5000 mm in the east and 900–1200 mm in the west due to the rain shadow effect. Vegetation in the eastern Hainan Island is tropical seasonal rainforest and rainforest, while seasonal rainforest or deciduous seasonal rainforest occurs in the west because of drier climatic condition (Wu, 1980).

Of the vegetation types in South China, key arboreal layers of lowland rainforests and montane rainforests are composed of Dipterocarpus, Hopea, Vatica, Parashorea, Shorea from Dipterocarpaceae; and other important elements are Heritiera littoralis, Pterospermum acerifolium and Sterculia monosperma from Sterculiaceae; Dysoxylum, Aglaia odorata and Aphanamixis from Meliaceae; Artocarpus nitidus subsp. lingnanensis, Ficus and Antiars from Moraceae, as well as Sapindaceae and Datisicaceae. Secondary layers of the forests are composed of Pouteria grandifolia and Sarcosperma laurinum from Sapotaceae, Barringtonia racemosa (Barringtoniaceae), Drypetes indica (Euphorbiaceae), Terminalia catappa (Combretaceae), Crypteronia paniculata (Crypteroniaceae), Xanthophyllum hainanensis (Crypteroniaceae). Shrubs, herbs, and xyloid epiphytes are composed of Annonaceae, Rubiaceae, Gutiferae, Combretaceae, Apocynaceae, Asclepiadaceae, Myrtaceae, Verbenaceae, Arecaceae, and Leguminasae (Wu, 1980).

The representative regional vegetation types are tropical semi-evergreen seasonal rainforest and tropical seasonal rainforest, except for a few occurrences of species of wet rainforest and understory. Key species include Bischofia, Cephalotaxus and Endospermum from Euphorbiaceae; Excenrodendron and Hainan from Tiliaceae; Amesiodendron (Sapindaceae), Aphanamixis and Walsura from Meliaceae; Ficus and Teonomia from Moraceae; Gironniera subaequalis and Celtis from Ulmaceae; Spondias, Chorospondias axillaris, and Spondias lakanensis from Anacardiaceae; Sindora (Caesalpiniaceae), Mesua (Guttafereae), Cryptocarya chinensis and Beilschmiedia (Lauraceae), Sterculia (Sterculiaceae), and Madhuca (Sapotaceae). Lower layers are composed of Rubiaceae, Rutaceae, Myrsinaceae, Ebenaceae, Caesalpinaceae, Annonaceae, Euphorbiaceae, and Myrtaceae. Deciduous elements are Bombax (Bombacaceae); Lannea, Buchanania and Spondia spinata from Anacardiaceae; Albizia and Accacia from Mimosaceae; Mayodendron, Markhamia, Oxaroxyl, and Radermachera from Bignoniacae; Terminalia (Combretaceae); Melia, Chukrasia, and Walsura from Meliaceae; Dillenia (Dilleniaceae); Garuga (Burseraceae); Kleinhovia, Sterculia and Eriolaena from Sterculiaceae; Lagerstroemia and Alangium from Alangiaceae. Some subtropical deciduous species are components of mixed or deciduous forests that occur locally in this region (Wu, 1980).

Broadleaved forests in tropical mountains (like montane rainforest and monsoonal evergreen broadleaved forests) are similar to those in the subtropics due to the cool and wet montane climate without a distinctive dry season. The dominant elements are Lauraceae, Fagaceae and Magnoliaceae. Common species are Castanopsis, Lithocarpus, and Cyclobalanopsis (Fagaceae), Machilus, Actinodaphne, Neolitsea, Lindera, Litsea, Cinnamomum, and Cryptocarya (Lauraceae), as well as Theaceae, Hamamelidaceae, Araliaceae, Elaeocarpaceae, Oleaceae, and Tetracentraceae. Understory is rich in Areaceae and Subfamily Bambusoideae. Diverse ferns include tree fern (Wu, 1980).

Temperate deciduous species occur at middle elevations on mountain slopes due to relatively lower temperatures, such as Carpinus, Betula, Alnus, Acer, and Nyssa. In the montane forests, warm temperate, temperate, and cool temperate elements occur from low to high altitudes, such as Podocarpus, Dacrydium, Pinus kwangtungensis, P. fenzeliana, Cephalotaxus hainanensis, P. yunnanensis, Tsuga, Keteleeria and Calocedrus. These montane conifers are mixed in broadleaf forests without dominance, however, Picea and Abies in high altitudes can form dominant conifer communities. In lowlands and low hills, tropical conifers that can form forests in large area are Pinus fenzeliana and P. kesiya (Wu, 1980).

Mangroves in south region are similar to those in Malaysia in terms of flora, forest structure, and form. The key species are from Rhizophoraceae and Sonneratia
(Lythraceae), followed by some species from different families, like *Aegiceras corniculatum* (Myrsinaceae), *Scyphiphora hydropallacea* (Rubiacae), *Xylocarpus granatum* (Meliacae), *Hertitiera littoralis* (Sterculiacae), *Excoecaria agallocha* (Euphorbiaceae), *Nypa fruticans* (Arecaceae), and so on. Arecaceae, tuft bamboo, and Cactaceae are important elements in different communities, that is once of formation characteristics of regional vegetation in south region.

Above the tropical middle mountains, evergreen bosquet, bosk, and mossy forest occur in peaks and mountain ridges. These habitats with relatively cooler condition are suitable for dominants of Ericaceae, Vacciniacae, and Rosaceae.

A distinct altitudinal gradient exists from tropical vegetation in the lowlands to transitional types of subtropical and temperate vegetation at higher elevations. In the lower altitudes, the subtropical montane vegetation is still more or less tropical in nature in terms of forest formation and structure.

In south region, semi-evergreen seasonal rainforests normally occur at elevations lower than 500−600 m a.s.l., however wet rainforest, deciduous seasonal rainforest, and moss-forest like bosquet can occur locally in the top and ridges of mountains. Above 1500 m a.s.l., the species numbers and abundance of gymnosperms show increasing trend, and the vegetation transitions to montane conifer-broadleaved forests.

### 1.4.2 Overview of Quaternary vegetation

Quaternary vegetation reconstruction in south region is based on pollen data from land and marine sediments (Shen* et al.*, 1989; Tang* et al.*, 1991e; Zheng, 1991a, b; Sun and Li, 1999; Sun* et al.*, 1999; Zheng and Lei, 1999; Zheng and Li, 2000; Lü* et al.*, 2003b; Zhang, 2008; Wang* et al.*, 2012; Dai and Weng, 2015). Palynomorphs are essentials to the reconstruction of Quaternary vegetation. The representative pollen types from land sediments in south region include: ①arboreal taxa characteristic of warm and wet climate in lowland or valley rainforest, including *Ficus, Elaeocarpus, Syzygium, Moraceae, Mallotus, Phyllanthus, Randia, Craibiodendron, Apocynaceae, Arecaceae, Apousa, Helicia, Rhodomyrtus, Croton, Alchornea, Breynia, and Melastoma; ②gymnosperm pollen types mainly include *Dacrydium, Podocarpus, Keteleeria,* and *Taxodiaceae*, indicating vegetation communities of montane rainforest, that are distinct from the other montane areas in China; ③abundant subtropical broadleaf species consisting of *Castanopsis, Lithocarpus, Altingia, Liquidambar, Myrica, Ilex, Rutaceae, Araliaceae, Anacardiaceae, Myrsinaceae, Sapindaceae, Symplocos, and Flacourtiaceae*, which are key components of montane evergreen broadleaved forest; ④coastal mangrove pollen mainly from *Rhizophora, Sonneratia, Kandelia, Ceriops,* and *Bruguiera*, indicating coastal and estuarine unique vegetation communities; ⑤middle subtropical arboreal pollen types in this area, such as *Fagus, Carpinus, Platycarya, Ailus, Pterocarya, Betula, Caryya,* and *Ulmus,* which are useful indicators of climatic cooling in south region; ⑥diverse assemblage of fern spores, such as *Dicranopteris, Pteris, Polyopodiodes, Hicriopteris, Cibotium, Lygodium, Adiantum, Cyclosorus, Microlepia, Schizaea, Pteridium, Osmunda,* and *Selaginella,* indicating rich understory of tropical-subtropical forests with warm and wet climate, as documented by several palynological studies from Huguangyan Marr Lake in the Leizhou Peninsula (Lü* et al.*, 2003b; Wang* et al.*, 2012; Meng* et al.*, 2017; Figure 1.25a, b, c).

#### 1.4.2.1 Vegetation since the late Pleistocene in the Pearl River Delta and Chaoshan Plain

**1. Late Pleistocene**

Palynological studies of late Pleistocene in south region mainly focus on the Pearl River Delta (Shen* et al.*, 1989; Zheng and Wu, 1989; Lei and Fang, 1990; Chen* et al.*, 1994) and the Chaoshan Plain in eastern coastal areas (Zheng, 1991b; Zheng and Li, 2000; Lü* et al.*, 2003b; Figure 1.26; Table 1.10).

Around 70−50 ka BP, tropical-subtropical arboreal pollen types are abundant in the palynological assemblages from the Chaoshan plain, such as *Castanopsis, Distylium, Ficus, Sycopsis, Schima, Symplocos, Calamus, Dacrydium,* fern spores
Chapter 1 Overview of Modern and Quaternary Vegetation in China

Atlas of Quaternary Pollen and Spores in China

Age/cal. a BP

Pollen zone

P1

P2

P3-1

P3-2

P3-3

Information function

Montane conifer

Broadleaved

Temperate trees

Subtropical trees

Tropical trees

Upland herbs

Wetland herbs

Trees

Herbs

Ferns
Figure 1.25  Key pollen types in the pollen diagrams from the sediment sequences of Huguangyan Marr Lake
a. Modified from Lü et al., 2003b; b. Modified from Wang et al., 2012; c. Modified from Meng et al., 2017
Figure 1.25 Key pollen types in the pollen diagrams from the sediment sequences of Huguangyan Marr Lake (continued)

a. Modified from Lü et al., 2003b; b. Modified from Wang et al., 2012; c. Modified from Meng et al., 2017
Figure 1.26  Pollen diagram of core CH2 in Chaoshan Plain (modified from Zheng and Li, 2000)
### Table 1.10 Quaternary vegetation, climate and environment in the Pearl River Delta

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Age (ka BP)</th>
<th>Pollen assemblage</th>
<th>Vegetation</th>
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<th>Pollen assemblage</th>
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<td>Castanopsis, Quercus, Helicia, Symlocos, Altingia, Pinus, Hicrephyllum, Monotes</td>
<td>Evergreen broadleaved and deciduous mixed forest</td>
<td>Warm &amp; wet</td>
<td>Castanopsis, Cyclobalanopsis, Pinus, Cupressaceae, Erica racemosa</td>
<td>Evergreen broadleaved and deciduous mixed forest</td>
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<td>Castanopsis/Lithocarpus, Bandia, Quercus, Rhizophora, Artemisia, Poaceae, Hicrephyllum, Monotes, Cibotum, Ficus</td>
<td>Evergreen broadleaved rainforest</td>
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<td>Castanopsis/Lithocarpus, Cyclobalanopsis, Erica racemosa, Ficus, Cyperaceae</td>
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**Shen and Guangzhou (Li et al., 1991)**
(Microlepia, Pteris, Lygodium), and herbs from Cyperaceae. The reconstructed vegetation based on such pollen assemblages suggests warm and wet climate. While in the southwestern area, pollen assemblages from Huguangyan Marr Lake are characterized by middle southern subtropical species, like Castanopsis/Lithocarpus, Altingia, Moraceae, Elaeocarpus, Syzygium, Adinandra, Dacrydium, and Podocarpus. The vegetation was composed of southern subtropical evergreen broadleaved forests, suggesting warm and humid climate. Around 56–50 ka BP in Huguangyan Marr Lake, subtropical pollen types increased, such as Fagus, Alnus, and Platycarya. The vegetation was succeeded by middle subtropical evergreen-deciduous broadleaved forest, indicating a less-warm climate.

During 50–42.5 ka BP, tropical and southern subtropical species increased, and the vegetation changed back to southern subtropical monsoonal evergreen forests, with warm and humid climate. Around 45 ka BP in the Chaoshan Plain, rich northern subtropical-temperate deciduous species and conifers occurred in pollen assemblages, such as Fagus, Quercus, Myrica, Artemisia, Chenopodiaceae/Amaranthaceae, and many ferns. The vegetation was composed of evergreen-deciduous broadleaved forest mixed with conifers, indicating cool and relatively dry climate.

During 45–28 ka BP, abundant pollen of mangrove alternated with that of Castanopsis in the pollen assemblages of the Chaoshan Plain. The vegetation was composed of evergreen broadleaved seasonal rainforest and montane rainforest, suggesting warm and humid conditions alternating with warm and wet climate. Tropical mangrove community of Sonneratia developed well on the coasts, indicating warm and humid climate. Around 40–36 ka BP, pollen assemblages from the sediments of Lingdingyang in the estuary of the Pearl River were composed of Castanopsis, Quercus, Altingia, Elaeocarpus, Ulmus, and ferns (Cibotium, Hicriopteris). The regional vegetation was characteristic of a montane evergreen broadleaf-conifer forest, indicating warm and wet climate.

During 28–23 ka BP, deciduous species and conifers increased in the pollen assemblages from the Chaoshan Plain (Table 1.10), such as Fagus, Quercus, Ulmus, Carpinus, Betula, Liquidambar, Pinus, and Abies, while tropical evergreen species such as Castanopsis and Distylium still occurred. The vegetation was characteristic of an evergreen-deciduous broadleaf mixed forest, indicating a climate that was wet but not as warm as before.

Before the Holocene, pollen types from Chenghai were dominated by Castanopsis, Quercus, Chenopodiaceae/Amaranthaceae, and monoolete spores. The vegetation was middle subtropical evergreen broadleaved forest, suggesting warm and wet climate.

2. Holocene

Regional vegetation has shown no obvious changes since 10 ka BP according to pollen records, which was composed of seasonal evergreen broadleaved forests of the southern subtropics, with dominant species from Fagaceae, Hamamelidaceae, Lauraceae, Myrsinaceae, Euphorbiaceae, and Pinaceae, and the climate also had no evident changes. Along the coasts, mangrove forests of Sonneratia or swamps dominated by Cyperaceae and Typha occurred alternately due to changes in depositional environment resulting from coastal morphodynamics or human activities.

During 10–8.5 ka BP, pollen assemblages from the Chaoshan Plain were dominated by Castanopsis, Quercus, Chenopodiaceae/Amaranthaceae, and monoolete spores. The vegetation was characteristic of middle subtropical evergreen broadleaved forests, suggesting warm and wet climate, and coastal swamps were dominated by Cyperaceae and Typha communities. During 10–7.7 ka BP, pollen assemblages from the Pearl River Delta were dominated by arboreal types (e.g., Pinus, Castanopsis, Ulmus, Rhizophora, Quercus, and Altingia) and ferns, and herbs were mainly from Artemisia and Cyperaceae. The regional vegetation was evergreen-deciduous broadleaved forests and conifer forests, and coastal mangroves developed well, indicating increasingly warm climate. In the southwest, early Holocene pollen assemblages from Huguangyan Marr Lake was composed of tropical and southern
subtropical species (*Ficus, Elaeocarpus, Syzygium, Moraceae, Arecaceae, Mallotus, Dacrydium*) with increasing montane conifers. The vegetation in the early stage was characteristic of tropical rainforest, and then followed by semi-evergreen seasonal rainforest and bosks as inferred from decreasing pollen of tropical and subtropical species and increasing fern and herbs.

In the middle Holocene (after 8.5 ka BP), pollen assemblages from the Pearl River Delta show a pronounced increase in arboreal taxa such as *Castanopsis, Lithocarpus,* and *Arecaceae,* while *Randia, Ilex,* *Menispermaceae,* *Quercus,* *Pinus,* and *Rhizophora* also occurred. Herbs included *Umbelliferae,* *Artemisia,* and *Poaceae,* and fern spores included a variety of monolete types such as *Hicriopteris,* *Cibotium,* *Adiantum,* and *Pteris* (Figure 1.26). The vegetation was composed of tropical and subtropical evergreen broadleaved forests, and the climate was warm and humid with high precipitation. During 8.5–4.0 ka BP, the pollen assemblage was dominated by tropical to southern subtropical arboreal species, such as *Castanopsis/Lithocarpus, Ficus, Elaeocarpus, Randia,* *Myrica,* *Mallotus,* *Myrsine,* and fern spores (*Cibotium,* *Adiantum,* and monolete types). Subtropical monsoonal evergreen broadleaf forests developed well in inland areas, and mangrove forests occurred along the coastline, indicating humid and warm climate (Table 1.11).

Since 2.0 ka BP, pollen assemblages have been dominated by *Pinus,* *Poaceae,* and *Adiantum* in the Chaoshan Plain. Inland secondary forests developed well; while bosk and grass occurred in coastal areas under a climate that was warm and somewhat dry (Table 1.11). In the Pearl River Delta, a rich assemblage of fern spores occurred, dominated by monolete types, *Lycopodium,* *Cibotium,* *Pteridium,* *Microlepia,* *Pteris,* *Alsophila,* *Osmunda,* and *Adiantum.* Arboreal pollen decreased significantly, suggesting tropical and subtropical evergreen broadleaved and conifers mixed forests under a warm and wet climate. After the mid-late 19th century, pollen assemblages in the Qinzhou bay area were dominated by conifer and temperate pollen types, suggesting relatively cooler regional climate conditions (Li Z et al., 2010). In the beginning of the 20th century, mangrove pollen (mainly *Rhizophora* and *Aegiceras*) decreased sharply, indicating degraded mangrove forest. In the 1960s and 1970s, the western coastline of Qinzhou bay retreated landward, and the areas of tidal flat decreased. In the 1980s, sedimentation rate was accelerated and arboreal and Poaceae pollen increased.

### 1.4.2.2 Vegetation and climate since the late Pleistocene in Leizhou Peninsula and Holocene vegetation and climate in Hainan Island

1. **Late Pleistocene vegetation and climate in Leizhou Peninsula**

During 400–280 ka BP, two subzones of vegetation and climate were recognized based on pollen assemblages (pollen zone T9a, T9b, Figure 1.27; Zheng and Lei, 1999). The early stage (about 400–340 ka BP) has low pollen abundance and relatively high frequencies of montane forest taxa, suggesting a slightly drier and cooler climate. The climate became wetter and warmer during the late stage, and the vegetation changed to a predominantly evergreen oak forest (Table 1.11) as represented by 72% *Fagaceae* pollen in the pollen assemblage (Figure 1.27).

The interval from 280–240 ka BP was marked by the first substantial increase of typical montane conifer forest elements, suggesting a cooler climate (pollen zone T8, Figure 1.27; Zheng and Lei, 1999). An altitudinal depression of conifer forest by >600 m can be inferred from this pollen change, because these montane taxa, as mentioned above, are found mostly from elevations of >800–1000 m in the neighboring mountains of Hainan Island today, and even >2500 m in Indonesia. In the modern locations of *Dacrydium* forest in Hainan mountains, the mean annual temperature is between 14–19°C, with a very high moisture level, and the rainfall reaches 2500 mm/a. Based on the modern altitudinal lapse rate (0.61°C per 100 m) and forest analogue comparison, the mean annual temperature during this interval was probably more than 4°C lower than that of today, i.e., at about 20°C (Zheng and Lei, 1999).

During 240–180 ka BP, a distinct change from
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<td>Pollen assemblage</td>
<td>Vegetation</td>
<td>Pollen assemblage</td>
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<tr>
<td></td>
<td></td>
<td>Landward</td>
<td>Seaward</td>
<td>Landward</td>
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<td>Holocene</td>
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<tr>
<td>Late</td>
<td>1</td>
<td>Pins, Poaceae, Adiantum type,</td>
<td>Warm &amp; slightly wet</td>
<td>Semi evergreen forest &amp; shrubs</td>
</tr>
<tr>
<td></td>
<td>2-3</td>
<td>Castanopsis, Altingia, Myrica,</td>
<td>Warm &amp; slightly wet</td>
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<tr>
<td></td>
<td></td>
<td>Adiantum, Monoletes</td>
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<tr>
<td>Middle</td>
<td>4</td>
<td>Mangrove</td>
<td>Warm &amp; wet</td>
<td>Mid sub-tropical evergreen broadleaved</td>
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<td></td>
<td>5</td>
<td>Castanopsis, Ficus, Quercus(E),</td>
<td>Cool &amp; wet</td>
<td>evergreen &amp; deciduous broadleaved forest</td>
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<td></td>
<td>6-7</td>
<td>Mallotus, Myrica, Randia, Esococcarla, Adiantum, Cibotium, Monoletes, Myriaceae, Poaceae, Cyperaceae, Typha</td>
<td>Warm &amp; slightly wet</td>
<td></td>
</tr>
<tr>
<td>Early</td>
<td>8</td>
<td>South sub-tropical evergreen</td>
<td>Warm &amp; slightly wet</td>
<td>Mid sub-tropical evergreen &amp; coniferous</td>
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<td></td>
<td>9</td>
<td>broadleaved forest</td>
<td>Warm &amp; slightly wet</td>
<td>mixed forest</td>
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<td>10</td>
<td>Marsh</td>
<td>Warm &amp; slightly wet</td>
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<td>11-12</td>
<td>Denudation</td>
<td>Warm &amp; slightly wet</td>
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<td>20</td>
<td>Castanea, Monoletes, Chenopodiaceae, Castanopsis, Liquidambar, Dizytax, Tsuga, Poaceae</td>
<td>Mid sub-tropical broadleaved forest &amp; deciduous broadleaved forest</td>
<td>Quercus (E), Ulmus, Phorocarpus, Carpinus, Fagus, Poaceae, Artemisia, Compositae, Cyperaceae, Typha</td>
</tr>
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<td></td>
<td>30-40</td>
<td>Castanopsis, Ficus, Quercus (E), Liquidambar, Acer, Someraria, Altingia, Symplocos, Myrica, Bruguiera, Pinus, Dacrydium, Parix, Myriaceae, Cibotium, Poaceae, Monoletes, Adiantum, Acrostichum</td>
<td>Mangrove (Evergreen)</td>
<td>Sedges swamp &amp; mangrove</td>
</tr>
<tr>
<td>Pliocene</td>
<td>50</td>
<td>Castanopsis, Quercus, Microlepia, Ficus, Scheila, Distyax</td>
<td>Evergreen broad-leaved forest</td>
<td>Swamp</td>
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<td></td>
<td>56</td>
<td>Ficus, Pinus, Quercus, Artemisia, Rhododendron</td>
<td>Evergreen deciduous coniferous forest</td>
<td>Quercus (E), Castanopsis/Lithocarpus, Altingia, Moraceae, Humametallacea, Elaeocarpus, Myrica, Syzygium, Mallotus, Dacrydium, Podocarpus, Pinus</td>
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<td></td>
<td>125</td>
<td></td>
<td>Swamp</td>
<td>Quercus (E), Castanopsis/Lithocarpus, Altingia, Moraceae, Humametallacea, Elaeocarpus, Myrica, Syzygium, Mallotus, Dacrydium, Podocarpus, Pinus</td>
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<tr>
<td></td>
<td>180</td>
<td></td>
<td>Swamp</td>
<td>Quercus (E), Castanopsis, Quercus (E), Altingia, Pinus, Cupressaceae, Altingia</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td></td>
<td>Swamp</td>
<td>Quercus (E), Castanopsis, Quercus (E), Altingia, Pinus, Cupressaceae, Altingia</td>
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<tr>
<td></td>
<td>280</td>
<td></td>
<td>Swamp</td>
<td>Quercus (E), Castanopsis, Quercus (E), Altingia, Pinus, Cupressaceae, Altingia</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td></td>
<td>Swamp</td>
<td>Quercus (E), Castanopsis, Quercus (E), Altingia, Pinus, Cupressaceae, Altingia</td>
</tr>
</tbody>
</table>
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Atlas of Quaternary Pollen and Spores in China

Depth/m

Pollen zone

Cupressaceae
Pinus
Dacrydium
Eurya
Papilionoideae
Arenga
Hamamelidaceae
Corylopsis
Zanthoxyllum
Apocynaceae
Myrtaceae
Elaeocarpus
Myrsinaceae
Distylium
Ulmus
Mallotus
Araliaceae
Ilex
Cycas
Urticaceae
Taxodiaceae
Symplocos
Nyssa
Carpinus
Carya
Palmae
Altingia
Keteleeria
Theaceae
Podocorpus
Quercus
Castanopsis
Figure 1.27  Pollen percentage diagram of the Tianyang core in Leizhou Peninsula (modified from Zheng and Lei, 1999)

a. Arboreal pollen; b. Herbaceous and aquatic pollen, fern spores, and other sporomorphs
Overview of Modern and Quaternary Vegetation in China

Chapter 1

The period 180–125 ka BP was characterized by more subdued vegetation changes than before (pollen zone T6, Figure 1.27; Zheng and Lei, 1999). The increase in conifer forest elements was indistinct, although the rise of the total montane forest group to 30%–50% is still notable (Figure 1.27). Two rapid forest transformations may be recognized in pollen zone T6 (Figure 1.27). The lower one is manifested by the first increase in Poaceae (21%). The upper abrupt change is characterized by the reappearance of montane elements, mainly Dacrydium, Pinus, Altingia, and Podocarpus, which might be attributed to the onset of a glacial substage (Zheng and Lei, 1999).

The period 125–65 ka BP was marked by the absence of Cupressaceae pollen, the reduction of Dacrydium, Podocarpus, and Altingia, and a dramatic increase in Quercus and, to a lesser extent, in Castanopsis. This pollen assemblage suggests the resurgence and dominance of fagaceous monsoon evergreen forest in this area (pollen zone T5, Figure 1.27; Zheng and Lei, 1999). Many other elements such as Pterolobium, Elaeocarpus, and Myrsinaceae were also common. Pollen assemblages indicate a dense forest under the warmer climate at MIS 5 (Zheng and Lei, 1999).

The interval 65–29 ka BP was a time of dramatic vegetation changes, as reflected by the significant fluctuations in the pollen frequencies of Pinus, Altingia, Podocarpus, and Urticaeae, as well as those of deciduous elements like Myrica, Nyssa, Carpinus, Ilex, and Carya (pollen zone T4, Figure 1.27; Zheng and Lei, 1999). The lowermost part of zone T4 was very poor in pollen. From about 60 ka BP, montane conifers and then temperate forest elements increased (Figure 1.27). In the alpine forests in neighboring Indochina today, tropical montane conifers are not being accompanied by a significant number of temperate deciduous elements at elevations below 1300 m. Thus, the presence of so many temperate taxa in the Tianyang area may imply a significant depression of altitudinal forest zones, by as much as 800–1000 m. It is thus reasonable to believe that the temperature was 5–6°C lower during the upper part of this interval assuming a 0.61°C/100 m altitudinal lapse rate (Table 1.11; Zheng and Lei, 1999).

The period 29–15 ka BP was remarkable because it was the first time in the entire recorded Quaternary history that the Pleistocene dense forests were transformed to grassland or savanna vegetation on the Leizhou Peninsula (pollen zone T3, Figure 1.27; Zheng and Lei, 1999). The dominance of Poaceae and Artemisia implies not only a cooler, but also a much drier climate. According to the 14C chronology (Table 1.11), the grassland expansion occurred between 29,000–15,000 a BP, during the LGM. Comparable sediment samples from a bay to the west of the peninsula show similar increases in Poaceae and Artemisia (Wang et al., 1990), suggesting a regional climate that was much cooler and drier than the present (Zheng and Lei, 1999).

Pollen records from Huguangyan Marr Lake suggest the following vegetation history since the last glacial with some cooling stages (Lü et al., 2003b): south subtropical evergreen broadleaved forests → mid subtropical evergreen broadleaved and deciduous mixed forests → south subtropical monsoon evergreen broadleaved forests → mid subtropical evergreen-deciduous broadleaved-conifers mixed forests (grassland around the lake) → tropical seasonal rainforests → semi evergreen seasonal rainforest. The data suggest that temperature changes between warm and cold phases were 4–6°C at the maximum (Lü et al., 2003b).

During 15–11 ka BP, the pollen assemblage shows the resurgence of montane forest typified by Taxodiaceae, Pinus, and Altingia, and the disappearance of savanna taxa (pollen zone T2, Figure 1.27; Zheng and Lei, 1999). However, it is hard to determine whether this marks the end of LGM or Younger Dryas (Table 1.11), due to inadequate material and uncertain radiocarbon dating. Nevertheless, it is more reasonable to attribute this to the Younger Dryas event, which has been recorded in southern China (Zheng and Li, 2000) and the South China Sea (Wang P X et al., 1995).

For the period 11 ka BP–present, only a few
pollen spectra were available from the upper section of the Holocene, and they were dominated by tree pollen taxa such as *Castanopsis*, *Quercus* and *Pinus* (pollen zone T1, Figure 1.27; Zheng and Lei, 1999). Poaceae and *Artemisia* were high at the same levels. It is likely that the typical montane forest disappeared and human impacts were locally intensified during this youngest period of Quaternary history (Table 1.11).

2. Modern Palynological study and Holocene vegetation and climate changes on Hainan Island

Zheng *et al.* (2003) reported altitudinal pollen distribution in the tropical rainforest based on a modern pollen rain study in Hainan Island. Pollen data show that the variation in pollen assemblages has a close relationship with altitudinal changes of forest communities. They also show that pollen diversity decreases with increasing altitude, whereas coniferous pollen increases and fern spores decreases with altitude. In the lowlands and low hills, the pollen spectra show a great influence of human disturbance, which was reflected by the pollen presence of windbreak trees *Casuarina*, decoration plants *Acacia confusa*, and pioneer ferns *Dicranopteris*; the latter can occur abundantly in pollen records following forest clearance.

Studies on Quaternary vegetation changes are relatively few on Hainan Island. Zheng *et al.* (2003) reported high-resolution Holocene pollen records from the Shuangchi Maar Lake in Hainan Island. They divided six pollen zones (H1-6) for the Holocene (Figure 1.28). Their pollen data suggest the occurrence of a Holocene thermal maximum (H4) and a brief climatic event in zone H3. Recently Dodson *et al.* (2019) reported new pollen data in the same site.

1.4.2.3 Late Quaternary pollen and spores, vegetation and climate records in the South China Sea

1. Palynomorphs, provenance and distribution in surface sediments from the northern South China Sea

The offshore deposits with high sedimentation rate in the northern South China Sea provide useful materials for high-resolution reconstructions of palaeoenvironmental changes based on palynological data. Palynomorphs as proxy of vegetation and climatic

![Figure 1.28 Pollen diagram of Shuangchi Marr Lake in Hainan Island (modified from Zheng *et al.*, 2003)](image)
Chapter 1 Overview of Modern and Quaternary Vegetation in China

condition play an important role in palaeoenvironment reconstruction in the continental shelf. However, pollen grains are carried by wind and/or water from terrestrial environments. Therefore, understanding pollen transfer mechanisms and dispersal patterns is essential for interpreting fossil pollen data from geological time. Lots of marine palynological investigations have been carried out on the surface marine sediments in the South China Sea (e.g., Tang and Shen, 1989; Shen et al., 1991a, b; Sun and Li, 1997; Sun et al., 1999; Zhang and Zhang, 2002; Luo et al., 2013, 2014; Dai et al., 2014). Approximately 160 pollen types from different families and genera have been identified in the South China Sea. Pollen from tropical evergreen forests is predominant types, with relatively less herbaceous pollen. The pollen assemblages reflected a floristically rich flora that includes alpine arboreal to coastal shrub elements, with characteristics of the Hainan flora as well as the as Malesian flora, including many endemic and tropical species. The ecological groups of palynoflora are tropical lowland (Macaranga, Mallotus, Ficus, Elaeocarpus, Artocarpus, Eugenia, Euphorbia, Syzygium, Nyssa, Arecaeae, Musa, Hainania), tropical montane (Lithocarpus, Castanopsis, Cyclobalanopsis, Cassia, Carallia), and subalpine rainforest with conifer species (Dacrydium, Podocarpus), coastal mangroves (Ceriops tagal, Rhizophora apiculata, Sonneratia caseolaris) (Table 1.12), and other temperate species like Alnus and Carpinus.

Sun and Li (1997) investigated pollen and spores in surface sediments from the southern South China Sea and found large differences between the southern and northern parts of the South China Sea in terms of quantitative patterns, provenance, and transport mechanisms and dispersal routes. In the north, Pinus pollen and spores are predominant in the pollen assemblages, due to the long-distance transport of Pinus pollen by wind and the floating ability of fern spores in water. The highest pollen concentration occurred in the Taiwan Strait and at the entrance of the Bashi Strait, decreasing towards the southwest. This pattern is consistent with the direction of prevailing winds in the winter and the consequent ocean currents, reflecting the importance of the winter monsoon and ocean currents as vectors of pollen transport. The source area of pollen is probably quite wide, including continental areas and islands along the northern and eastern coasts of China. Other important pollen types are Quercus and the main tropical and subtropical taxa characterized by small size and relatively high density. Their pollen abundance decreases from the nearshore waters to the deep sea, suggesting that rivers and offshore currents are the main pollen transportation mechanisms. Similar distribution patterns were also found in the southern parts of the South China Sea, suggesting that rivers and offshore currents are also important transport mechanisms here, but the pollen provenances probably include some islands south of the South China Sea, such as Kalimantan (Table 1.12).

Dai et al. (2014) conducted palynological analysis of surface sediments from the estuaries of the Pearl River and the northern South China Sea. They found that Pinus pollen and Dicranopteris spores are the dominant types in the pollen assemblages. There is also a great abundance of tropical and subtropical pollen taxa, especially Quercus (E) (Figure 1.29). According to the spatial distribution patterns based on pollen percentages and concentrations, the main transport mechanisms include: ①the Pearl River is a key pollen carrier, particularly for Pinus and Dicranopteris, to the northern part of the South China Sea; ②Pinus pollen and fern spores are comparatively easy to be transported, as inferred from higher percentages in the open sea area than in the littoral zone.

Considering the diverse pollen types found in the surface sediments from the Nansha Islands and their vicinities (Tang and Shen, 1989; Shen et al., 1991a, b), the parent vegetation of these pollen types is probably located in the Malaysian islands, Hainan Island, and the southern areas of Guangdong Province. In the Nansha Islands and the surrounding seas, the tropical climate with rainforest is controlled by the Intertropical Convergence Zone. Most plant species from the tropical montane rainforests flower in the summer, and much pollen is carried, by rain or by wind, from Australia by the Southeast Monsoon controlled by high air pressure,
Table 1.12 Late Quaternary pollen, vegetation, and climate around the South China Sea

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Age (ka BP)</th>
<th>Nansha Islands sea area NS-88-11 (Shen et al., 1991; Tang et al., 1991)</th>
<th>Northern part of the South China Sea (Zhang, 2008)</th>
<th>Sunda Shelf, southern part of the South China Sea (Wang et al., 2008)</th>
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<tbody>
<tr>
<td>Epoch</td>
<td>Age (ka BP)</td>
<td>Pollen assemblage</td>
<td>Vegetation</td>
<td>Climate</td>
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<tr>
<td>Holocene</td>
<td>1</td>
<td>Artocarpus, Ficus, Elaeocarpus, Rhizophora, Bruguiera, Dacrydium, Podocarpus, Polypodiaceae</td>
<td>Lowland rainforest, expanded mangrove, shrank montane rainforests and subalpine forest</td>
<td>Temperature close to present</td>
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<td>Late Pleistocene</td>
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<td>Mid Pleistocene</td>
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Chapter 1

Overview of Modern and Quaternary Vegetation in China

Atlas of Quaternary Pollen and Spores in China

Sample:
- Alpine conifers
- Temperate components
- Tropical and subtropical components

Pinus
Araliaceae
Picea
Abies
Podocarpus
Taxodiaceae
Cupressaceae
Quercus
Alnus
Carpinus
Corylus
Celtis
Juglans
Pterocarya
Ulmus
Tilia
Quercus
Castanopsis
Acanthaceae
Anacardiaceae
Rubiaceae
Annonaceae
Altingiaceae
Carya
Combretaceae
Casuarinaceae
Magnoliaceae
Myricaceae
Myrtaceae
Myrsinaceae
Meliaceae
Melastomataceae
Moraceae
Ficus
Tsuga
Dacrydium
Phyllocladus
Betula
Salix
Figure 1.29 Pollen percentage diagrams of the marine and fluvial surface sediments from the northern South China Sea (modified from Dai et al., 2014)

The colored backgrounds showing different sea areas: blue (N), north region near the China mainland; yellow (W), west region near the Hainan Island; pink (S), south region over the middle continental slope; green (E), east region near the Taiwan Island; purple, the ocean basin; red (P), the Pearl River.
via the Malaysian islands to the Nansha, Zhongsha, and Philippine islands. Another pollen source is three rivers from the Kalimantan Island, which deliver runoff and pollen from high mountains, lowland rainforests, and coastal mangroves to the South China Sea. Cluster analysis of pollen data from ocean sediments around Nansha indicates three zones:

① northwest of Nansha and north Xianbin reef and southern Nanping reef, the ocean sediments are dominated by fern spores (78%) from Polypodiaceae, Microlepia, and Alsophila. Arboreal pollen is mainly composed of Pinus, and herbs mainly of Poaceae and Cyperaceae;

② southwest of Nansha, and south of Nansha islands, the oceanic sediments are dominated by fern spores (58%). Arboreal pollen from tropical montane rainforests is composed of Dacrydium, Podocarpus, Cyclobalanopsis/Quercus, Castanopsis/Lithocarpus, and Macaranga/Mallotus, while coastal mangroves are mainly from Sonneratia and the increased herbaceous pollen types are from Poaceae (33%) and Cyperaceae (7%); 

③ southeast of the Nansha Islands, close to the west coasts of Brunei, the area has increasing arboreal pollen (52%) from tropical montane forests, especially abundant pollen from Macaranga/Mallotus, Artocarpus/Ficus, and Eugenia/Syzygium, while fern spores (44.4%) decrease (Table 1.12).

2. Late Quaternary vegetation and climate in Nansha Islands and vicinities

Pollen analysis from the scientific exploration cores (NS-88-11, NS-87-8, NS-87-11) from the Nansha Islands and vicinities showed that around 200 pollen types were recognized (Shen et al., 1991a, b; Tang et al. 1991). They belonged to ecological groups of mangroves, tidal flat vegetation, montane rainforest and subalpine forest, and lowland rainforest. Pollen concentrations showed pronounced changes throughout the late Quaternary. The vegetation underwent the following major changes.

230−190 ka BP, degraded lowland rainforest; expansion of montane rainforest and subalpine forest; coastal mangrove and intertidal flat vegetation developed; the climate was warmer than present.

190−120 ka BP, shranked lowland rainforests, significant expansion of lowland rainforest and subalpine forests; proliferation of coastal vegetation, including mangrove; the climate was slightly cooler than today.

120−70 ka BP, expanded lowland rainforest, shranked montane rainforest and subalpine forests, the temperature was higher than today.

70−10.5 ka BP, dramatically shranked lowland rainforests, significant expansion of montane rainforests and subalpine forests, increased coastal vegetation meanwhile, sedge (Cyperaceae)-dominated wetlands prevailed in open areas outside of forests, the temperature was lower than today.

After 10.5 ka BP, lowland rainforest expanded, while montane rainforest and subalpine forest degraded; however, mangroves expanded significantly, indicating temperature higher than today’s (Table 1.12).

3. Late Quaternary vegetation from the Sunda Platform in southern South China Sea

Wang X M et al. (2008) reported palynological results from a few cores in the Sunda Platform: ①Phyllocladus, Dacrycarpus, Myrica, and Rhododendron, comprising alpine rainforest in a tropical climate; ②Castanopsis, Quercus, Theaceae, Myrtaceae, and Elaeocarpus, comprising tropical lowland rainforest; ③Dipterocarpaceae, Sapindaceae, Moraceae, Meliaceae, Rubiaceae, Rutaceae, Rhizophora, Sonneratia, Bruguiera, comprising lowland rainforest.

During MIS 3 (31.3−23.5 ka BP), mangrove (Rhizophora) pollen and fern spores were abundant in the cores of Sonne 18300, 18302 and 18323, and the exposed continental shelf was vegetated with tropical lowland rainforest and low hill rainforest, and mangrove developed along coastlines; sea level was low during a time of relatively cool and wet climate.

During LGM (23.5−16.3 ka BP), mangrove pollen decreased dramatically while herbaceous pollen and fern spores increased significantly as the sea level dropped and the continental shelf was exposed, thus inhibiting mangrove growth at the site but making the habitats favorable for pioneering fern communities (as indicated by abundant spores).

During the deglaciation period (16.3−13.9 ka BP),
arboreal pollen types increased, such as Castanopsis, Theaceae, Myrtaceae, Elaeocarpus, and Rhizophora, while herbaceous pollen and fern spores decreased, indicating that lowland rainforests and coastal mangroves prevailed again under a climate that was wet but not as cool as before.

During 13.9−10 ka BP, pollen types from tropical rainforest and fern spores increased sharply while pollen from lowland rainforest decreased, suggesting rising temperature in the southern South China Sea.

During the early Holocene (10−7 ka BP), fern spores decreased significantly, indicating decreasing temperature with drier climate conditions. During the mid-Holocene (7−3.6 ka BP), fern spores increased sharply, reflecting temperature 1−3°C higher than today’s. The tree line must have ascended about 200−600 m (Table 1.12).

4. Pleistocene vegetation history in northern South China Sea

To date, a few palynological sequences from marine cores from the northern South China Sea have been published addressing continental vegetation history and climate changes. These records were from cores MD05-2904 (Chang et al., 2013), MD05-2906 (Dai and Weng, 2015), ODP1144 (Sun et al., 2003), ODP1145 (Luo and Sun, 2012), and SO17940 (Sun et al., 1999). The palynological sequence from ODP1144 revealed long-term vegetation changes since 1.02 Ma BP. Pollen types (excluding Pinus) were divided into the following ecological groups: herbaceous group dominated by Artemisia, Poaceae, Cyperaceae, as well as Compositae and Chenopodiaceae; montane (boreal) conifer arboreal group including Picea and Abies; tropical montane conifer group including Podocarpus, Dacrycarpus, Dacrydium, and Phyllocladus; temperate deciduous arboreal group including Betula, Alnus, Carpinus, Juglans, and Ulmus; tropical-subtropical species group including Altingia, Ilex, Castanopsis/Lithocarpus, Macaranga/Mallotus, Euphorbiaceae, Arecaceae, Melastomataceae, Meliaceae; fresh-water hydrophytes including Typha, Myriophyllum, and Nymphoides; mangroves including Rhizophora and Sonneratia. Throughout ODP1144, Pinus pollen always dominated, followed by herbaceous pollen and the pollen assemblages from the lower part of the core corresponded to MIS 11−29. Prior to MIS 22, the cool and dry-tolerant herb Artemisia prevailed over the continent. During MIS 22, the continent was covered by herbs from Poaceae, Cyperaceae, and Artemisia. After MIS 20, the continent was mainly vegetated by Poaceae and Cyperaceae. During MIS 12, Artemisia pollen increased, together with Poaceae, suggesting the development of herbaceous vegetation cover in the continent during glacial times. After 0.82 Ma BP, tropical conifers Phyllocladus occurred, along with Poaceae and Cyperaceae replacing Artemisia, indicating an intensified summer monsoon. In the late sequence of ODP1144, Pinus alternated with herbaceous pollen in the pollen record. Eight pollen zones were recognized, with each pollen-stratigraphic zone generally corresponding to each of MIS 1 to 8. During the interglacial periods (pollen zones 7, 5, 3, 1, equivalent to MIS 7, 5, 3, 1), Pinus pollen dominated, indicating climate conditions similar to today’s. In the glacial period (pollen zones 8, 6, 4, 2, equivalent to MIS 8, 6, 4, 2), herbaceous pollen peaked, suggesting exposed continental shelf due to a lower sea level that allowed herbs to prevail. Zone 8 was dominated by Poaceae and Cyperaceae, but low Artemisia. Artemisia pollen gradually increased until the LGM, when it became dominant under a relatively dry and cool climate (Figure 1.30).

In core SO17940, during the LGM, tropical and subtropical evergreen broadleaved species accounted for 10%−20%, with diverse pollen types, suggesting subtropical to southern subtropical climate at that time (Sun et al., 1999).

Core MD05-2906 provided pollen evidence of vegetation changes since 18.8 cal. ka BP along the exposed continental shelf and adjacent inland areas (Dai and Weng, 2015; Figure 1.31). From LGM to the last deglaciation (18.8−11.3 cal. ka BP), pollen assemblages were dominated by herbs, especially Artemisia, Poaceae, and Cyperaceae. Meanwhile, tropical and subtropical broadleaved species accounted for 15%−20%, suggesting subtropical climate at the time. Moreover,
some thermophilous taxa, like *Castanopsis*, *Trema*, Anacardiaceae, and Combretaceae, occurred frequently, indicating south tropical climate, while herbaceous pollen also occurred in great abundance. Dai and Weng (2015) attributed the provenance of Poaceae and Cyperaceae pollen to the exposed continental shelf at the time, and the herbs as regional vegetation distributed in the lower plain areas. While abundant *Artemisia* pollen was probably carried by the intensified winter monsoon from the exposed continental shelf, they could also be transported by ocean currents via the Taiwan Strait and Bashi Strait. As modern biogeography suggests that *Artemisia* plants are mainly distributed in temperate arid to semi-arid areas, it is unlikely that this herb occurred in large scale in southern subtropical areas during that time. Since the early Holocene, *Pinus* pollen and spores increased quickly, probably due to high sea level stands similar to todays. This must have allowed the Pearl River, which carried pollen and spores from inland hilly regions, to significantly influence pollen deposition in the northern South China Sea (Dai and Weng, 2015).

Zhang (2008) presented Holocene palynological records from core C4 in the northern South China Sea. Pollen assemblage of the early Holocene was characteristic of *Pinus- Pteridium-Polypodiaceae-Microlepias*, coupled with confers mixed with evergreen-deciduous forests, suggesting climate warming from cool conditions. During the mid-Holocene, pollen assemblage was evergreen *Quercus-Polypodiaceae-Alsophila-Pinus*, featuring tropical semi-evergreen seasonal rainforest under a warm climate. Pollen assemblage of the late Holocene was *Pinus-*evergreen *Quercus-Polypodiaceae-Alsophila-Pinus*, reflecting tropical evergreen-deciduous broadleaved forests, indicating warm and wet climate conditions (Table 1.12).

5. Late Pleistocene-Holocene vegetation history in northern South China Sea

A new palynological study addressing the last glacial and deglacial vegetation and climate changes was published recently (Yu *et al*., 2017), which contributes new insights to the coastal-shelf paleoenvironment of the northern South China Sea (SCS). Yu *et al*. (2017) presents a marine palynological record of the Asian summer monsoon and sea level change in the LGM and the deglacial period in the northern SCS derived from core STD 235 (855 cm in length) and 273 surface sediment samples. Results from fossil pollen show that the main
pollen source region fundamentally changed as sea level rose rapidly from the LGM to the deglacial period (Figure 1.32). The modern marine surface samples show that pollen concentrations in the estuary of the Pearl River are extremely high, and modern pollen assemblages are in good agreement with the regional vegetation (Figure 1.32; Yu et al., 2017). However, wind transport becomes more important over the deeper ocean as the percentages of *Pinus*, a taxon with very high pollen production and dispersal capacity, are highest in these sediments, which otherwise have very low pollen concentrations in marine sediments. Total pollen concentrations between surface and fossil pollen samples are compared to determine the possible vegetation source areas for the marine core (Yu et al., 2017; Figure 1.32). With pollen concentration as high as >100 grains/g at the LGM, it is suggested that the paleo-shoreline was located within 80 km of the core (Yu et al., 2017). Consequently, pollen would mostly have been derived from the exposed continental shelf in the northern SCS. By contrast, pollen concentrations were very low due to a much greater transport distance (318 km at present, core STD 235) during times of higher sea levels, and windblown pollen would have played a more important role because of the limitation of riverine input into the deep ocean during this highstand period. Such alternations in pollen input and source distance should be repeated during all glacial-interglacial cycles, reflecting closely sea level and climate dynamics. According to fossil pollen assemblages from Core STD 235, Yu et al. (2017) conclude that wetland and/or grassland communities with sparse subtropical trees dominated most of the exposed shelf during the LGM, rather than forests that characterize the region today. The existence of a predominantly open landscape on the exposed continental shelf suggests lower precipitation during the LGM, which in turn indicates a weaker Asian summer monsoon. This finding is supported by other records from the Okinawa Trough and the East China Sea, suggesting that a weaker summer monsoon was a key characteristic of the LGM in East Asia (Yu et al., 2017; Figure 1.32).

Li et al. (2017) reported, for the first time, the palynological records of terrestrial palynomorphs and dinoflagellate cysts from a sediment core in the northern South China Sea (SCS) spanning the last 12,500 years, mainly Holocene (Figure 1.33). Both terrestrial and marine palynomorph records show strong signals of the sea-level change during the studied interval. The highest

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**Figure 1.31** Pollen diagram of core MD05-2906 (upper section: 191−1439 cm) from northern South China Sea (modified from Dai and Weng, 2015)
Figure 1.32: Pollen percentage diagram of the STD 235 core (all taxon percentages show 5 times exaggeration in grey).

SACF: subalpine coniferous forest, MMF: mid-montane mixed forest, LMF: lower montane evergreen forest, LSMF: lowland and sub-montane forest (modified from Yu et al., 2017).
Figure 1.33 Terrestrial palynomorph assemblage composition (percentage %), total concentrations (grains/g and grains/cm³), and fluxes [grains/(cm²·a)] from core GLW31D. Only major pollen and spore types (exceeding 2%) are shown. The dashed lines across the figure distinguish palynological zones and subzones (PI to PV) (modified from Li et al., 2017).
herb pollen content was associated with extensive grasslands on the exposed shelf at the low sea-level stand during the Younger Dryas and early Holocene. The increase in fern spores and decrease in concentrations of dinoflagellate cysts and terrestrial palynomorphs was observed during the sea-level rise interval from 12,500 to 6800 (or 6000) cal. a BP. Then, the sea level became stabilized and consistently low dinoflagellate cyst abundance and high abundance of fern spores were recorded (Figure 1.33). Li et al. (2017) also found that a high abundance of Impagidinium in the period 12,000–10,400 cal. a BP possibly resulted from increased input of western Philippine Sea waters into the SCS and the branching of the Kuroshio Current. A short-term decrease of Impagidinium at 11,700–11,000 cal. a BP corresponding to the MWP-1B event might be associated with input of the East China Sea waters through the Taiwan Strait (for detailed diagram of dinoflagellate cysts, see Li et al., 2017).

Li et al. (2017) also discussed the relationship between the sedimentation rates and the concentrations of terrestrial palynomorphs, which indicates a predominantly water transport mechanism for pollen and spore dispersal prior to 6300 cal. a BP, whereas wind transport became more prominent thereafter. The timing of this change corresponds to the highest sea-level stand at 6800–6000 cal. a BP, when the present oceanographic setting was formed (Li et al., 2017). The mid-Holocene Optimum can be inferred from the highest abundance of subtropical-tropical broad-leaved arboreal pollen and by the highest abundances of Dapsilidinium pastielsii. Three strengthened winter monsoon intervals at 5500 cal. a BP, 4000 cal. a BP, and 2500 cal. a BP are suggested by increases in Pinus pollen content after the present oceanographic condition had formed (Li et al., 2017; Figure 1.33).

1.4.2.4 Vegetation and climate since the late Pleistocene in Hong Kong

Located in Chek Lap Kok in the northern Lantau Island of Hong Kong, the core (B13/B13A) contained dark grey silty clay between 16.14–16.42 m. This sedimentary unit yielded rich pollen from Sonneratia, Bruguiera, Rhizophora and associated Acrostichum spores, suggesting marine transgression during 30–20 ka BP (Zhou, 1988). In another study from Shan Ha Tsuen, Yuen Long, Tung Chung, Fanling, Clear Water Bay Road, and Taipo, 70 pollen and spore types were found that dated to the late Pleistocene. They were mainly composed of tropical and subtropical taxa, such as Cyclobalanopsis, Quercus, Alnus, Altingia, Fagaceae, Rosaceae, as well as rich tropical fern spores, such as Cibotium, Alsophila, Lygodium, and Lindsaea. However, there were no mangrove pollen and algae from coastal sediment settings, thus suggesting a non-marine facies in Shan Ha Tsuen, Yuen Long (Tang and Li, 1998). Yim (1999) reported Sonneratia coseolris pollen from late Quaternary marine sediments during 32.5–16.3 ka BP from Chek Lap Kok (Hong Kong new airport), Shan Ha in Xinjie, and Gaodao catchment, which was interpreted that the temperature was 2°C higher than that of today. Zheng and Wu (1989) also presented palynological data from marine surface sediments off the Hong Kong coasts, indicating regional vegetation of a southern subtropical monsoonal evergreen broadleaved forest dominated by Castanopsis and Lithocarpus. Meanwhile, a rich assemblage of spores occurred as well. The quantity of monolete and trilete spores was different under different hydrodynamic settings; the latter (trilete spores) were relatively richer in estuarine and inlet areas, similar to the pattern of arboreal pollen.

1.5 Southwest Region

1.5.1 Overview of modern vegetation

1.5.1.1 Evergreen broadleaved forest in the Yunnan-Guizhou Plateau and western Sichuan Plateau

Southwest region, a plateau region, includes the whole Yunnan-Guizhou Plateau and the southern edge of the Western Sichuan Plateau. The Central Yunnan Plateau with an elevation of about 2000 m is its main body. Its northern part is the southern edge of the Western Sichuan Plateau at an elevation of over 3000 m with mountains and river valleys such as Jinsha River and Yalong River.
Its western part is the Hengduan Mountains, and its southern part is the large slope down south of the Yunnan-Guizhou Plateau at elevations of 1500–2000 m.

The climate of southwest region is basically a plateau monsoon type. In summer and autumn, its climatic conditions are warm and humid, controlled by warm and moist airmass of the Southwest monsoon from the Indian Ocean. In winter and spring, its climatic conditions are warm and dry, controlled by warm and dry air mass of the southern branch of the westerly jet in the tropical continent. The yearly climatic conditions are thus without distinct seasonality in temperature but with marked dry and wet seasons in precipitation. Overall, this region is characterized by marked alternations between dry and wet seasons, plateau terrains with low elevations in the south rising to high elevations in the north, which are incised by small and large rivers, resulting in heterogeneous habitats. Therefore, diverse vegetation types with different features occur in this region, and interfingering and mosaic patterns are common features in its vegetation distribution.

The zonal vegetation is evergreen broadleaved forests with certain drought-tolerant characteristics. It consists of evergreen tree species of Fagaceae such as *Cyclobalanopsis glaucoides* and *Castanopsis delavayi*. In terms of different water conditions, altitudes, latitudes, and floristic combinations, they can be further divided into semi-humid, monsoonal, and mid-montane humid evergreen broadleaved forests (Table 1.13).

Sclerophyllous oaks grow in this region, especially the north, where they continuously develop to form forests. Coniferous forests are common in southwest region. Among them, *Pinus yunnanensis* is widely distributed in its central part but is replaced by *P. kesiya* var. *langbianensis* in regions at lower elevations and by *P. densata* in regions at higher elevations. *Abies georgei*, *A. delavayi* and *Keteleeria evelyniana* occur in alpine mountains of Yunnan. Affected by the foehn effect, the valley areas are often occupied by dry and hot valley scrub-grasslands consisting of *Bombax ceiba*, *Eriolaena spectabilis*, *Heteropogon contortus*, and so on.

In terms of vegetation types, the zonal vegetation can be divided into mid-subtropical and southern subtropical evergreen broadleaved forest zones, including five forest districts (Table 1.14).

### Table 1.13 Subregions of evergreen broadleaved forest in western southwest region

<table>
<thead>
<tr>
<th>Vegetation subregion</th>
<th>Semi-humid evergreen broadleaved forest</th>
<th>Monsoonal evergreen broadleaved forest</th>
<th>Mid-montane humid evergreen broadleaved forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution</td>
<td>Central Yunnan Plateau (1500–2500 m)</td>
<td>Central-southern Yunnan Plateau (1100–1500 m)</td>
<td>Mid-montane (2200–2800 m)</td>
</tr>
<tr>
<td>Dominant family</td>
<td>Fagaceae</td>
<td>Fagaceae, Theaceae</td>
<td>Lauraceae, Magnoliaceae, Fagaceae, Theaceae, Hamamelidaceae</td>
</tr>
<tr>
<td>Dominant genus</td>
<td><em>Cyclobalanopsis</em>, <em>Castanopsis</em></td>
<td><em>Castanopsis, Lithocarpus, Schima</em></td>
<td><em>Lithocarpus, etc.</em></td>
</tr>
<tr>
<td>Dominant species</td>
<td><em>Cyclobalanopsis glaucoides</em>, <em>Castanopsis delavayi</em>, <em>C. concolor</em></td>
<td><em>Castanopsis hystrix, C. indica, C. cleveyi, Schima wallichii</em></td>
<td><em>Lithocarpus crassifolius, L. echinophorus, Schima noronhae, Cinnamomum tenuepis, etc.</em></td>
</tr>
</tbody>
</table>

### Table 1.14 Modern vegetation zonation in Yunnan and Guizhou

<table>
<thead>
<tr>
<th>Vegetation Zone</th>
<th>Vegetation Region</th>
<th>MAT*/°C</th>
<th>ACT*/°C</th>
<th>JMT*/°C</th>
<th>AP*/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mid-Subtropical evergreen broadleaved forest zone</td>
<td>Mid-subtropical evergreen broadleaved forest (<em>Cyclobalanopsis glaucoides</em> + <em>Castanopsis delavayi</em>)</td>
<td>15–17</td>
<td>5000–5500</td>
<td>8–10</td>
<td>900–1200</td>
</tr>
<tr>
<td></td>
<td>1.1 <em>Cyclobalanopsis glaucoides</em>, <em>Castanopsis</em> and <em>Pinus yunnanensis</em> forests in basins and valleys of Central Yunnan Plateau</td>
<td>14–17</td>
<td>4500–5500</td>
<td>8–10</td>
<td>700–1200</td>
</tr>
<tr>
<td></td>
<td>1.2 <em>Pinus yunnanensis</em> forests and dry-hot valley forests in Jinsha River valleys of Sichuan and Yunnan</td>
<td>17.1 (Xichang)</td>
<td>5350</td>
<td>9.5</td>
<td>1040</td>
</tr>
<tr>
<td></td>
<td>1.3 Vertical forests of <em>Tsuga</em> and <em>Abies</em> in mountains and valleys of western Yunnan</td>
<td>11 (Lanpin, Weixi)</td>
<td>3300</td>
<td>4</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>Monsoonal evergreen broadleaved forest</td>
<td>17–19</td>
<td>5500–6500</td>
<td>10–12</td>
<td>1000–1200</td>
</tr>
<tr>
<td>2. Southern subtropical evergreen broadleaved forest zone</td>
<td>Monsoonal evergreen broadleaved forest</td>
<td>17.5–21.0</td>
<td>6000–7500</td>
<td>10–12</td>
<td>900–1200</td>
</tr>
<tr>
<td></td>
<td>2.1 <em>Machilus pingii</em>, <em>Cyclobalanopsis glauca</em> and <em>Pinus yunnanensis</em> var. <em>tenuefolia</em> forests in limestone areas of Yunnan, Guizhou, and Guangxi</td>
<td>170–190 (Simao)</td>
<td>6500–7000</td>
<td>11–12.5</td>
<td>1200–1600</td>
</tr>
<tr>
<td></td>
<td>2.2 <em>Castanopsis, Schima wallichii</em> and <em>Pinus kesiya</em> var. <em>langbianensis</em> forests in mid-montane and valleys of central Yunnan</td>
<td>170–190 (Simao)</td>
<td>6500–7000</td>
<td>11–12.5</td>
<td>1200–1600</td>
</tr>
</tbody>
</table>

* MAT: mean annual temperature; ACT: Annual cumulative temperature with temperature ≥ 10°C; JMT: January monthly temperature; AP: annual precipitation
1.5.1.2 Vegetation dominated by coniferous forests in the southeastern part of the Tibetan Plateau

The Tibetan Plateau is called “the third pole” of the Earth. It was formed by the collision between the Indian plate and the Eurasian plate causing strong uplifts during the Paleogene and Neogene. The formation of the Tibetan Plateau not only is a big Cenozoic event of the earth’s geological structure, but also has a great influence on climate and organisms in East Asia. It thus formed the unique plateau climate and vegetation. The southeastern part of the Tibetan Plateau includes western Sichuan, eastern Xizang, and northwestern Yunnan, i.e., the Hengduan Mountains. A series of mountains and valleys occupy this region with relatively low elevations and broken terrains incised by river valleys. Climatologically, the westerly winds and cold-dry climatic conditions prevail during winter and spring seasons. From May to October, the Southwest Monsoon and Southeast Monsoon penetrate into the interior of the Tibetan Plateau along river valleys, producing a lot of rainfall for this region.

Annual precipitation varies between 400 mm and 900 mm in this region, which gets the most rainfall over the Tibetan Plateau. Mean annual temperature is 6−8°C. In addition, the terrain has great influence on the regional climate. Vegetation in this region is characterized by high floristic diversity, complex vegetation types, and distinct altitudinal zonation. The westernmost boundary of China’s forest distribution occurs there. The dominant vegetation is cold alpine spruce and fir coniferous forests, adjacent to subtropical evergreen broadleaved forests in the east, and adjacent to high-cold alpine shrub meadows in the west.

In terms of the combination of vegetation types and vertical zone structure of montane vegetation, the following four vegetation regions can be recognized.

1. Humid evergreen broadleaved forest, spruce forest, and fir forest in gorges and mountains of Western Sichuan

This vegetation region is located in the drainage basin of the Dadu River east of the Zheduo Mountains and west of the Qionglai Mountains. It is strongly affected by the Southeast Monsoon. The structure of the vegetation vertical zonation is complex. The dry and hot valleys at elevations of lower than 1800 m are widely distributed with thorn scrubs and succulent shrubs. From 1800 m to 2400 m are humid evergreen broadleaved forests composed of *Cyclobalanopsis* and *Castanopsis*. From 2400 m to 3200 m, alpine pine (*Pinus densata*) forests and oak shrubs occur on south-facing slopes, whereas mixed coniferous and broadleaved forests of hemlock and birch occur on north-facing slopes. From 3200 m to 4000 m, cold coniferous forests of spruce and fir exist on north-facing slopes and sclerophyllous alpine oak forests on south-facing slopes.

2. Spruce-fir forests in highlands and gorges of the northern Hengduan Mountains

This vegetation region is located in watersheds of the Yalong River, Jinsha River, Lancang River and Nujiang River. The vegetation is dominated by shrubs of *Sophora viciifolia* at elevations of lower than 3400 m. Cold coniferous forests dominated by *Picea likiangensis var. balfouriana* are found from 3200 m to 4200 m.

3. Spruce-fir forests and sclerophyllous oak forests in gorges of the southern Hengduan Mountains

This vegetation region includes southwestern Sichuan, southeastern Xizang, and northwestern Yunnan. Its climate is mainly influenced by the Southwest Monsoon. Regional vegetation shows distinct vertical zonation. The zone at 2800–3200 m is occupied by dry and hot valley shrubs, and 3000–4200 m by spruce-fir forests. Alpine shrubs and meadows, mainly various small-leaved rhododendron shrubs and *Kobresia* meadows, occur at elevations of more than 4200 m. At 4800–5200 m is the open vegetation with sparse plants growing on screes.

4. Spruce-fir forests and alpine pine (*Pinus densata*) forests on the north-facing slopes of East Himalayas

This vegetation region is located between the eastern part of Nyainqêntanggula Mountains and East
Himalayas. Below 2500 m is evergreen broadleaved forest dominated by oak. Alpine pine forests, spruce-fir forests, subalpine shrubs, and meadows occur at 2500−3200 m, 3000−4000 m, and 4000−4500 m, respectively.

1.5.2 Overview of Quaternary vegetation

Due to the uplift of the Tibetan Plateau during the Cenozoic era, many tectonic faulted basins developed in the Yunnan Plateau. These basins have long evolution histories and huge thick sediments, thereby providing ideal materials for understanding the process of plateau uplift and studying lake ecological and environmental evolution. At the same time, southwest region is a region with the highest biodiversity in China and the most well-developed vertical vegetation zonation.

Yunnan, Guizhou, and Sichuan belong to a typical region influenced by the Southwest monsoon. In Quaternary palynological studies, the dominant pollen type is Pinaceae, especially Pinus such as *P. yunnanensis*, whose pollen percentages are generally above 30%. *Picea*, *Abies*, and *Tsuga* have higher pollen percentages than *Pinus* during cold and wet periods, but *Pinus* pollen dominates during dry periods. *Podocarpus*, *Dacrydium*, and *Dacrycarpus* pollen can be found in the tropical northern edge such as Xishuangbanna. The evergreen broadleaved plants are represented by sclerophyllous forest elements such as xerophilous sclerophyllous oaks. Other evergreen broadleaved components such as *Cyclobalanopsis*, *Castanopsis*, *Lithocarpus*, *Ilex*, and Euphorbiaceae are common. *Quercus*, *Alnus*, *Fagus*, *Betula*, *Corylus*, and *Carpinus* are commonly found as temperate deciduous plants and *Rhododendron* as shrub elements. Cyperaceae, Poaceae, Compositae (including *Artemisia*) and Polygonaceae are frequently present herbaceous pollen. Ferns are abundant, usually composed of Polypodiaceae, Davalliaceae, Lycopediaceae, and *Cyathea*.

1.5.2.1 Quaternary vegetation in northwestern Yunnan

Located in the northwestern part of Yunnan Plateau, the Heqing basin at 2200 m a.s.l. is representative of many lake basins on the plateau. It has a long sequence of sediments. Its pollen records reveal regional vegetation and climate history (Yang *et al*., 1998; Jiang *et al*., 1998, 2001). They show that regional climate experienced a complete cycle from the last interglacial to the last glaciation, comparable with the characteristic cold/warm climate fluctuations found in deep-sea oxygen isotopic records.

A long pollen record from the HQ core of the Heqing basin shows that regional vegetation and climate have experienced six major changes since 2.78 Ma BP (Xiao *et al*., 2006b, 2007a, b). ①2.78−2.73 Ma BP, montane pine forests, reflecting relatively warm and dry climate; ②2.73−2.61 Ma BP, an increase in the area of cold coniferous forests and hemlock forests, and occurrence of clearly structured vertical vegetation zonation, suggesting relatively warm and humid climatic conditions in adjacent regions at lower elevations; ③2.61−1.55 Ma BP, montane pine forests and an ascent of cold coniferous forest zone, indicating overall warm-dry climatic conditions; ④1.55−0.88 Ma BP, more vertical vegetation zones and larger vertical shifts of zones, suggesting cold climatic conditions in most of the period and more dramatic climate changes with more complex patterns; ⑤0.88−0.25 Ma BP, vegetation zones similar to the present and the largest shift of zone boundaries, indicating more dramatic and complex climate changes; ⑥0.25 Ma BP to present, expansions of pine forests and semi-moist evergreen broadleaved forests, reflecting the decrease in magnitude of cold/warm climate fluctuations. Xiao *et al*. (2006b, 2007a, b) stated that external factors such as orbital parameters are initially considered as forcings that drive vegetational and environmental changes, and the uplift of the Tibetan Plateau plays a very important role in environmental changes in the Heqing region (Figure 1.34; Table 1.15).

Xiao *et al*. (2014) presented a pollen record from Tiancai Lake, an alpine ice-scour lake at an elevation of 3898 m in northwestern Yunnan. Their results show that: 12.2−11.5 ka BP, a period with open subalpine meadows and relatively cold and dry climatic conditions, corresponding to the YD event; 11.5−10.0 ka BP, spruce and fir forests
Figure 1.34  Pollen record since 2.78 Ma BP from Heqing basin in Yunnan (modified from Xiao et al., 2006b, 2007a, b)
<table>
<thead>
<tr>
<th>Epoch</th>
<th>Age /ka BP</th>
<th>Heqin Basin, Northwestern Yunnan</th>
<th>Tiancai Lake, Northwestern Yunnan</th>
<th>Luojishan Lake, Western Sichuan</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(Jiang et al., 2001; Xiao et al., 2007a, b)</td>
<td>(Xiao et al., 2014)</td>
<td>(Li and Liu, 1988)</td>
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<tr>
<td></td>
<td></td>
<td>Major pollen type</td>
<td>Vegetation</td>
<td>Climate</td>
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<tr>
<td></td>
<td></td>
<td>Tsuga, Pinus, Abies, Picea, Quercus (E)</td>
<td>Humidity decreased</td>
<td>Small climate fluctuations</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>Pinus, Quercus (D), Tsuga, Picea, Abies, Betula</td>
<td>Pine forest and expansion of semi-humid evergreen broadleaved forest</td>
<td>Shrinkage of hemlock forest</td>
</tr>
<tr>
<td>2</td>
<td>250</td>
<td>Pinus, Tsuga, Abies, Picea</td>
<td>Conifer forest + mixed coniferous &amp; broadleaved forest</td>
<td>Frequent climate fluctuations</td>
</tr>
<tr>
<td>3</td>
<td>800</td>
<td>Pinus, Abies, Picea</td>
<td>More vertical zones</td>
<td>Cold</td>
</tr>
<tr>
<td>4</td>
<td>1800-2000</td>
<td>Pinus, Abies, Picea</td>
<td>Cold-temperate conifer forest</td>
<td>Cool and wet</td>
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<tr>
<td>5</td>
<td>2000-2100</td>
<td>Pinus, Castanea, Ulmus, Abies, Picea, Quercus (E)</td>
<td>Cold-temperate conifer forest</td>
<td>Warm and dry</td>
</tr>
<tr>
<td>6</td>
<td>2100-2400</td>
<td>Pinus, Abies, Picea</td>
<td>Cold-temperate conifer forest</td>
<td>Warm and dry</td>
</tr>
<tr>
<td>7</td>
<td>2400-2540</td>
<td>Pinus, Abies, Picea</td>
<td>Cold-temperate conifer forest</td>
<td>Mild and wet</td>
</tr>
<tr>
<td>8</td>
<td>2540-2600</td>
<td>Pinus, Abies, Picea, Castanopsis/Lithocarpus</td>
<td>Cold-temperate conifer forest</td>
<td>Warm and dry</td>
</tr>
<tr>
<td>9</td>
<td>2600-2800</td>
<td>Pinus, Abies, Picea, Castanopsis/Lithocarpus</td>
<td>Cold-temperate conifer forest</td>
<td>Mild and dry</td>
</tr>
<tr>
<td>10</td>
<td>2800-3000</td>
<td>Pinus, Abies, Picea, Castanopsis/Lithocarpus</td>
<td>Cold-temperate conifer forest</td>
<td>Mild and dry</td>
</tr>
<tr>
<td>11</td>
<td>3000-3200</td>
<td>Pinus, Abies, Picea, Castanopsis/Lithocarpus</td>
<td>Cold-temperate conifer forest</td>
<td>Mild and dry</td>
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</tbody>
</table>
and subalpine rhododendron shrubs, indicating increased temperature and humidity; 10.0–6.1 ka BP, the continuous expansion of hemlock forests, denoting warm and wet climatic conditions; 6.1–3.4 ka BP, a period with hemlock forests, corresponding to the Holocene climatic optimum; and after 3.4 ka BP, shrunken hemlock forests indicating decreased humidity. This study suggests that regional climate changes are closely related to the strength of the Southwest Monsoon, i.e., strong monsoon associated with warm-humid climate, and weak monsoon associated with cold-dry climate (Figure 1.35).

1.5.2.2 Quaternary vegetation and monsoonal climate history in western and south-central Yunnan

The Yunnan-Guizhou Plateau is a region with concentrated distribution of fault depression basins in China. Most of these basins have developed since the late Cenozoic. Central and southwestern Yunnan is located in tropical and subtropical transitional zones and not affected by Quaternary glaciation. Palynological studies focused on Dianchi Lake in Kunming, Erhai Lake and West Lake in Dali, and Menghai Lake in Xishuangbanna.

1. Vegetation succession since the early Pleistocene in Kunming Basin

Pollen records from Can1, Kunlú, ZK1, and Puji cores in Kunming Basin show (Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences et al., 1989): in the late Pliocene, pollen spectra are dominated by pollen of tropical and subtropical evergreen arboreal plants, especially evergreen elements of Fagaceae. Pollen of gymnosperms such as Cedrus and Tsuga dumosa, and xerophilous herbs are common.

**Early Pleistocene** 139–142 m of the Can1 core and the Matuyama polarity; pollen assemblages are characterized by greater abundance of coniferous taxa Abies and Picea together with some Cedrus and Tsuga, and the frequent appearance of pollen from temperate deciduous broadleaved tree species of Betulaceae, Ulmaceae, and several genera of Fagaceae. Herbaceous pollen is present in small amounts, and fern spores are triletes.

**Middle Pleistocene** The age at 71 m of the Can1 core is 87.0 ka BP determined by Uranium-series dating, and another age at 24 m of the same core is 17.29 ka BP determined by $^{14}$C dating. Pollen assemblages are dominated by components of Pinaceae, Fagaceae, and Ulmaceae, including Pinus yunnanensis, Quercus, Alnus, and Ulmus. Some pollen of tropical and subtropical components is present. Herbaceous pollen mainly from Poaceae and Ranunculaceae is common. The ferns are dominated by Polypodiaceae.

**Late Pleistocene** Pollen assemblages are dominated by Cyclobalanopsis, Castanopsis, and Poaceae. Arboreal pollen is mainly from subtropical amentaceous plants such as Cyclobalanopsis, Castanopsis, Alnus, Ulmus, Ilex, Symlocos, Fagus, Rutaceae, and Leguminasea. A certain amount of arboreal pollen is from several species of Pinus such as Pinus yunnanensis. Herbaceous pollen is from Poaceae, Polygonum, Composita, Ranunculaceae, and Cruciferae. Spores of Polypodiaceae often appear.

**LGM Phase** A pollen record from Xingyun Lake in central Yunnan (1772 m a.s.l.) reveals regional vegetation and climate history since 36 ka BP (Chen et al., 2014) (Figure 1.36). ①MIS3 stage (36.4–29.2 ka BP), coniferous and evergreen broadleaved mixed forests dominated by pines and evergreen oaks developed in the study region; ②LGM stage (29.2–17.6 ka BP), cold temperate coniferous forests mainly consisting of spruce and fir occupied the region; ③17.6–13.4 ka BP, hemlock forests and spruce-fir forests began to decline, and they completely disappeared until 13.4 ka BP. They were replaced by pine forests and evergreen broadleaved forests. The reconstructed vegetation history suggests that regional climatic conditions tended to dry, implying the weakness of the Indian Monsoon. Especially, the weakest of the Indian Monsoon and the driest climatic conditions occurred in the early period of the last deglacial. LGM stage was the coldest period during the past 36 ka. It was estimated that temperature at this period was at least 3°C lower than the present.

Additionally, pollen spectra during the past 8.5 ka
Figure 1.35  Pollen percentage diagram since the late Pleistocene from Tiancai Lake in Yunnan (modified from Xiao et al., 2014)
Figure 1.36  Pollen percentage diagram from Xingyun Lake in central Yunnan (modified from Chen et al., 2014)
from the upper part of the same core (Chen et al., 2014) indicate that 8.5−5.5 ka BP was the warmest and wettest period of the Holocene. Regional climatic conditions tended to be dry after 5.5 ka BP, and unstable after 2.0 ka BP. However, a warm and wet interval, likely the Medieval Warm Period, is documented by the pollen record.

Holocene Both Chengjiang profile and Niumo profile near Fuxian Lake have basal black clay deposits $^{14}$C-dated to be 12.2 ka BP and 11.83 ka BP. Pollen records from these two profiles reflect Holocene vegetational and environmental changes in the Fuxian Lake region. In the early Holocene, pollen was abundant, mainly including *Pinus, Alnus, Quercus* (E), *Betula, Corylus, Rhododendron*, and *Compositae*. There were very few tropical and subtropical components, and a few temperate pollen types such as *Rosaceae, Quercus* (D), *Ulmus*, *Leguminasae*, *Ilex*, and *Polygonum*. Pollen spectra represent cooler and drier climatic conditions than the present. In the mid-Holocene, pollen types mentioned above still remained. *Castanopsis, Juglans, Carya, Corylus, Quercus, Morus*, and *Poaceae* pollen increased. More tropical and subtropical arboreal pollen were present in the pollen spectra, indicating warmer climatic conditions than those in the early Holocene. Pollen spectra of the late Holocene were similar to those from local top soils, mainly consisting of *Castanopsis, Alnus, Rosaceae, Pinus tabuliformis, Tsuga*, *Leguminasae, Ulmus*, *Polypodiaceae, Hicriopteris*, and *Pediastrum*.

Two pollen records from Dianchi Lake reveal regional vegetation and climate changes during the past 16000 years (Sun and Wu, 1984, 1987b; Table 1.16). Five phases are identified: ①during the late Pleistocene, deciduous broadleaved and coniferous mixed forests indicate cool climatic conditions; ②from the beginning of the Holocene to 8.4 ka BP, regional vegetation was still deciduous broadleaved and coniferous mixed forests, but with more tropical and subtropical components, implying climate warming; ③during 8.4−7.1 ka BP, the tropical and subtropical components were reduced, suggesting a cooling reversal; ④during 7.1−3.1 ka BP, luxuriant vegetation was dominated by subtropical evergreen broadleaved forests, indicating warm and humid climatic conditions (i.e., the Holocene climatic optimum); ⑤from 3.9 ka BP to present, forest coverage has been reduced and tropical components have declined, denoting that the climate has cooled.

2. Vegetation changes since the late Pleistocene in the Dali basin

Pollen records from cores Z18 and Z27 reveal the late Quaternary vegetation changes in the Dali basin (Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences et al., 1989). The early late-Pleistocene pollen assemblages contained more gymnosperm pollen mainly composed of *Pinus and Tsuga dumosa*, less arboreal angiosperm pollen dominated by *Quercus*, and abundant fern spores including *Polypodium, Pteris*, and *Hymenophyllaceae*. The middle Late Pleistocene pollen assemblages were still dominated by *Pinus and Tsuga dumosa*, arboreal angiosperm pollen *Castanopsis* instead of *Quercus*, less herbaceous pollen, and a few *Polypodium* and *Lepisorus* spores. The late Late-Pleistocene pollen assemblages contained more pollen types than those in the early periods, including arboreal pollen such as *Pinus, Tsuga dumosa, Quercus, Castanopsis, Castanea, Betula, and Alnus*, herbaceous pollen such as *Artemisia*, *Compositae*, and *Poaceae*, and fern spores such as *Polypodiaceae* and *Hymenophyllaceae*.

The pollen record from West Lake in Eryuan of Northwest Yunnan (Lin, 1987) shows that: ①15−12 ka BP, spruce-fir temperate evergreen coniferous forests with sparse oak forests, indicating cold climatic conditions (cold-wet in its early interval and cold-dry in its late interval); ②12−10 ka BP, coniferous and broadleaved mixed forests composed of *Pinus, Picea, Abies, Quercus*, and *Juglans*, implying increasing temperature and cool-wet climatic condition; ③10−7.7 ka BP, pine-dominated forests or hemlock-pine-spruce-fir forests, and more evergreen oaks in its late interval, suggesting cool and dry climatic conditions; ④7.7−4.5 ka BP, an expansion of coniferous and broadleaved trees, and vigorous growth of pine forests and evergreen oak forests, indicating another rise of temperature (Table 1.16).
<table>
<thead>
<tr>
<th>Epoch</th>
<th>Major pollen type</th>
<th>Vegetation</th>
<th>Climate</th>
<th>Major pollen type</th>
<th>Vegetation</th>
<th>Climate</th>
<th>Major pollen type</th>
<th>Vegetation</th>
<th>Climate</th>
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<td>Mild-wet</td>
<td>Pinus, Poaceae</td>
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<td>Mild-wet</td>
<td>Pinus, Cyclobalanopsis, Castanopsis</td>
<td>Evergreen broadleaf forest</td>
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<td>Pinus, Cyclobalanopsis, Castanopsis</td>
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<td>Pinus, Quercus (E)</td>
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<tr>
<td>30</td>
<td>Fagaceae, Podocarpus, ferns</td>
<td>Cool-dry MCBF*</td>
<td>Mild-wet</td>
<td>Pinus, Quercus (E)</td>
<td>Pine and sclerophyllous oak forest</td>
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</table>

* MCBF: Mixed conifer and broadleaf forest
In addition, pollen records from a small lake in the Menghai basin of Xishuangbanna, Southwest Yunnan reveal seven stages of vegetation successions since the Late Pleistocene (Liu and Tang, 1984). These pollen records are characterized by the alternating appearance of two pollen assemblages, which reflect alternating dry and wet climatic conditions. Pollen zones 1, 3, 5, and 7 are represented by the first pollen assemblage. This pollen assemblage reflects coniferous and broadleaved mixed forests consisting of Podocarpaceae, Cyclobalanopsis, Castanopsis, Lithocarpus, and Quercus. It is speculated that the vegetation type reconstructed from this pollen assemblage is similar to modern rain forests in the Wuzhi Mountains of Hainan Island, thus implying warm and wet conditions. The other zones are represented by the Pinus-Fagaceae-herbs assemblage. This assemblage reflects the vegetation dominated by pine and herbs that could endure dry and cool climatic conditions. It suggests sparse vegetation and a dry-cool climate (Table 1.16).

1.5.2.3 Vegetation since the mid-Pleistocene in western Sichuan

1.Vegetation and climate since the mid-Pleistocene in the Zoigê region

Palynological and environmental studies from the RM and RH sediment cores as well as the Wasong section of Zoigê basin provided some proxy climate records since the mid-Pleistocene, and thus important data to study the role of the Tibetan Plateau in the development and strength of the Asian monsoon (Liu et al., 1995; Wang and Xue, 1996; Wang et al., 1996; Shen C M et al., 2005). Palaeomagnetic dating at the bottom 285.72 m of the RM core indicates an age of 780 ka BP. The pollen record from the upper 60 m of this core (Figure 1.37) provides a relatively complete sequence of vegetation and climate change during the middle-late Pleistocene (Shen C M et al., 2005), while pollen records from the Wasong and Hongyuan peat sections reveal the Holocene environmental history in the Zoigê region (Wang F B et al., 1996). The following is a description of the two pollen records.

190–169 ka BP: Cyperaceae and Poaceae dominate with pollen percentages of 40%–60% and 8%–18%, respectively. Artemisia, Chenopodiaceae, Compositae, Caryophyllaceae, Ranunculaceae, and Thalictrum are common. The pollen concentration is high. The pollen spectra reflect subalpine sedge meadows and cold-wet climatic conditions.

169–157 ka BP: Pollen spectra are characterized by a marked drop in pollen concentration, a decrease in Cyperaceae pollen, and a gradual increase in Chenopodiaceae and Poaceae pollen, indicating sparse alpine meadows and cold-dry climatic conditions.

159–134 ka BP: Pollen concentration is very low. Pollen percentages of Pinus probably attributable to long-distance transport are relatively high. Chenopodiaceae, Cyperaceae, Poaceae, Compositae and Artemisia, are common. Pollen spectra reflect sparse vegetation in screes and desert under harsh periglacial conditions.

134–120 ka BP (corresponding to the last interglacial): Pollen spectra are characterized by the highest percentages of arboreal pollen (40%–90%), dominated by Picea and Pinus, together with some Quercus, Corylus, Cyperaceae, and Poaceae pollen. Pollen spectra indicate subalpine spruce-fir forests and warmer and wetter climatic conditions than the present.

120–86 ka BP: Pollen spectra are characterized by a decrease in arboreal pollen and a marked increase in Cyperaceae pollen, implying subalpine sedge meadows with scattered spruce-fir forests.

86–71 ka BP: Pollen percentages of Picea and Abies increase to form another strong peak with a maximum of 36.7%, representing a major spruce-fir forest expansion under warm and humid climatic conditions.


43–39 ka BP: Pollen spectra are dominated by Picea, together with some Pinus, Abies, Quercus, Cyperaceae, Poaceae, and Ranunculaceae, suggesting spruce-fir forests and grass-sedge meadows in regions surrounding the lake basin under climatic conditions
with higher temperature and precipitation than those of today.

39–32 ka BP: Pollen concentrations increase and pollen spectra are dominated by Poaceae and Cyperaceae, suggesting grass meadows.

32–18 ka BP: Pollen spectra with very low pollen concentrations are dominated by herbaceous pollen, mainly including Poaceae, Cyperaceae, Compositae, Artemisia, and Chenopodiaceae, reflecting an alpine periglacial desert under very cold and dry conditions of the last glacial maximum.

18–15 ka BP: *Pinus, Betula, Abies, and Picea* pollen increases with a rise of pollen concentrations. Pollen spectra indicate a reappearance of subalpine spruce-fir forest.

15–10 ka BP: High pollen percentages of *Pinus, Abies, Betula, Quercus, Corylus, Hippophae*, and Rosaceae indicate an expansion of forests and a shrinkage of alpine meadows, suggesting climatic conditions with temperature and precipitation equal to or higher than those of today. The pollen record from the Wasong peat section shows abundant arboREAL pollen with two peaks of *Abies* pollen at 14–10 ka BP. Cyperaceae pollen is common at this period. Pollen

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**Figure 1.37** Pollen record and chronological sequence for the upper 60 m of RM core in Zoigê basin of western Sichuan (modified from Shen C M et al., 2005)
spectra represent gradual recovery of sedge meadows and repeated appearance of fir forests in the study area.

10–9.4 ka BP: Pollen spectra are dominated by Cyperaceae pollen, with some Artemisia and Compositae pollen, indicating the development of meadows and swamps in foot slopes and lowlands. Pollen spectra from the Hongyuan peat section also have several peaks of Picea, Abies and Betula pollen, showing the invasion of forests as scattered patterns into the plateau interior and climatic fluctuations of warm-wet and cool-dry conditions.

9.4–4.0 ka BP: Pollen spectra are distinctly dominated by Picea and Abies pollen, indicating a period of dark spruce-fir forest. However, intense fluctuations occurred in the forest area. Fir forests disappeared from south-facing slopes from 4.05 ka BP, and then spruce migrated to the north-facing slopes.

4.0 ka BP to present: Modern vegetation of the Zoigê Plateau was established in this phase. Dark coniferous forests dominated by spruce together with some fir were scattered in island patterns, subalpine meadows and shrub meadows expanded, and swamps spread from open valleys and foot slopes to lowlands causing an extensive development of swamps in the meander belts of the Zoigê basin (Table 1.17).

2. Holocene vegetation in Lujishan Mountain

The pollen record from Dahaizi Lake in western Sichuan shows abundant Quercus and Pinus pollen together with some sclerophyllous oak, Abies, Betula, Corylus, Alnus, Lithocarpus, Castanopsis, and few Tsuga pollen during the period of 12.4–12.0 ka BP. Fir and rhododendron trees gradually encroached into the pollen source area of the lake during 12–10 ka BP, indicating a rise of the forest line and a warm climate condition. In the Shayema Lake region of Sichuan (Mianning County), there were forests dominated by fir, birch, and deciduous oaks during the interval of 11–9 ka BP (Jarvis, 1993). From 10 ka BP to 7.6 ka BP, pollen concentrations of Quercus were reduced by half, and Abies pollen increased to the highest point of the Holocene. At the same time more Tsuga pollen, less sclerophyllous oak and rhododendron pollen, and less Poaceae pollen were present. Pollen records from Dahaizi, Shayema, Yihai, Hong, and Maomao lakes show an increase of evergreen oak and Tsuga pollen from 9.1 ka BP to 7.8 ka BP, indicating warm and wet climatic conditions (Jarvis, 1993). From 7.6 to 2.0 ka BP, pollen spectra from Dahaizi Lake show a further decrease of Pinus and Quercus pollen and an increase of evergreen Lithocarpus and Castanopsis pollen, implying a rise of forest line, and thus a rise in temperature. In Shayema Lake and Yihai region, sclerophyllous forests expanded in the period of 7.8–4.0 ka BP, suggesting a marked seasonality in rainfall (Jarvis, 1993). The pollen record from Dahaizi Lake shows a decrease in pollen concentrations of all plant taxa, especially Pinus, Tsuga, and Quercus, indicating that vegetation changes are correlated to climatic deterioration and human activities (Li and Liu, 1988). In the Shayema Lake region sclerophyllous forests have continued to develop until now (Jarvis, 1993; Table 1.15).

1.5.2.4 Quaternary vegetation and environment in Guizhou

Guizhou is one of the most developed regions of karst environment in the world, and the center of China’s karst landforms. Its plateau karst landforms have some influence on the development of Quaternary sediments. Due to tectonic movement and erosion, fluvial and lacustrine sediments accumulate in some ravines, basins and karst depressions in central and western Guizhou. Pollen records are represented by those from cores CK17 and CK15 in Caohai Lake region, Zhaojiayuanzi, Daganba, and Nantun peat sections in central and western Guizhou, and the Jiulongchi section in Fanjingshan Mountains of eastern Guizhou. The Quaternary pollen sequence in Caohai Lake region is described as follows (Chen, 1987).

The Pleistocene 2.9–2.2 Ma BP is a pollen zone dominated by Quercus pollen with its pollen percentages over 30%, even as high as 63.7%. Other elements of broadleaved trees such as Betula, Castanopsis, Carpinus, Alnus, Ulmus, Corylus, and Rhododendron are also present in this pollen assemblage. Elements of the undergrowth are represented by abundant pteridophyte
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<tr>
<th>Epoch</th>
<th>Age /ka BP</th>
<th>Pollen</th>
<th>Vegetation</th>
<th>Pollen</th>
<th>Vegetation</th>
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<tr>
<td></td>
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<td>Zoigê core (Shen et al., 1996; Liu et al., 1994)</td>
<td>Hongyuan Wasong section, Zoigê Basin (Wang et al., 1996)</td>
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<tr>
<td>Late Holocene</td>
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<td>Picea, Pinus, Abies, Betula, Hippophae, Quercus, Corylus, Poaceae</td>
<td>Shrub &amp;steppe</td>
<td>Cyperaceae</td>
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<td>Compositae, Chenopodiaceae, Hippophae, Picea, Abies</td>
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<td>Sedge meadow</td>
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<td>Picea, Abies, Betula, Hippophae, Quercus, Corylus, Poaceae</td>
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<td>Betula, Picea, Abies, Rosaceae, Cyperaceae</td>
<td>Sedge marshes, coniferous and broad-leaved mixed forest</td>
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Table 1.17 Quaternary pollen and vegetation in the Zoigê Basin
spores including Polypodiaceae, Lycopodium, and Pteris. Pollen percentages of coniferous trees are less than 20%. This pollen assemblage reflects mixed coniferous and broadleaved forests dominated by oaks. 2.2–0.8 Ma BP is a pollen zone dominated by fern spores with percentages of 40.5%–76.5%. This assemblage consists of ferns such as Lycopodium, Polypodiaceae, and Davalliaeae, abundant alpine shrubs and herbs such as Eriaceae and Cruciferae, and less (13.3%–24%) arboreal pollen such as Pinus and Castanea. 0.8–0.15 Ma BP is a pollen zone dominated by Fagaceae pollen. Pollen percentages of broadleaved trees are more than 60.0%, and the main components include evergreen oaks, Castanopsis, Betula, and Juglans. Pollen percentages of understory shrubs and herbs such as Rosaceae, Ericaceae, and Cruciferae show a great fluctuation. Pollen assemblages reflect a mixed evergreen and deciduous broadleaved forest. 0.15–0.01 Ma BP is a pollen zone dominated by pollen of herbs with percentages of 30.9%–60.5%, mainly consisting of Poaceae, Cruciferae, and Polygonum. Pollen assemblages contain some pollen of alpine coniferous trees such as Abies and Tsuga, little pollen of deciduous broadleaved or sclerophyllous oaks, birch, alder, and chestnut. Meanwhile, the pollen record from the Zhaojiayuanzi section indicates mixed evergreen and deciduous broadleaved forests during 41.8–37.3 ka BP, sedge grasslands during 37.3–36.2 ka BP, and mixed evergreen and deciduous broadleaved forests during 36.2–21.0 ka BP (Chen et al., 1993). The pollen record from the Daganba section shows that dense subtropical montane forests dominated by Fagus occurred before 23 ka BP, and sparse forests dominated by ferns after 23 ka BP (Han and Yu, 1988). The pollen record from the Zhaojiayuanzi section shows a significant increase of Fagus pollen in 21.0–19.1ka BP, reflecting an occurrence of deciduous forests under cool and wet climatic conditions. The pollen record from the Nantun peat section indicates alternating appearances between forest-steppe and mixed coniferous and broadleaved forests in 15.7–10.78 ka BP (Chen P Y et al., 1991; Table 1.18).

The Holocene The pollen record from the Nantun peat section shows a sequence of Holocene vegetation succession from a forest-steppe, through phases of hardwood expansion and retraction, and back to forest-steppe again during the interval of 10.78–5.4 ka BP. Episodes of mixed coniferous and broadleaved forests dominated by pine alternating with pine forests occurred during 5.4–0.7 ka BP. After 0.7 ka BP, mixed coniferous and broadleaved forests composed of pines and oaks thrived. The pollen record from the Jiulongchi section in Faningshan mountains shows that meadow and deciduous broadleaved forest occurred at 10–7.8 ka BP, and then evergreen broadleaved forests flourished from 7.8 ka BP to 1.8 ka BP. Deciduous broadleaved forests dominated in 1.8–0.8 ka BP. After 0.8 ka BP, modern vegetation with deciduous broadleaved forest and meadow was gradually established (Qiao et al., 1996; Table 1.18).

1.5.2.5 Vegetation and monsoonal climate history since the late Pleistocene in southeastern Xizang

The landscape in southeastern Xizang is characterized by river gorges punctuating the Himalayan mountain barrier. It thus enables the Indian monsoon to penetrate deeply into the Tibetan Plateau and the western interior parts of China. Due to the warm and moist air mass brought by the Indian monsoon, forests instead of high-cold steppes and meadows develop in southeastern Xizang. For instance, Nyingchi, known as “Jiangnan in Xizang” (literally meaning “regions south of the Yangtze River in Xizang”), has a climate with no severe cold in winter and no intense heat in summer.

Surface pollen samples were mainly collected from moss polsters in southeastern Xizang (Shen et al., 2006). Pollen spectra of these samples are characterized by high percentages of arboreal pollen. Major arboreal pollen types are Pinus, Abies, Picea, Quercus, and Betula. Common herbaceous pollen types include Artemisia, Poaceae, Cyperaceae, Compositae, Thalictrum, and Ranunculaceae. Salix, Rhododendron, and Rosaceae are common shrub pollen types. Pollen spectra from forests exhibit different characteristics due to differences in local plant community. Pollen spectra from subalpine
### Table 1.18 Quaternary vegetation and climate changes in Guizhou Province

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Major pollen type</th>
<th>Vegetation</th>
<th>Climate</th>
<th>Major pollen type</th>
<th>Vegetation</th>
<th>Climate</th>
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<tr>
<td>230</td>
<td>Quercus (E), Castanopsis, Betula, Juglans, Rosaceae, Ericaceae, Polypodiaceae</td>
<td>Warm periods: MCBF* dominated by evergreen and deciduous broadleaved trees. Cold periods: cold-temperate coniferous forest</td>
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<td>800</td>
<td>Lycopodiaceae, Polypodiaceae</td>
<td>Fern flora</td>
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<td>2200</td>
<td>Quercus, Pinus, Salix</td>
<td>DBF* or MCBF*</td>
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<td>Poaceae, Brassicaceae, Polygonum, Abies, Tisaga</td>
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<td>Alternative of sylvo-meadow and MCBF* dominated by pine</td>
<td>3 cold periods and 2 warm periods</td>
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<td>9</td>
<td>Pinus, Quercus, Cyclobalanopsis, Alnus, Cyperaceae</td>
<td>Steppe with sparse trees + deciduous trees decline + more deciduous trees + meadow with sparse trees</td>
<td>cold + cool-wet + warm-wet + warming</td>
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<td>Alternative of MCBF* dominated by pine and pine forest</td>
<td>alternative of mild-dry and mild-wet</td>
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<td>Mild</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2900</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* MCBF: mixed coniferous and broadleaved forest; DBF: deciduous broadleaved forest; MEDBF: mixed evergreen and deciduous broadleaved forest;
coniferous and broadleaved mixed forests are dominated by *Pinus*, *Abies*, *Picea*, *Quercus*, and *Betula*, together with some pollen of *Tsuga*, *Larix*, *Alnus*, and *Corylus*. *Picea*, *Pinus*, *Quercus*, and *Betula* are dominant pollen types of spruce, pine, oak, and birch forests, respectively. Pollen spectra from larch forests contain more than 60% of *Larix* pollen, while pollen spectra from cypress forests contain more than 25% of Cupressaceae pollen. Pollen spectra from oak-birch forests are dominated by *Quercus* and *Betula* pollen, but some have high percentages of *Artemisia* pollen. Pollen spectra from pine-oak forests contain high percentages of *Pinus* and *Quercus* pollen, and *Artemisia* is also a common herbaceous pollen type.

Few Quaternary pollen records are available in southeastern Xizang. Three pollen records from Ren Co (Figure 1.38; Tang et al., 2004), and Yidun Lake (Figure 1.40; Shen et al., 2006) from this region are representatives to reconstruct their regional vegetation histories since the Last Glacial Maximum (Table 1.18). The Ren Co area was occupied by desert steppe consisting of Chenopodiaceae (50%), *Artemisia*, *Poaceae*, and *Cyperaceae* in the late glacial stage (20–12.4 cal. ka BP), but sedge meadow developed at 16.7–16.3 cal. ka BP and it was replaced by subalpine meadow mainly composed of *Cyperaceae*, *Artemisia*, and *Poaceae* after 13.5 cal. ka BP. Concurrently, the Yidun Lake area was occupied by steppes consisting of *Artemisia* and *Poaceae*. Quantitative reconstructions of climate at that time based on this pollen record show dry and cold climatic conditions with annual precipitation reaching only about 60% of today’s value and July temperature of 4°C lower than the present. In the early-mid Holocene, the Hidden Lake area was occupied by steppes, mainly composed of *Artemisia*, *Poaceae*, and *Cyperaceae*, at 12.4–11.4 cal. ka BP. Steppes were replaced by alpine meadows dominated by *Cyperaceae* with pollen percentages more than 60% at 11.4–9.4 cal. ka BP. Simultaneously, regional vegetation of the Yidun Lake area changed from meadow to forest at 11.5–9.2 ka BP, and quantitative reconstructions of climate show a trend of nonlinear increase in precipitation and temperature. Mixed coniferous and broadleaved forest dominated by birch and pine occurred at 9.2–6.8 ka BP. Annual precipitation increased to reach the Holocene

![Figure 1.38](image-url)
Figure 1.39  Pollen percentage diagram of major pollen types from Hidden Lake in southeastern Xizang (modified from Tang et al., 2004)
Figure 1.40  Pollen percentage diagram of major pollen types from Yidun Lake in southeastern Xizang (modified from Shen et al., 2006)
maximum ca. 100–120 mm higher than the present and July temperature showed an increasing trend and fluctuated around the modern value from 9.0 ka BP to 7.5 ka BP. The pollen record of Hidden Lake shows a gradual decline in herbaceous pollen such as Cyperaceae and a marked increase in *Betula* and *Pinus* pollen, indicating a gradual transition from alpine meadow to birch and pine mixed forest as well as cool to warm climate since 9.0 ka BP. Pollen spectra from the Ren Co is characterized by distinct decreases in Chenopodiaceae pollen and significant increases in *Betula* pollen at 12.4–5.7 cal. ka BP, indicating that regional vegetation changed from desert to forest-steppe and climatic conditions changed from cold-dry to warm-wet. In the late Holocene, pollen spectra from Yidun Lake are dominated by *Pinus* and *Betula* pollen at 6.8–2.5 ka BP, when mean annual precipitation was about 700 mm, and July temperature was 1–1.2°C higher than the present. After 2.5 ka BP, oak forests expanded, mean annual precipitation decreased, and July temperature dropped to the current level. Similarly, regional vegetation in the Hidden Lake area changed from forest to alpine meadow dominated by Poaceae, Cyperaceae, and *Artemisia* after 2.4 cal. ka BP, reflecting cooler climatic conditions (Table 1.19).

**Table 1.19  Late Quaternary vegetation and climate changes in southeastern Xizang**

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Age /ka BP</th>
<th>Ren Co, Basu, Xizang (Tang et al., 2004)</th>
<th>Hidden Lake, Kunggar, Xizang (Tang et al., 2004)</th>
<th>Yidun Lake, Litang, Sichuan (Shen et al., 2006)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Major pollen type</td>
<td>Vegetation</td>
<td>Climate</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td><em>Artemisia</em>, <em>Betula</em>, <em>Abies</em>, <em>Picea</em></td>
<td>Alpine forest and steppe</td>
<td>Cool and dry</td>
</tr>
</tbody>
</table>
Chapter 2

Major Types of Quaternary Pollen and Spores and Their Characteristics in Different Regions of China
2.1 Northwest Region

2.1.1 Types of Quaternary pollen and spores in northwest region

The northwest region, located in the eastern part of the extremely arid area of Asia, mainly includes Xinjiang, Qinghai, Gansu, western Inner Mongolia, northern Tibetan Plateau, and western Loess Plateau. In this vast region, only 66 families of Quaternary pollen and spores were found. We collected the photomicrographs of these pollen and spore taxa, and compiled them into 63 plates. These plates cover 64 families, including 7 families of pteridophyte spores, 3 families of gymnosperm pollen, and 54 families of angiosperm pollen. This region, except for the Altay, Tianshan, and Qilian mountains, has been occupied by arid and semi-arid herbaceous or subshrub steppes and desert steppes for a long time, because it has been affected by the harsh arid continental climate since the Neogene. According to published literature (e.g., Yang and Jiang, 1965; Song et al., 1965; Xi, 1988; Xi and Ning, 1994; Li et al., 1990), the common types of Quaternary pollen and spores in northwest region are summarized in the following table (Table 2.1).

<table>
<thead>
<tr>
<th>Type</th>
<th>Common taxa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees</td>
<td><em>Picea, Pinus, Abies, Larix, Cupressaceae, Betula, Ulmus, Carpinus, Salix, Populus, Juglans</em></td>
</tr>
<tr>
<td>Shrubs or subshrubs</td>
<td><em>Ephedra, Rosaceae, Chenopodiaceae, Nitraria, Tamarix, Caragana, Zygophyllum, Tribulus, Peganum, Zygophyllaceae, Leguminasae, Umbelliferae, Elaeagnus, Hippophae, Calligonum, Haloxylon, Nanophyton, Anabasis</em></td>
</tr>
<tr>
<td>Herbs</td>
<td><em>Artemisia, Aster, Taraxacum, Compositae, Poaceae, Leguminosae, Caryophyllaceae, Ranunculaceae, Lonicera, Polemonium, Thalictrum, Caryophyllaceae, Cruciferae, Polygonum, Amaranthaceae, Convolvulaceae, Labiatae, Cucurbita, Hamulus, Urtica, Plantago, Allium</em></td>
</tr>
<tr>
<td>Aquatic herbs</td>
<td><em>Typha, Myriophyllum, Sparganium, Iris</em></td>
</tr>
<tr>
<td>Ferns</td>
<td><em>Lycopodium, Selaginella, Polypodiaceae</em></td>
</tr>
</tbody>
</table>

As shown in Table 2.1, major pollen types in Quaternary strata were mainly from arid and semi-arid herbaceous and subshrub plants, such as *Zygophyllaceae, Umbelliferae, Chenopodiaceae, Tamaricaceae*, and *Elaeagnaceae*. These plants are dominants of steppes and desert steppes, fully reflecting the characteristics of regional vegetation in this region. Another notable feature is the emergence of special pollen taxa, which are seldom seen in other regions, such as *Limonium* of Plumbaginaceae, *Polemonium* of Polemoniaceae, *Calligonum* of Polygonaceae, *Tamarix* of Tamaricaceae, and *Peganum*, *Tribulus*, *Zygophyllum*, and *Nitraria* of Zygophyllaceae. These taxa are drought-resistant herbs and subshrubs, which are dominants of regional vegetation. This fact further reflects that the vegetation in this region has obvious drought-resistant characteristics.

2.1.2 Identifiable features of major Quaternary pollen and spores in northwest region

2.1.2.1 Identifiable features of main pollen types of Compositae

Compositae is a large family with the largest number of genera and species in seed plants, and it is widely distributed. As far as we know now, Compositae includes 235 genera and 2299 species in the flora of China, so the pollen types of Compositae preserved in Quaternary strata should be diverse. However, only *Artemisia* type, *Aster* type, and *Taraxacum* type were identified for Compositae pollen in previous studies. Furthermore, most studies just listed *Artemisia* and/or Compositae. Compositae is the largest family with the highest of differentiation in the angiosperms; it also has a great adaptability to any environment. Obviously, it is inadequate that only a few fossil pollen types of this family were identified in past studies. Table 2.2 lists the identifiable features of 4 major Compositae pollen types.

The pollen polymorphisms of Compositae plants were resulted from their ancestors’ long-term evolution, diversification, and development under geological and climatic environments. The ancestors of Compositae appeared in the early Eocene or Paleocene under slightly arid and warm conditions of subtropics. As the climate and ecological environments changed, they first differentiated into species suitable for the tropical and subtropical climate conditions in the American tropics, and then developed into species tolerating...
high-cold alpine conditions of the temperate zone. In particular, most species have gradually migrated and differentiated to adapt temperate arid environments in Eurasia and high-cold alpine conditions in the region of Hengduan Mountains-Himalaya Mountains. These facts reveal the great significance of East Asia in the origin of Compositae and the important role of the uplift of Tibetan Plateau in the differentiation of Compositae in China.

Table 2.2  Identifiable features for 4 pollen types of Compositae

<table>
<thead>
<tr>
<th>Pollen type</th>
<th>Pollen photomicrographs</th>
<th>Pollen features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. <em>Artemisia</em> type</td>
<td><img src="image1.png" alt="Image" /></td>
<td>Exine thick, sexine with distinct columella and tectum, small and degraded spines on the surface</td>
</tr>
<tr>
<td>2. <em>Aster</em> type</td>
<td><img src="image2.png" alt="Image" /></td>
<td>Pollen grains with spines, each lobe with 5-6(–7) spines in polar across view</td>
</tr>
<tr>
<td>3. <em>Taraxacum</em> type</td>
<td><img src="image3.png" alt="Image" /></td>
<td>Pollen surface usually have 12–30 brochi, muri with spines</td>
</tr>
<tr>
<td>4. <em>Echinops</em> type</td>
<td><img src="image4.png" alt="Image" /></td>
<td>Pollen size large (more than 50 μm of polar axis), exine extraordinary thick, sexine with obvious columella and thick tectum, surface with small blunt spines</td>
</tr>
</tbody>
</table>

1. *Artemisia* type: 1–4. *Artemisia*
2. *Aster* type: 1, 2. *Aster*; 3, 4. *Erigeron*
Chapter 2  Major Types of Quaternary Pollen and Spores and Their Characteristics in Different Regions of China

Table 2.3  Morphological comparison of Aster type, Erigeron type, and Solidago type pollen

<table>
<thead>
<tr>
<th>Aster type</th>
<th>Erigeron type</th>
<th>Solidago type</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Pollen grains oblate, spheroidal to subprolate, P/E = 0.80–1.70; 3-lobed (occasionally 2- or 4-lobed) circular in polar view; exine 1.1–4.0 µm thick; sexine/nexine = 1.0–1.4; spines 2.0–5.0 µm high, with one to multi rows of perforations at the base and 1.7–3.9 µm in diameter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Pollen grains spheroidal, occasionally subprolate or suboblate, P/E = 0.76–1.44; 3-lobed circular or triangular (occasionally 4- or 5-lobed circular) in polar view; exine 1.5–3.0 µm thick; sexine/nexine = 1.5–3.0; spines 1.9–4.2 µm high, with scattered, or one to two rows, or without perforations at the base and 1.4–4.5 µm in diameter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Pollen grains spheroidal, suboblate, or subprolate, P/E = 0.76–1.25; 3-lobed (occasionally 4- or 6-lobed) circular in polar view; exine 1.7–3.0 µm thick; sexine/nexine = 1.5–2.5; spines 1.5–4.6 µm high, with scattered, or one to three rows of perforations at the base and 1.4–3.3 µm in diameter</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fossil pollen found in Quaternary strata from Barkol Lake of Xinjiang, Baiyangdian Lake of Hebei, and lakes and sections in Xizang, northwestern Sichuan, northern Jiangsu, Yunnan, and Guangdong

<table>
<thead>
<tr>
<th>Perennial herbs, subshrubs, or shrubs</th>
<th>Annual or perennial herbs, seldom subshrubs</th>
<th>Perennial herbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distributed in Northwest, North and South China</td>
<td>Widely distributed</td>
<td>Widely distributed</td>
</tr>
</tbody>
</table>

* P: the polar axis; E: the equatorial diameter

Identifiable features can be summarized as follows.

1. Exine with spines

Five fossil pollen types of Compositae belong to this pattern, namely, Artemisia type, Echinops type, Aster type, Erigeron type, and Solidago type. Among them, pollen grains of Artemisia type and Echinops type are 3-lobed circular in polar view, with small spines or distinct ornamentation. Pollen grains of Aster type, Erigeron type, and Solidago type are spheroidal or subspheroidal with distinct spines. Since the identifiable features of Artemisia type, Echinops type, and Aster type were introduced in Table 2.2. Table 2.3 shows a morphological comparison of Aster type, Erigeron type, and Solidago type.

2. Exine with columella

Five fossil pollen types of Compositae belong to this pattern, including Saussurea type, Senecio type, Anthemis type, Arctium type, and Ainsliaea type. An identification key to these five fossil pollen types is as follows:

1. Pollen grains prolate or spheroidal, 24–70 µm in size, 3-cporate, exine with columella.
2. Pollen grains spheroidal, 3-cporate, endoaperture large, surface with 5–8 spines, 2–3 µm high .................................. Saussurea type
3. Pollen grains 24–30 µm in size, exine spiny, spine acuminate, 3-lobed in polar across view, 5 spines in each lobe, 3.5 µm high ................................................................. Senecio type
4. Pollen grains 35–40 µm in size, exine thick with obvious columella, tectum coniform, 3-lobed in polar across view, 4–5 spines in each lobe, ca. 3 µm high ........................................................................ Anthemis type
5. Pollen grains prolate, ca. 50 µm in size, 3-cporate, exine thick with columella, tectum spiny.
6. Pollen grains 3-cporate, endoaperture lalongate, spine-shaped protuberances on the surface with uneven sizes and blunt tips ................................................................. Arctium type
7. Pollen grains 3-cporate, endoaperture slightly long, colpate long and thin, edge unevenness, spine-shaped protuberances on the surface with broad base and subacute tips .................................................................................. Ainsliaea type

3. Exine with big brochi

Ten fossil pollen types of Compositae belong to this pattern, including Faberia type, Sonchus type, Achyrocorpus type, Crepis type, Elephantopus type, Ixeris type, Scorzonera type, Taraxacum type, Luctua type, and Cichorium type. Since their pollen morphology is similar to each other, the following identification key is provided to further distinguish them.
Compositae plants have long been influenced by geographic, topographic, and climatic factors; the polymorphism of Compositae pollen and the diversity of Compositae plants were thus shaped by long-term natural selection through time. Fossil pollen of Compositae (Raven and Axelrod, 1974) shows that Compositae plants developed in the tropics, and then diversified and migrated from the tropics to the subtropics. They gradually adapted to the tropical and subtropical environments. In response to climate change, Compositae plants finally diversified and developed to enter temperate and alpine mountains. As a result, the habitat gradient of Compositae plants is very wide. According to previous ecological studies of plant and pollen (Lin, 1993, 1997), the habitat of modern plant genera, to which the above-mentioned 21 pollen types of Compositae belong, can be summarized as follows.

1. Alpine and cold-resistant group: Astér, Erigeron.
2. Arid and semi-arid desert or desert steppe group: Anthemis, Echinops, Crepis, Scorzonera, Targopogon, Arctium, Solidago, Artemisia, Sonchus. For example, Scorzonera plants grow mostly in arid and semi-arid mountains or sandy lands; its species gradually decrease along a gradient of increasing precipitation from Northwest to Southeast China, and finally disappear in South China and Taiwan.
3. Subalpine meadow and scrub meadow group: Saussurea, Senecio, Elephantopus, Ixeris, Faberia, Achyrophorus, and Ainsliae. For example, Ainsliaea is an endemic genus in East Asia; it is a dominant of herbaceous plants in subtropical evergreen forests to subalpine coniferous forests.
2.1.2.2 Identifiable features of Artemisia, Tamarix, and Zygophyllum pollen

In Quaternary sediments in the arid and semiarid regions of northwest region, pollen grains that bear the following characteristics are often found—spherical or nearly spherical, 3-lobed circular in polar view, and tricolpate, tricolporate, or tricolporoidate. As pollen grains may not be clearly visible under the microscope, sometimes it is difficult to distinguish Artemisia, Tamarix, and Zygophyllum. Especially, it should be noted that the smaller Artemisia pollen is not easily distinguished from the pollen of some Zygophyllum species. The pollen grains of the latter have indistinct porus or poroid, and the pollen wall has thin tectum without granules. Moreover, if the porus of Artemisia pollen is not clear, it may be difficult to distinguish it from the pollen of some Tamarix species. However, the absence of a porus and the occurrence of coarse granules on the pollen surface of Tamarix can be used as diagnostic features to distinguish them from Artemisia. Detailed morphological features of the three genera are compared in Table 2.4.

2.1.2.3 Identifiable features of Rhamnus, Hippophae, and Elaeagnus pollen

Rhamnus, Hippophae, and Elaeagnus plants are widely distributed in the arid and semiarid region of China. They are arid- and cold-resistant shrubs, and they are also adapted to poor soils. They grow on dry and sandy river beds of floodplains or valleys as well as hillsides of mountains and hills, thus they have important ecological implications. Their pollen grains are often found in Quaternary strata in Northwest, North, and Southwest China. However, it is difficult to distinguish them due to their similar morphology. Their pollen grains are spheroidal to oblate, obtuse triangular in polar view, and they have three colpores and reticulate ornaments on the pollen surface. For the convenience of pollen identification, a morphological comparison of their pollen grains is made (Table 2.5).

2.1.3 Descriptions of morphological features for major Quaternary pollen and spores in northwest region

2.1.3.1 Photomicrographs of major Quaternary pollen types in northwest region

Pollen types in this region are mainly those of herbaceous and shrubby plants. Herbaceous pollen is dominated by Chenopodiaceae (except Haloxylon) and the Compositae (including Artemisia type, Aster type, Echinops type, and so on). The shrub pollen is from desert plants such as Nitraria and Ephedra. Arboreal pollen is characterized by Picea schrenkiana. The main pollen types in northwest region are listed in Figure 2.1.

2.1.3.2 Descriptions of morphological features of major Quaternary pollen types in northwest region

**Tamaricaceae**

*Tamarix*, Figure 2.1: 3, 4; Northwest Region Plate 58: 12–19

Pollen grains nearly spherical; 3-lobed circle in polar view; 19.1 (15.7–20.0) μm × 17.4 (14.8–18.3) μm; tricolpate, colpi indistinct, with wide middle and sharp ends; exine ca. 1.5 μm in size, distinctly layered, sexine as thick as nexine; sexine reticulate, lumina becoming small near the edges of colpi. No endoapertures, atectate surface, and coarse reticula are three diagnostic features that distinguish it from Artemisia pollen.

**Modern distribution** Hyperarid subshrub of desert, salt desert, desert steppe or sand land; distributed mostly in Northwest and Southwest China.

**Fossil distribution** Quaternary deposits from Chaiwopu and Barkol basins in Xinjiang, Dadiwan basin in Gansu, Qaidam basin in Qinghai, and Mau Us Desert in Inner Mongolia.

**Plumbaginaceae**

*Limonium*, Figure 2.1: 7; Northwest Region Plate 45: 1–6

Pollen grains subspherical, sometimes oblate or prolate; 3-lobed circular or 3 lobes in polar view, elliptic or nearly round in equatorial view; 76.9 (60.9–84) μm × 68.4 (65.1–77.1) μm in size; tricolpate, colpi long and
thin; exine thick, ca. 11 μm; nexine thin, sexine thick and reticulate, muri high, lumina irregular and deep; clavae with pointed ends on muri.

**Modern distribution**  Perennial herb; distributed in deserts and desert steppes in Xinjiang, Inner Mongolia, and other regions.

**Fossil distribution**  Quaternary deposits from Barkol basin in Xinjiang and Mau Us Desert in Inner Mongolia.

**Umbelliferae**

*Bupleurum*, Figure 2.1: 8; Northwest Region Plate 61: 4–9

Pollen grains prolate or rhomboidal; obtuse-triangular in polar view; aperture at angels, elliptic in equatorial
### Table 2.4  Morphological comparison of *Artemisia*, *Tamarix*, and *Zygophyllum* pollen

<table>
<thead>
<tr>
<th><em>Artemisia</em></th>
<th><em>Tamarix</em></th>
<th><em>Zygophyllum</em></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Images</th>
<th>Images</th>
<th>Images</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image 1" /></td>
<td><img src="image2.png" alt="Image 2" /></td>
<td><img src="image3.png" alt="Image 3" /></td>
</tr>
<tr>
<td><img src="image4.png" alt="Image 4" /></td>
<td><img src="image5.png" alt="Image 5" /></td>
<td><img src="image6.png" alt="Image 6" /></td>
</tr>
<tr>
<td><img src="image7.png" alt="Image 7" /></td>
<td><img src="image8.png" alt="Image 8" /></td>
<td><img src="image9.png" alt="Image 9" /></td>
</tr>
<tr>
<td><img src="image10.png" alt="Image 10" /></td>
<td><img src="image11.png" alt="Image 11" /></td>
<td><img src="image12.png" alt="Image 12" /></td>
</tr>
</tbody>
</table>

- **Pollen grains**
  - *Artemisia*:
    - Spherical or spheroidal, 3-lobed circular in polar view
    - 3-colporate
    - Exine thinned near the colporus, sexine with distinct columnella and tectum, the surface usually with small spines
    - Mostly 19–25 μm in size

- **Pollen grains**
  - *Tamarix*:
    - Spheroidal to prolate, 3-lobed circular in polar view
    - 3-colporate, colpi not obvious
    - Layers of sexine not obvious, exine surface smooth, or with blurry fine or coarse reticulate ornaments
    - Mostly 16.5–19.1 μm × 15.7–17.4 μm in size

- **Pollen grains**
  - *Zygophyllum*:
    - Spheroidal to prolate, 3-lobed circular in polar view
    - 3-pseudocolporate, colpi slender and constricted at the equator, endoaperture not obvious or lengthwise
    - Sexine and nexine equal in thickness, surface nearly smooth or with weak finely reticulate ornaments
    - Mostly 20–16 μm × 12–15 μm in size
view; 30.1 (27.4–35.6) μm × 22.5 (19.2–26.5) μm in size; tricolporate, colpi thin, as long as grain and almost confluent in polar regions; endoapertures large, usually square or transversely rectangular, almost connected with adjacent endoapertures and constricted perpendicular to the two sides of colpi; exine slightly thickened at the poles, with distinct layers; sexine and nexine in equal thickness, with faint and fine reticulate ornamentation.

**Modern distribution** Xerophytic shrub in salt deserts.

**Fossil distribution** Quaternary deposits from Chaiwopu and Barkol basins in Xinjiang and Qaidam basin in Qinghai.

**Zygophyllaceae**

**Peganum**, Figure 2.1: 9; Northwest Region Plate 63: 8–12

Pollen grains subspheroidal, slightly long; 3-lobed circular or 3 lobes in polar view; 19.0 (17.4–22.6) μm × 17.7 (16.5–19.1) μm in size; tricolporate; colpi wide and long, connected at poles, with colpus membrane; endoapertures large, pore membrane slightly raised; exine with distinct layers; sexine and nexine in equal thickness, with faint and fine reticula.

**Modern distribution** Perennial herb; distributed in Xinjiang, Qinghai, Gansu, Inner Mongolia, and other regions.

**Fossil distribution** Quaternary deposits from Chaiwopu and Barkol basins in Xinjiang, and basins in Inner Mongolia, Qinghai, and Gansu.

**Nitraria**, Figure 2.1: 13, 14; Northwest Region Plate 62: 7–18

Pollen grain ellipsoidal; outline slightly triangular in polar view; laterally oval, slightly close to spindle-shaped; 30–40 μm × 20–30 μm in size; tricolporate; colpi thin and long, with prismatic or cat-eyed endoapertures at the middle; exine thick; surface near smooth or unclear fine reticula; outline smooth.

---

**Table 2.5** A comparison of identifiable features for *Rhamnus*, *Hippophae*, and *Elaeagnus* pollen

<table>
<thead>
<tr>
<th></th>
<th>Rhamnus</th>
<th>Hippophae</th>
<th>Elaeagnus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pollen grains</td>
<td>spheroidal to suboblate, obtuse</td>
<td>spheroidal to suboblate,</td>
<td>suboblate, obtuse</td>
</tr>
<tr>
<td><strong>observed</strong></td>
<td>triangular in polar view</td>
<td>circular (with three sharp</td>
<td>triangular in polar view</td>
</tr>
<tr>
<td><strong>measurements</strong></td>
<td>(23‒27)-(23.5‒29) μm</td>
<td>angle) in polar view</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pollen grains 3-colporate, colpi</td>
<td>Pollen grains 3-colporate,</td>
<td>Pollen grains 3–4-colporate,</td>
</tr>
<tr>
<td><strong>description</strong></td>
<td>slender, endoapertures</td>
<td>colpi slender and apex at both</td>
<td>colpi short, endoapertures</td>
</tr>
<tr>
<td></td>
<td>large, usually square or</td>
<td>both ends, exine protruding</td>
<td>big and round, obviously</td>
</tr>
<tr>
<td></td>
<td>transversely rectangular, almost</td>
<td>from the pollen outline near</td>
<td>protruding, exine thickened</td>
</tr>
<tr>
<td></td>
<td>connected with adjacent</td>
<td>end apertures, surface with</td>
<td>near the colpi and endoapertures,</td>
</tr>
<tr>
<td></td>
<td>endoapertures and constricted</td>
<td>fine reticulate ornamentation</td>
<td>surface with weak finely</td>
</tr>
<tr>
<td></td>
<td>perpendicular to the two sides</td>
<td></td>
<td>reticulate ornamentation</td>
</tr>
<tr>
<td></td>
<td>of colpi; exine slightly</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>thickened at the poles, with</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>distinct layers; sexine</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>and nexine in equal</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>thickness, with faint and fine</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>reticula.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The equatorial diameter (23‒27)-(23.5‒29) μm</td>
<td>The equatorial diameter 25–27 μm</td>
<td>The equatorial diameter ca. 42–59 μm</td>
</tr>
</tbody>
</table>

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Chapter 2  Major Types of Quaternary Pollen and Spores and Their Characteristics in Different Regions of China

**Modern distribution**  Shrub; favored in sandy and alkaline soils, and adapted to dry and windy plains; distributed in Inner Mongolia, Gansu, Shaanxi, Qinghai, Xizang, and Northeast China.

**Fossil distribution**  Quaternary deposits from lakes and basins in Xinjiang, Qinghai, Gansu, and Inner Mongolia.

### Poolemoniaceae

*Poolemonium*, Figure 2.1: 15; Northwest Region Plate 51: 1, 2

- Pollen grains spherical; 50.5 (40.0–53.9) μm in size; aperture indistinct, usually scattered small pores; exine thick, ca. 5 μm, indistinct layers; sexine with irregular thick striae; the shape, thickness and direction of the striae irregular.

**Modern distribution**  Perennial herb; distributed in steppes and desert steppes in Xinjiang, Inner Mongolia, and other regions.

**Fossil distribution**  Quaternary deposits from Barkol basins in Xinjiang, and Mau Us Desert in Inner Mongolia.

### Elaeagnaceae

*Elaeagnus*, Figure 2.1: 17; Northwest Region Plate 33: 3–7

- Pollen grains super-oblate; oblate in equatorial view and triangular in polar view; 39.0 μm × 61.8 μm in size; P/E-ratio 0.63; tricolporate; colpi short and especially thin, with colpus membrane; endoapertures large and round, distinctly elevated, protruding, large endoaperture and small eutoapertures forming an obvious and large atrium; exine slightly thickened at the edge of colporate; nexine thicker than sexine; sexine surface with faint and fine reticula.

**Modern distribution**  Evergreen shrub; distributed in Shaanxi, Gansu, and Southeast and Southwest China.

**Fossil distribution**  Quaternary deposits from Dadiwan basin in Gansu, Barkol basin in Xinjiang, and basins in Qinghai and Inner Mongolia.

## 2.2 North Region

### 2.2.1 Types of Quaternary pollen and spores in north region

North region mainly includes most parts of North China Plain and Northeast China. The studies of Quaternary pollen analysis mainly focused on areas of forest meadow and swamp in the North China Plain, Sanjiang Plain, Changbai Mountain, and Jilin. Fossil pollen types found at these sites are not as abundant as those found in Southeast and Southwest China. A total of 80 families and 144 genera were collected in this book. The main taxa are listed in Table 2.6. We collected the photomicrographs of these pollen and spores, and compiled them into 63 plates. These plates cover 5 families of algae spores, 1 family of bryophyte spores, 9 families of pteridophyte spores, 4 families of gymnosperm pollen, and 61 families of angiosperm pollen (see North Region Plates 1–63).

| Trees | *Pinus, Abies, Picea, Larix, Cupressaceae, Alnus, Betula, Carpinus, Corylus, Ostrya, Quercus, Ulmus, Celtis, Aphananthe, Tilia, Fraxinus, Acer, Salix, Populus, Juglans* |
| Shrubs | *Rosaceae, Dryas, Caragana, Leguminosae, Rhododendron, Ephedra* |
| Herbs | *Artemisia, Aster, Compositae, Poaceae, Chenopodiaceae, Oleaceae, Leguminosae, Cyperaceae, Ranunculaceae, Thalictrum, Caryophyllaceae, Rosaceae, Sanguisorba, Cruciferae, Liliaceae, Araliaceae, Polygonum, Amaranthaceae, Umbelliferae, Labiatae* |
| Aquatic herbs | *Typha, Myriophyllum, Sparganium* |
| Ferns | *Equisetum, Lycopodium, Selaginella, Osmunda, Polypodiaceae* |

The characteristics of pollen and spore types in this region are as follows: ① Pollen of temperate coniferous and deciduous broadleaved trees is dominant. Among them, species of Pinaceae are abundant, especially *Pinus* and *Picea*. *Pinus* species include *Pinus koraiensis*, *P. pumila*, and *P. sylvestris* var. *sylvestriformis*, while *Picea* species include *Picea koraiensis*, *P. koraiensis* var. *pungsanensis*, *P. jezoensis* var. *komarovii*, and so on. Among deciduous broadleaved trees, 5 genera of Betulaceae, i.e., *Alnus, Betula, Carpinus, Corylus*, and *Ostrya* have a lot of species. Other genera of tall trees such as *Tilia, Ulmus*, and *Quercus* also have many species, for example, *Tilia mandshurica, Ulmus propinqua, Quercus wutaishanica*, and *Q. mongolica*. A large number of these species represent the occurrence of well-developed temperate coniferous and broadleaved
mixed forests in this region. A great diversity of Compositae pollen among herbaceous pollen types. Sixteen Compositae genera are often found. In addition to the common genera Arctemisia and Aster, they are Axonopus, Bidens, Cichorium, Cirsium, Crepis, Echinops, Faberia, Lactuca, Ligularia, Prenanthes, Pertya, Scorzonera, Xanthium, and Taraxacum. They grow not only in the North China Plain, but also in the steppes of other area of north region. For the first time Dryas pollen has been found in the Holocene peat sediments of the Jilin Province (see North Region Plate 57: 11–20). Dryas belongs to the family of Rosaceae, and only one species, Dryas octopetala var. asatica occurs in China. It is now distributed in the tundra zone above the Betula ermanii forest zone at elevations of 2000–2300 m in the Changbai Mountains. It grows as a prostrate shrub in an open land of small area (about 100 m²). Dryas is a typical alpine tundra (meadow) plant, indicating cold and humid climatic conditions. Today, few plants of Dryas occur in Europe. According to records, its plants were also found in the Tianshan Mountains. They belong to the same species as those found in the Changbai Mountains, also known as “the East Asian Dryas”.

2.2.2 Identifiable feature of major Quaternary pollen types in north region

2.2.2.1 Identification key of pollen morphology to the genera of Pinaceae

Pinaceae is a large family of gymnosperms, most species of which are evergreen or deciduous trees, rarely shrubs as forest components. In China, there are 10 genera and 113 species of Pinaceae, mostly distributed in the mountainous areas of North, Northwest, Southwest, and South China, forming vast forests. They are also important tree species for forest regeneration and afforestation. Fossil pollen of Pinaceae were found in strata from the Mesozoic to the Quaternary (for more details, see North Region Plates 11–24). The identification key of saccate pollen belonging to 7 genera of Pinaceae is presented below:

1. Distinct boundaries between sacchi and the corpus, forming concave corners at the proximal base in lateral view.
2. Pollen grains small, generally ca. shorter than 110 μm in length, exine 3–8 μm in thickness.
   3. Sexine often thinned near the proximal base, without marginal ridge, sacchi with thin reticula ................................................. Pseudolarix
   3. Sexine not thinned near the proximal base, with marginal ridge, sacchi with thick reticula...................................................... Pinus
2. Pollen grains large, generally ca. longer than 110 μm in length, exine 3–8 μm in thickness.
   3. Cap with wormlike ornamentation ......................................................................................................................... Abies
   3. Cap with fine granula .............................................................................................................................................. Keteleeria
1. Indistinct boundaries between sacchi and the corpus, not forming concave corners at the proximal base in lateral view.
2. Pollen grains large, longer than 110 μm in length ................................................................. Picea
2. Pollen grains small, shorter than 110 μm in length.
   3. Sacchi undeveloped, with indistinct reticula in lateral view................................................................. Cedrus
   3. Sacchi well-developed, with distinct reticula in lateral view ............................................................ Cathaya

Pinus, Abies and Picea are major constructive components of coniferous forests as well as coniferous and broadleaved mixed forests in northeastern China and North China Plain. They are also the dominant components of arboreal pollen types in the Quaternary strata of North China. However, there are still some difficulties in the fossil pollen identification of these three genera. Table 2.7 is a comparison of their pollen morphological features.

2.2.2.2 Identifiable features of pollen morphology for the genera of Betulaceae

Betulaceae plants are widely distributed in north region. They are important components of the northern temperate forests. Fossil pollen was first discovered in the Cretaceous–Neogene strata in Fushun of Liaoning
and Shanwang of Shandong, and then largely found in the Paleogene–Quaternary strata in north region. They are the major arboreal pollen, especially *Betula* pollen, in Quaternary pollen assemblages in north region. Betulaceae has 6 genera, i.e., *Alnus*, *Betula*, *Carpinus*, *Corylus*, *Ostrya*, and *Ostryopsis*. It is easy to distinguish *Alnus* pollen from the pollen of other genera, because *Alnus* pollen has obvious inter-pore thickened band structure. However, it is difficult to distinguish other pollen because they have similar pollen morphology (see North Region Plates 27 and 28). The pollen identification key to 6 genera of Betulaceae is presented below:

1. Pollen grains 4–5-porate, thickened and curved bands (arcus) conspicuous ....................................................... *Alnus*
2. Pollen grains 3–5-porate, thickened and curved bands (arcus) not conspicuous.
   1. Sexine thickened significantly at pores, nexine thickened or slightly thickened, often with 3 (sometimes 2, 4, 5–8) pores —— *Betula*
   2. Sexine often not thickened at in pores, nexine not thickened, often with 3 (occasionally 2, 4, 5) pores.
      1. Pores distinctly protruding, relatively thin exine —— *Carpinus, Ostrya*
      2. Pores not protruding, relatively thick exine —— *Corylus, Ostryopsis*

### Table 2.7 Identifiable features of fossil *Pinus, Abies*, and *Picea* pollen

<table>
<thead>
<tr>
<th>Genus</th>
<th>Pinus</th>
<th>Abies</th>
<th>Picea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photomicrographs</td>
<td><img src="image1" alt="Pinus" /></td>
<td><img src="image2" alt="Abies" /></td>
<td><img src="image3" alt="Picea" /></td>
</tr>
<tr>
<td>Pollen size</td>
<td>Small, shorter than 110 μm</td>
<td>Large, longer than 110 μm</td>
<td>Large, longer than 110 μm</td>
</tr>
<tr>
<td>Cap sculpture</td>
<td>Coarse granula</td>
<td>Wormlike ornamentation</td>
<td>Fine granula</td>
</tr>
<tr>
<td>Marginal ridge</td>
<td>With developed marginal ridge</td>
<td>Without marginal ridge</td>
<td>Without marginal ridge</td>
</tr>
<tr>
<td>Sacci</td>
<td>Distinct boundaries between sacci and the corpus, forming concave corners at the proximal base in lateral view</td>
<td>Distinct boundaries between sacci and the corpus, forming concave corners at the proximal base in lateral view</td>
<td>Indistinct boundaries between sacci and the corpus, not forming concave corners at the proximal base in lateral view</td>
</tr>
<tr>
<td>Lateral view</td>
<td>Two saccii arranged on both sides of the corpus, forming concave corners with the corpus</td>
<td>The intersection of two sacci and the corpus into circular, forming concave corners between sacci and the corpus</td>
<td>Two saccii arranged on both sides of the corpus, not forming concave corners with the corpus</td>
</tr>
</tbody>
</table>

2.2.2.4 Identifiable features of tricolpate pollen from Ranunculaceae and Labiatae

The pollen morphology of Ranunculaceae is diverse. Among pollen types of Ranunculaceae, pollen grains of tricolpate pollen type are easily confused with those of tricolpate pollen type from Labiatae. Table 2.9 summarizes the distinguishable features of tricolpate
Table 2.8 A comparison of identifiable morphological features for *Salix* and Cruciferae pollen

<table>
<thead>
<tr>
<th><em>Salix</em></th>
<th><em>Cruciferae</em></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5. <em>Cardaria</em>; 7, 8. <em>Brassica juncea</em></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pollen grains 3-pseudocolpate</th>
<th>Pollen grains 3-colpate</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-lobed circular in polar view</td>
<td>3-lobed in polar view</td>
</tr>
<tr>
<td>Narrow oval in equatorial view</td>
<td>Circular or oval in equatorial view</td>
</tr>
<tr>
<td>Distinct reticula, mesh nonuniform and diminishing near colpi</td>
<td>Distinct reticular sculpture, mesh fine and uniform</td>
</tr>
<tr>
<td>Exine without columellae</td>
<td>Exine with distinct columnellae, their ends slightly swelled</td>
</tr>
<tr>
<td>Outline conspicuously undulated</td>
<td>Outline slightly undulated</td>
</tr>
</tbody>
</table>

pollen types of both Ranunculaceae and Labiatae.

**2.2.3 Description of morphological features for major Quaternary pollen and spores in north region**

**2.2.3.1 Photomicrographs of major Quaternary pollen types in north region**

Quaternary pollen in north region is typically dominated by arboreal pollen from deciduous and coniferous plants. Deciduous plants are mainly composed of *Betula*, *Carpinus*, *Ulmus*, *Acer*, and *Tilia*. Coniferous plants are composed of *Pinus*, *Larix*, *Picea*, and *Abies*. Special non-arboreal pollen is *Dryas* in alpine areas. The photomicrographs of major pollen types in north region are listed in Figure 2.2.
2.2.3.2 Description of morphological features for major Quaternary pollen types in north region

**Pinaceae**

*Larix*, Figure 2.2: 18; North Region Plates 12: 3–6, 13: 1, 2

Pollen grains spherical, 63–79 μm in diameter; non-saccate and inaperturate; sexine clearly thicker than nexine, sometimes exine 3-layered seen under microscope with 600 times of magnification; sexine without sculpture; however, very fuzzy and faintly granular spots on grain surface visible under oil immersion; sexine often folded or ruptured.

**Betulaceae**

*Alnus*, Figure 2.2: 1; North Region Plate 26: 5–16

Pollen grains oblate, 22–38 μm in equatorial diameter; wide elliptic in equatorial view, concave obtuse (4–5) 5-sided in polar view; 4–5 pores; pore structure very special; exine distinctly 2-layered, sexine

**Modern distribution** Deciduous tree; widely distributed in the mountains of northeastern and southwestern China; usually pure coniferous forests at altitudes of 3800–4000 m on high-cold mountains.

**Fossil distribution** Holocene strata in Changbai Mountains and Huinan of Jilin, Pleistocene strata in Yushe of Shanxi.
Figure 2.2 Photomicrographs of major pollen types in north region


protruding out of the outline of pollen grain; nexine and sexine separated at the edge of pore to form a large and inverted funnel-shaped vestibulum; in the optical section, sexine thickened at the pores, prominent arcus extending between the pores; grain surface psilate.

**Modern distribution**  Tree or shrub; widely distributed in China except Northwest China, and most species found in eastern and northern China.

**Fossil distribution**  The earliest deposits in which fossil pollen has been recorded are the upper Cretaceous strata in northeastern China, and then in Paleogene–Neocene, and Quaternary strata mainly in northeastern and southwestern China.

Betula, Figure 2.2: 2, 3; North Region Plates 26: 17–19, 27: 1–19

Pollen grains suboblate to oblulate; obtuse 3–5-sided in polar view; wide elliptic in equatorial view; ca.
Major Types of Quaternary Pollen and Spores and Their Characteristics in Different Regions of China

21.5–40 (59) μm in equatorial diameter; 3–5 pores; sexine rising to form protruding pores; both sexine and nexine thickened to form vestibulum; nexine of some species indistinctly thickened or not thickened, no vestibulum formed; grain surface granular.

**Modern distribution**  Deciduous tree or shrub; mainly distributed in North, Southeast, and Southwest China.

**Fossil distribution**  The earliest deposits in which fossil pollen has been recorded are the upper Cretaceous strata in northeastern China, and then the Miocene strata in Shanwang of Shandong, and Quaternary strata widely in China.

*Carpinus*, Figure 2.2: 5; North Region Plate 28: 7–10

Pollen grains nearly spherical to oblate; the polar axis slightly shorter than the equatorial diameter, the equatorial diameter ca. 25–43 μm; nearly circular to wide elliptic in equatorial view; circular in polar view; 3 or 4 pores; sexine of pores generally not thickened (slightly thickened for individual cases), more or less elevated to protrude out of the outline; nexine not thickened, often interrupted at the elevated place of sexine; sometimes the boundary between sexine and nexine indistinct; exine relatively thinner than that of *Betula* and *Alnus* pollen grains, with granules.

**Modern distribution**  Tree; widely distributed in China.

**Fossil distribution**  The earliest deposits in which fossil pollen, leaves, and small nuts have been recorded are the upper Paleogene-Neogene strata in northeastern China; and then the Miocene strata in Shanwang of Shandong, and Quaternary strata widely in China.

*Corylus*, Figure 2.2: 4; North Region Plate 28: 11–17

Pollen grains nearly spherical to oblate; the equatorial diameter ca. 23–40.5 μm; 3–4 pores; sexine of pores not thickened, slightly elevated, not as protruding as those of *Betula* and *Carpinus* pollen grains; exine granular.

**Modern distribution**  Small tree or shrub; distributed in North China and Southwest China.

**Fossil distribution**  The earliest deposits in which fossil pollen has been recorded are the Cretaceous strata, and then in the Neogene to Quaternary strata in Liaoning, Yunnan, Guizhou, and Sichuan.

**Rosaceae**

*Dryas octopetala*, Figure 2.2: 6, 7; North Region Plate 57: 1–20

Pollen grains ellipsoidal; nearly circular in polar view, ca. 30.8 μm in diameter; elliptic in lateral view, ca. 36.4 μm × 30.1 μm in size; 3 colpi, long up to two poles, with a poroid in the middle; exine 2-layers, sexine thicker than nexine; finely granular, granules arranged in irregular stripes.

**Modern distribution**  Small shrub; only distributed in tundra meadows at elevations of ca. 2200 m in Changbai Mountains of Jilin.

**Fossil distribution**  Holocene strata in Changbai Mountains and Late-Pleistocene strata in Huinan of Jilin, and Holocene strata in Heilongjiang.

*Sanguisorba*, Figure 2.2: 8, 9; North Region Plate 58: 13–19

Pollen grains ellipsoidal; round in polar view, and elliptic or nearly circular in lateral view; 32.3 (20.3–35) μm × 28.7 (28–30.3) μm in size; two types of aperture, one 6-colporate, another 3-colporate; colpi long and thin; endoaperture lalongate and wide; exine thick, 2-layered; sexine significantly thicker than nexine, with distinct columellae; surface with fine reticula.

**Modern distribution**  Perennial herb; widely distributed in the hillsides and grasslands in China.

**Fossil distribution**  Quaternary deposits in North China.

**Ulmaceae**

*Ulmus*, Figure 2.2: 15; North Region Plate 61: 2–19

Pollen grains oblate; 31 (28–34) μm × 36.5 (29.5–39.5) μm or 22 (21–22.5) μm × 27.5 (25.5–29.5) μm in size; 4–6 pores, mostly 5 pores; pores relatively small and nearly circular; sexine with brain-striate sculpture; the outline undee.

**Modern distribution**  Deciduous tree; distributed in mixed hardwoods in hills and mountains of North, Northwest, South, and Southwest China.

**Fossil distribution**  Quaternary deposits at many sites in China.
**Southeast Region**

### 2.3 Southeast Region

#### 2.3.1 Types of Quaternary pollen and spores in southeast region

Southeast region includes Anhui, Jiangsu, Zhejiang, and Shanghai in the lower reaches of the Yangtze River as well as Fujian and Taiwan. Located in the subtropical evergreen broadleaved forest zone, the vegetation in southeast region mainly consists of deciduous broad-leaved forests with some evergreen broad-leaved species in the Huaiyang and Jianghuai hills and plains; evergreen oak forests, oil camellia forests, and pine forests in the southern hills of the Yangtze River; evergreen oak forests and pine forests in the mountains of Zhejiang and Fujian; and southern subtropical evergreen broad-leaved forest with ingredients of rainforests in central and northern Taiwan Island. There is a diversity of constructive and dominant species of subtropical vegetation. The climate in southeast region is marked by four distinct seasons with evenly distributed dry and rain seasons. Abundant pollen and spore types have been recorded in a large number of Quaternary pollen records from lacustrine sediments, peats, and sections at archaeological sites in southeast region. A total of 157 families and about 600 genera are included in this book. We collected the photomicrographs of these pollen and spores. Most of them are fossils and subfossils, and a small part of them are modern. We then compiled these photomicrographs into 108 plates. These plates cover 6 families of algae spores, 2 families of bryophyte spores, 23 families of pteridophyte spores, 6 families of gymnosperm pollen, and 117 families of angiosperm pollen.

The regional vegetation revealed by those pollen and spore types shows the following features: ①A great diversity of subtropical plant components in the regional vegetation. Among them, most plants are evergreen trees, and many are even constructive or dominant elements of vegetation formations. In the plates, evergreen and deciduous broad-leaved elements include *Cyclobalanopsis*, *Quercus* (E), *Quercus* (D), *Castanopsis*-Lithocarpus, *Fagus*, *Carpinus*, *Platycarya*, *Pterocarya*, *Juglans*, *Betula*, *Corylus*, *Ulmus*, *Altingia*, *Celtis*, *Pistacia*, *Liquidambar*, *Hamamelidaceae*, *Myrica*, *Ilex* and so on. ②The occurrence of many aquatic and hygrophilous herbs (close to 20 families) reveals the typical warm and humid subtropical climate conditions. Aquatic and hygrophilous herbs include *Cyperaceae*, *Typha*, *Myriophyllum*, *Potamogeton*, *Alisma*, and *Azolla*. The common pollen and spore types are summarized in Table 2.10.

<table>
<thead>
<tr>
<th>Plant life form</th>
<th>Pollen and spore type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees</td>
<td><em>Pinus, Cyclobalanopsis, Quercus, Castanopsis-Lithocarpus, Fagus, Carpinus, Platycarya, Pterocarya, Juglans, Betula, Corylus, Ulmus, Altingia, Celtis, Pistacia, Liquidambar, Hamamelidaceae, Myrica, Ilex</em></td>
</tr>
<tr>
<td>Upland herbs</td>
<td><em>Poaceae, Artemisia, Compositae, Cruciferae, Polygonum</em></td>
</tr>
<tr>
<td>Aquatic and hygrophilous herbs</td>
<td><em>Cyperaceae, Typha, Myriophyllum, Potamogeton, Alisma, Azolla</em></td>
</tr>
<tr>
<td>Ferns</td>
<td><em>Dichroandriris, Pteris, Polypodium, Hicriopteris, Lygodium, Adiantum, Selaginella, Pteridium, Microlepia</em></td>
</tr>
<tr>
<td>Algae</td>
<td><em>Pediastrum, Zygnema, Dinoflagellate</em></td>
</tr>
</tbody>
</table>
2.3.2 Identifiable features of major Quaternary pollen and spores in southeast region

2.3.2.1 Identifiable features of pollen morphology for Fagaceae

Quaternary strata in southeast region contain a lot of pollen types. Among them, the dominant pollen types are forest components from Fagaceae. Nowadays, Fagaceae is an important group of the subtropical forests in the eastern monsoonal region of China. It is also one of the oldest angiosperm groups as well as one of the angiosperm groups with the most abundant fossils. Since the Cenozoic, it has been a main component of the flora in the strata of the northern and southern hemispheres, especially the middle and low latitudes (Wang and Pu, 2004).

Fagaceae pollen in China can be generally divided into three main types, i.e., Castanea type, Quercus type and Fagus type. These three pollen types are from three subfamilies of Fagaceae: Castaneoideae, Quercoideae, and Fagoideae. Pollen grains of Quercus type are oblate or subspheroidal, with large size and coarse ornamentation; pollen grains of Fagus type are large and round, with distinct poroids or pores; pollen grains of Castanea type are prolate to perprolate, small size, and obscurely ornate. The details of pollen morphology for these three pollen types are summarized as follows.

1. Quercus type

From the ecological standpoint, Quercus generally includes deciduous and evergreen oaks, i.e., Quercus (D) and Quercus (E). However, the latter in fact comprises evergreen oak and Cyclobalanopsis. In actual identification process of fossil pollen, it is difficult to distinguish between them because of the occurrence of transitional pollen types between them. Furthermore, sclerophyllous oak is very common in Southwest China and southeastern Tibetan Plateau. From the pollen morphology, sclerophyllous oak pollen belongs to Quercus (E) and should be distinguishable from Cyclobalanopsis pollen. The exact separation of Quercus (D) and Quercus (E) pollen is possible by the size and pattern of granular ornamentation at the high magnification with the aid of scanning electron microscope.

2. Castanea type

Three genera of the Castaneoideae (Castanea, Castanopsis, and Lithocarpus) have relatively small pollen and very few morphological differences, thus it is difficult to identify them to the level of the genus. Wang and Pu (2004) attempted to distinguish them in their study of pollen morphology of Castaneoideae. Pollen grains of Castanea are the smallest in size, with protruding and bulging pore area and edge at the equatorial axis, and grains have striate or rugulate ornamentation. Pollen grains of Castanopsis are the largest in size and have blunt ends at the polar areas, and grains are without striate or rugulate ornamentation. Pollen grains of Lithocarpus are the middle in size and slight acute at polar areas, and grains have striate ornamentation. From the ecological perspective, deciduous arboreal Castanea is often distributed in the temperate or subtropical regions at higher altitudes, whereas evergreen Lithocarpus and Castanopsis are important constructive components of forests in the subtropics, especially in the middle and southern subtropics.

In addition, the small pollen grains of Castaneoideae are easily lost when filtered by 10 μm aperture sieve in the process of pretreatment, thus it is better to use the 5‒7 μm aperture sieve.

3. Fagus type

Pollen grains of Fagus are large in size (39–42 μm), 3-colporate; the colpi are short and acuminate; endoapertures are large, with pore membrane. It is easy to distinguish them from other pollen types by these pollen features.

2.3.2.2 Identification key of pollen morphology to several genera of Fagaceae

Having considered the importance of Fagaceae pollen and the difficulty in pollen identification, we list the identification key to major genera or pollen groups in Fagaceae below to distinguish them:
1. Pollen grains prolate; 3-colporate; small in size, the largest diameter generally less than 21 μm.
2. Polar axis 14–20 μm, equatorial diameter 8.5–13.5 μm.
3. Endoaperture lalongate, located at the middle of the colpi, and the connective part between endoaperture and colpus constricted, sexine surface with finely reticulate or granular ornamentation ——— Castanea
4. Pollen grains spheroidal 3-colporate; pores indistinct; sexine surface with granular ornamentation; outline undee ——— Lithocarpus

2. Polar axis 15–21 μm (sometimes up to 27.5 μm), equatorial diameter 8.5–13.5 μm (sometimes up to 18.6 μm). Endoaperture lalongate, thin colpi with sharp tips close to the polar; sexine surface with indistinct reticula ——— Castanopsis

1. Pollen grains oblate, spheroidal or prolate; large in size (more than 24 μm); 3-colporate or 3-colporoidate, or 3-colpate without endoaperture.
2. Pollen grains oblate or spheroidal; larger in size (39–42 μm); 3-colporate, colpi short and acuminate; endoaperture large, slightly elliptic, and with membranes, exine slightly thickened near the endoapertures ——— Fagus
3. Pollen grains mostly spheroidal; 3-colporate; less than 26 μm × 23.5 μm in size; sexine surface with smooth or granular ornamentation; outline slightly undee.
4. Pollen grains prolate; 3-colporoidate; less than 26 μm × 23.5 μm in size; sexine surface with smooth or granular ornamentation; outline slightly undee.
5. Pollen grains spheroidal 3-colporate; pores indistinct; sexine surface with granular ornamentation; outline undee ——— Cyclobalanopsis

2.3.2.3 Comparison of identifiable features of the pollen morphology among several common and confusable genera of Fagaceae

Castanea, Castanopsis, Lithocarpus, Cyclobalanopsis, and Quercus (E) in the Fagaceae are common in Quaternary strata in southeast region. However, they are also confusable in pollen morphology to be easily distinguished. Table 2.11 shows a comparison of their pollen morphology in terms of pollen size, shape, ornamentation and other characteristics.

2.3.2.4 Identifiable features of pollen morphology for several common and confusable genera in tropical and subtropical regions

1. Comparison of pollen morphology of Aquifoliaceae, Celastraceae, and Oleaceae

Aquifoliaceae, Celastraceae, and Oleaceae are common shrubs or trees in regions south of the Yangtze River in China. Their pollen grains frequently appear in Quaternary strata in tropical and subtropical regions. However, it is not easy to distinguish them because of their similar pollen morphology. Here, we selected Ilex, Celastrus, and Osmanthus as representative genera of Aquifoliaceae, Celastraceae, and Oleaceae, respectively, for a comparison of their pollen morphology (Table 2.12).

2. Comparison of pollen morphology of Anacardiaceae, Araliaceae, and Rutaceae

The Anacardiaceae, Araliaceae, and Rutaceae plants are also common shrubs or trees in regions south of the Yangtze River in China. Their pollen grains also frequently appear in Quaternary strata in tropical and subtropical regions. Again, it is not easy to distinguish them due to their similar pollen morphology. We selected Rhus, Aralia, and Evodia as representative genera of Anacardiaceae, Araliaceae, and Rutaceae, respectively, for a comparison of their pollen morphology (Table 2.13).
### Table 2.11  A comparison of identifiable features among 5 common and confusable pollen types of Fagaceae

<table>
<thead>
<tr>
<th>Genera</th>
<th>Castanea</th>
<th>Lithocarpus</th>
<th>Castanopsis</th>
<th>Cyclobalanopsis</th>
<th>Quercus (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Photomicrographs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="Castanea" /></td>
<td><img src="image" alt="Lithocarpus" /></td>
<td><img src="image" alt="Castanopsis" /></td>
<td><img src="image" alt="Cyclobalanopsis" /></td>
<td><img src="image" alt="Quercus" /></td>
<td></td>
</tr>
<tr>
<td><strong>Shape</strong></td>
<td>Prolate; flat at both ends in equatorial view; 3-lobed circular in polar view</td>
<td>Prolate; obtusely triangular in polar view</td>
<td>Prolate spheroidal with two-lobed circar in polar view or obtusely triangular in polar view</td>
<td>Prolate</td>
<td>Spheroidal or sub-spheroidal</td>
</tr>
<tr>
<td><strong>Average size</strong></td>
<td>15.6 μm × 10 μm (smallest)</td>
<td>16 μm × 19 μm (smaller)</td>
<td>17.8 μm × 13.3 μm (moderate)</td>
<td>23.1 μm × 12 μm (larger)</td>
<td>24.8 μm × 12.5 μm (largest)</td>
</tr>
<tr>
<td><strong>Aperture</strong></td>
<td>3-colporate; aperture lalongate or circular</td>
<td>3-colporate; equatorial area of aperture slightly convex; colpi thin, long</td>
<td>3-colporate; aperture lalongate or elliptic, with cavity</td>
<td>3-colporate; colpi slightly narrowed at their middle part, wide and long</td>
<td>3-colporate or 3-colporate; pori indistinct</td>
</tr>
<tr>
<td><strong>Sculpture</strong></td>
<td>Very fine, nearly smooth</td>
<td>Obscurely granulate</td>
<td>Very fine</td>
<td>Finely or coarsely granulate</td>
<td>Coarsely granulate and distinct</td>
</tr>
</tbody>
</table>

### Table 2.12  Morphological comparison of Ilex, Celastrus and Osmanthus pollen

<table>
<thead>
<tr>
<th>Genera</th>
<th>Ilex</th>
<th>Celastrus</th>
<th>Osmanthus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Photomicrographs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="Ilex" /></td>
<td><img src="image" alt="Celastrus" /></td>
<td><img src="image" alt="Osmanthus" /></td>
<td></td>
</tr>
<tr>
<td><strong>Shape</strong></td>
<td>Prolate to sub-spheroidal</td>
<td>Spheroidal to sub-spheroidal</td>
<td>Prolate to sub-spheroidal</td>
</tr>
<tr>
<td><strong>Average size</strong></td>
<td>25 μm × 24 μm</td>
<td>22.5 μm × 25.5 μm</td>
<td>19.5 μm × 22 μm</td>
</tr>
<tr>
<td><strong>Aperture</strong></td>
<td>3(4)-colporate; aperture laonrgate, colpi wide</td>
<td>3-colporate; colpi wide, with colpus membrane and two sharp ends; aperture large, elliptic, slightly lalongate</td>
<td>3-colporate; aperture indistinct</td>
</tr>
<tr>
<td><strong>Sculpture</strong></td>
<td>Distinct verruca or clava</td>
<td>Distinct reticula with irregular meshes</td>
<td>Fine reticula</td>
</tr>
</tbody>
</table>
2.3.3 Descriptions of morphological features for major Quaternary pollen and spores in southeast region

2.3.3.1 Photomicrographs of major Quaternary pollen types in southeast region

There are various subtropical plants in composition, especially evergreen or deciduous broad-leaved trees, in southeast region. Here we list some pollen types as their representatives, including arboreal pollen types such as *Castanea*, *Castanopsis*, *Lithocarpus*, *Cyclobalanopsis*, *Quercus* (E), *Quercus* (D), *Fagus*, *Liquidambar*, *Ilex*, *Symplocos*, *Pistacia*, *Rhus*, *Pterocarya*, and so on; and herbaceous pollen types such as *Typha* and *Cyperaceae* from swampy or aquatic plants in plains (Figure 2.3).

2.3.3.2 Descriptions of morphological features for major Quaternary pollen types in southeast region

**Fagaceae**

*Quercus*, Figure 2.3: 7, 8; Southeast Region Plate 56: 1–22

*Quercus* is the most widely distributed genus of Fagaceae, and mainly distributed in Asia. It is the dominant component of evergreen broad-leaved forest and evergreen and deciduous broad-leaved mixed forest in subtropical and temperate zones of the Northern Hemisphere. It contains about 160 species in China. Traditionally, these species are classified into subgenus *Quercus* and subgenus *Cyclobalanopsis*.

Pollen grains of *Quercus* mostly subspheroidal, rarely subprolate or suboblate; 16.8–50.4 μm in size; 3-colporate or 3-colporoidate, rarely 3-colporate; pores indistinct; colpi distinct, with obtuse ends; exine 2-layered, 0.4–1.8 μm thick; sculpture verrucate or granulate-spinulate.

*Quercus* (D): Pollen grains spherical; 27.36–42 μm × 25.2–33.6 μm in size; 3-colpate, rarely 3-colporoidate; colpus surface with distinctly coarse granula; exine 2-layered, sexine thicker than nexine, thickened at mesocolpia; sculpture circularly or oblately verrucate granulate.

*Quercus* (E): Pollen grains spherical, 25.2–33.6 μm × 18.9–29.4 μm in size; 3-colporoidate, rarely 3-colpate; exine 2-layered, sexine thicker than nexine,
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thickened at mesocolpia; sculpture distinctly granulate, or indistinctly and finely granulate, or granulate-spinulate.

*Cyclobalanopsis*: Pollen grains spheroidal; 23.1‒31.5 μm × 21‒25.2 μm in size; 3-colporate, rarely 3-colpate; exine 2-layered, sexine thicker than nexine; sculpture distinctly granulate or indistinctly and finely granulate, or granulate-spinulate.

**Modern distribution**  Evergreen and deciduous trees; important components of various forests distributed in all provinces of China.

**Fossil distribution**  The Quaternary strata of Southeast China; *Quercus* type pollen generally as the dominant pollen of fossil pollen spectra, for example, from Quaternary deposits of Dajiuhu wetlands in Shennongjia, Jianghan Plain, the lower reaches of the Yangtze River, Fujian mountainous region and its coastal plain.

*Lithocarpus, Castanopsis and Castanea*, Figure 2.3:

1‒4; Southeast Region Plates 53: 15‒24, 54: 1‒14, and 55: 17‒33

Subfamily Castaneoideae consists of *Lithocarpus, Castanopsis*, and *Castanea*.

Pollen grains of Castaneoideae are prolate (P/E=1.22‒1.42); small in size (20‒22 μm × 14‒18 μm); 3-colporate, colpi long and pores small; pores lalongate or elliptic, exine near pores thickened and protruding to form distinct or indistinct vestibulum; polar area round; sculpture psilate in LM, indistinctly striate or finely...
striate in SEM.

**Modern distribution**  Evergreen or deciduous tree; widely distributed in hilly regions at low elevations of temperate, subtropical, and tropical zones.

**Fossil distribution**  Castaneoideae type pollen are widely distributed in the Quaternary strata of Southeast China, especially the strata since the last glacial period such as the Holocene strata in the middle and lower reaches of the Yangtze River, Fujian, and Zhejiang.

*Fagus*, Figure 2.3: 9, 10; Southeast Region Plate 55: 1–16

Pollen grains spheriodial, or subspheroidal, or suboblate; generally >30 μm in size, close to or larger than 50 μm, the largest size in pollen grains of Fagaceae; 3-colporate, rarely 4-colporate; colpi generally thin and long, about 3–6 times as the diameter of the aperture; pores large and circular; exine 2-layered, thin; sculpture granulate or striate.

**Modern distribution**  Tree of the canopy layer in deciduous broadleaved forest or evergreen and deciduous broadleaved forest; often growing in the north-facing slopes or shady slopes of mountains, and favoring sandy soils; five species in China, distributed in regions east of the Tibetan Plateau, south of the Yellow River, and north of the southern slopes of Wuling Mountains; also distributed in regions from northeast and southeast Yunnan to Saba area in northeast Vietnam.

**Fossil distribution**  *Fagus* type pollen has been recorded in some Quaternary strata of Southeast China, but generally at low frequencies; slightly more abundant in the middle Pleistocene strata in Fengxian of Shanghai, the late Pleistocene strata in Pinnan of Fujian, and the Holocene strata in the Dajiuhu wetland of Shennongjia, Hubei; infrequently found in the Holocene strata of the Yangtze River Delta.

**Hamamelidaceae**

**Liquidambar,** Figure 2.3: 14; Southeast Region Plate 59: 15–22

Pollen grains spherical; 48 (38.5–57) μm in diameter; pantoporate, with 10–15 pores; pores oval or round, variable in size, 4.3–10.7 μm in diameter, distance between pores 4.3–12.9 μm, porus membrane coarsely granulate; sexine thicker than nexine; sculpture granulate.

**Modern distribution**  Tree; distributed in provinces south of Qinling Mountains and Huaihe River, west of Taiwan, east of Sichuan, Yunnan, and Xizang; also found in northern Vietnam, southern Laos, and DPR Korea.

**Fossil distribution**  *Liquidambar* type pollen common in the Quaternary strata of subtropical and tropical regions, such as Jiangsu, Zhejiang, Fujian, Hubei, Hunan, and so on; but generally at low frequencies.

**Comments**  It is difficult to distinguish *Liquidambar* from *Altingia* due to the similarities in their pollen morphology. Generally, the former is larger in size with more pores, whereas the latter is smaller in size with fewer and larger pores. *Altingia* pollen increases gradually in the Quaternary strata of the middle subtropical zone, especially the southern subtropical zone.

**Ulmaceae**

**Celtis,** Figure 2.3: 17; Southeast Region Plate 104: 17–22

Pollen grains oblate; 20–30 μm × 25–35 μm in size; 3-porate, rarely 4–5 porate; pores small, narrowly elliptic; subtriangular to circular in polar view; exine surface granulate.

**Modern distribution**  Deciduous tree; favoring sunlight, resistant to dry conditions and poor soils, but intolerant to saline-alkali soils; distributed in all provinces except Qinghai and Xinjiang of China.

**Fossil distribution**  The Quaternary strata of the Jianghan Plain, lower reaches of the Yangtze River, Fujian, and Zhejiang.

**Anacardiaceae**

**Pistacia,** Figure 2.3: 16; Southeast Region Plate 27: 5

Pollen grains spherical or spheroidal; uniform in size, 30 μm in diameter; pantoporate, with 4–8 pores irregularly distributed; pori elliptic, with rough edge exhibiting ruminate; exine 2-layered, sexine thicker than nexine; exine surface reticulate, lumina uniform, and
Chapter 2  Major Types of Quaternary Pollen and Spores and Their Characteristics in Different Regions of China

Aquifoliaceae

*Ilex*, Figure 2.3: 19; Southeast Region Plate 29: 1, 2

Pollen grains prolate, spheroidal or oblate; 3-lobed circular in polar view; 18‒40 μm × 18‒38 μm in size; 3-colporate, colpi wide; endoaperture lalongate and narrow, usually indistinct; exine relatively thick, sexine thicker than nexine or as thick as nexine; exine surface distinctly tuberculate, tubercula densely distributed.

**Modern distribution** Tree or shrub; about 200 species in China, mainly distributed in the vast regions south of the Qinling Mountains and the Yangtze River; most abundant in Southwest and South China.

**Fossil distribution** The Quaternary strata in Hubei, Hunan, Jiangsu, Zhejiang, Anhui, Fujian, and North China.

Myricaceae

*Myrica*, Figure 2.3: 18; Southeast Region Plate 75: 24–26

Pollen grains oblate; 20‒25 μm × 23‒30 μm in size; obtusely triangular in polar view, each corner with one porus, widely elliptic in equatorial view; 3‒4-porate, large atrium, endoaperture much larger than ectoaperture; sexine slightly thickened and protruding at pores; inner aspis distinctly serrated, shaped like “the hind legs of an insect”; sexine surface granulate.

**Modern distribution** Tree or shrub; widely distributed in all provinces; often found in wetlands or swamps; Cariceale frequently growing in Northeast, Northwest, and North China or alpine region of Southwest China; fewer species in South China.

**Fossil distribution** The Quaternary strata of Southeast China; a large number of *Myrica* pollen grains in strata from peatlands and wetlands in Dajiuhu of Shennongjia, Jianghan Plain, the middle and lower reaches of the Yangtze River, and Fujian coastal plain.

Cyperaceae

*Typha*, Figure 2.3: 20; Southeast Region Plate 104: 1‒9

Pollen grains irregular, spherical, ellipsoidal or obtuse triangular; 20‒40 μm × 18‒40 μm in size; one porus at distal pole; exine 2-layered, sexine thicker than nexine; sexine surface reticulate, with granulate muri; pollen grains of some species in tetrad.

**Modern distribution** Evergreen or deciduous, marsh, aquatic, or hygrophilous herb; ca. 16 species, mainly distributed in tropical to temperate zones of Eurasia and North America, and 3 species in Oceania; 11 species in China, widely distributed in all provinces, more species in temperate regions.

**Fossil distribution** The Quaternary strata of Southeast China; a large number of *Typha* pollen grains...
in strata from the wetlands of Jianghan River Plain, the middle and lower reaches of the Yangtze River, and coastal plains.

2.4 South Region

2.4.1 Types of Quaternary pollen and spores in south region

This region includes Guangdong, Guangxi, and Hainan Island. Tropical seasonal monsoonal climate prevails from Guangdong to western Guangxi. This monsoonal climate is characterized by high temperature and rainfall as well as distinct wet and dry seasons, thus it shapes regional vegetation of subtropical evergreen broadleaved forests. In the southern Leizhou Peninsula and Hainan Island, the climate is typically tropical monsoonal with high temperatures and rainfall. The climate supports tropical semi-evergreen seasonal rainforests and tropical seasonal rainforests, composed of rich flora forming diverse vegetation types. Around 90 families are included in the palynomorphs based on the published literature (Lü et al., 2003a; Mao et al., 2006, 2012; Li et al., 2008; Yang et al., 2015). Lü et al. (2003a) found rich pollen and spores well preserved in Huguangyan Marr Lake. Mao et al. (2006) and Li et al. (2008) investigated pollen types and their relation with vegetation using surface samples from mangrove wetlands, supported by pollen reference materials collected from living plants (Mao et al., 2008, 2009, 2012). Recently Meng et al. (2017) identified 138 families and genera of pollen, including 93 arboreal taxa, 24 non-arboreal taxa, 5 aquatic taxa, and 16 fern taxa. Based on plant ecology and modern distributions, the pollen fossils were classified into six groups: ① montane conifer taxa, including Pinus, Podocarpus, and Dacrydium; ② tropical rainforest tree taxa, including Menispermaceae, Ficus, Moraceae, Mallotus, Phyllanthus, Euphorbiaceae, Melastomataceae, and Rubiaceae; ③ subtropical evergreen broadleaved taxa, such as Cyclobalanopsis, Castanopsis-Lithocarpus, Altingia, Hamamelidaceae, Myrica, Rutaceae, Ilex, Oleaceae, Anacardiaceae, and Araliaceae; ④ montane deciduous broadleaved taxa, including deciduous Quercus, Castanea, Betula, Alnus, Corylus, Carpinus, Juglans, Ulmus and Fagus; ⑤ herbaceous taxa, with Poaceae and Artemisia as major components and Porana, Compositae, Cyperaceae, and Chenopodiaceae as minor elements; ⑥ aquatic taxa, such as Halorraghis, Myriophyllum, Polygonum, and Typha. Moreover, a few samples contained fern spores, such as Polypodiaceae, Microlepia and Pteris, whereas others contained algae, such as Pediastrum and Concentricystes.

The common identified pollen types are listed in Table 2.14. All the pollen plates for this region are illustrated in the South Region Plates (1-44). For some representative pollen taxa in the region, pollen identification keys and illustrations are also presented in this book (see section 2.4.2 below).

<table>
<thead>
<tr>
<th>Life form &amp; Group</th>
<th>Palynomorph types</th>
</tr>
</thead>
<tbody>
<tr>
<td>ArboREAL</td>
<td>Pinus, Dacrydium, Podocarpus, Keteleeria, Tsuga, Taxodiaceae, Cycadaceae, Fagus, Carpinus, Platyctena, Alnus, Pterocarya, Juglans, Betula, Corylus, Caryya, Ulmus, Quercus, Castanopsis-Lithocarpus, Altingia, Hamamelidaceae, Myrica, Rutaceae, Ilex, Oleaceae, Anacardiaceae, Myrsinaceae, Araliaceae, Sapindaceae, Symphoconis, Placouartia, Engelhardia, Celastraceae, Menispermaceae, Ficus, Elaeocarpus, Syzygium, Moraceae, Mallotus, Phyllanthus, Randa, Cribbiodendron, Apocynaceae, Pierloobium, Palmae, Aporosa, Helicia, Rhodomyrtus, Creaton, Alichacea, Breynia, Euphorbiaceae, Loranthaceae, Melastomataceae, Pterospermum, Acanthaceae, Combretaceae, Elaeocarpaceae, Meliaceae</td>
</tr>
<tr>
<td>COASTAL TAXA</td>
<td>Sonneratia, Avicennia marina, Rhizophora, Bruguierea, Ceriops, Kandelia, Aegiceras, Clerodendrum inerme, Scyphihora, Xylocarpus, Gerbera manghas, Hibiscus (Hibiscus tiliaxus), Heritiera</td>
</tr>
<tr>
<td>Herbs</td>
<td>Amaranthaceae/Chenopodiaceae, Caryophyllaceae, Labiatae, Convolvulaceae, Compositeae, Iris, Brassicaceae, Polygonum, Rubiaceae, Verbenaceae, Rumunculaceae, Umbelliferae, Pooaceae, Artemisia, Commellina, Smilax, Arisaeae, Sciruraceae</td>
</tr>
<tr>
<td>WetLAND and aquatic taxa</td>
<td>Cyperaceae, Nymphaea, Typha, Myriophyllum, Potamogeton, Alisma, Acorus</td>
</tr>
<tr>
<td>FERNS</td>
<td>Acrodictum, Dicranopteris, Pteris, Polypodium, Hicrioteris, Lygodium, Adiantum, Cyclosorus, Cibotium, Cyathea, Schizaea, Selaginella, Osmunda, Pteridium, Microlepia</td>
</tr>
</tbody>
</table>
2.4.2 Identifiable features of selected Quaternary pollen and spores in south region

There are rich pollen taxa with high diversity of pollen morphology from south region; for example, coastal mangroves (dominated by Sonneratia and Rhizophora) and conifers (mainly dominated by Dacrydium and Podocarpus) from tropical mountain rainforests. Such special pollen taxa have good palaeoecological and palaeoenvironmental indication according to their unique habitats. In this book, mangrove pollen frequently occurring in estuarine sediments are selected for identification guides according to detailed diagnostic keys, as well as brief introduction on recent geographical distribution, palaeoecological significance, and past biogeographical information.

2.4.2.1 Modern distribution and paleophytogeography of Sonneratia and its identifiable features of pollen morphology

1. Modern distribution and paleophytogeography

Sonneratia (mangrove apple) is an endemic genus in the Indo-West Pacific (IWP) region, which grows along the frontal margins of estuarine mangrove swamps or tidal inlets and bays from coastal tropical East Africa to Indo-Malaysia, South China, New Guinea, Australia, and islands in the Western Pacific. Sonneratia grows mostly along the banks of tidal rivers, creeks, and within the sheltered bays of offshore islands and reef cays. It is a typical constituent of mangrove communities throughout its geographical range. Living Sonneratia consists of nine species, including three putative hybrids, namely Sonneratia alba, S. apetala, S. caseolari, S. griffithii, S. guingai, S. hainanensis, S. lanceolata, S. ovata, and S. urama. In China, there are 6 species (Sonneratia alba, S. apetala, S. caseolari, S. guingai, S. hainanensis, S. ovata) in the genus, including one species (S. apetala) introduced from Bangladesh since late 1980s, and two hybrids (S. guingai and S. hainanensis). The natural distribution is confined to Qinglan Harbor (Wenchang) and southern Hainan Island.

Ancestral Sonneratia (Florschuetzia) migrated from the center of origin in southeastern Asia probably during early Eocene, and radiated and expanded northward to China and Japan, southward to Australia, and westward to east Africa. Until the warmer period of the early middle Miocene (Langhian), Sonneratia had the largest geographical range suggested by abundant fossil pollen from southern mainland China and southwestern Japan, outside of the modern latitudinal limit of this genus. In early Quaternary, the prevalence of tropical warm condition is indicated by pollen records of Sonneratia cf. alba along the coasts of northern South China Sea (SCS), which suggests Sonneratia expanded beyond current latitudinal limits (Wang and Zhang, 1998; Zheng and Li, 2000). High sea level stands during the warm period maintained the vegetation zonation and the structure of mangrove ecosystem. However, sea-level dropped sharply as a result of subsequent glaciations in the late Pleistocene, especially during the Last Glacial Maximum (LGM). The mangroves and their sedimentation settings failed to keep up with the pace of sea level lowering and the resultant loss of intertidal habitats. Therefore, Quaternary glaciations, especially the LGM of the late Pleistocene (21–18 ka), played a significant role in shaping the current distribution range of Sonneratia in southern China (Zheng and Li, 2000; Mao and Foong, 2013).

2. Identifiable features of pollen morphology

Sonneratia is a tree, and different species prefer to grow from the upper part to the lower part of estuaries. It can be the dominant communities in mangrove forests. Their pollen grains are moderately large with distinctive morphology, easily identifiable in Quaternary sediments. Moreover, Sonneratia pollen are major contributors to the organic matter preserved in estuarine and marine deposits, which are therefore important indicator of estuarine or offshore settings, and are well recorded in the studies of marine palynology and tropical climate change. Sonneratia can occur in a wide range of sizes, so the characteristics of the tectum, sexine, polar cap, and meridional ridge must be regarded as more important than size for distinguishing these pollen types (Figures 2.4,
Mao et al. (2009) recently discussed some subtypes of the pollen of *S. gulngai* and grouped six species of *Sonneratia* pollen into four types: A, *Sonneratia alba*, *S. hainanensis*, *S. gulngai*; B, *S. caseolaris*; C, *S. ovata*; D, *S. apetala* (Figure 2.4).

**Type A (SA=*Sonneratia alba*, SHA=*S. hainanensis*, SG=*S. gulngai*)**

Pollen grains of *S. alba* are prolate, with distinct meridional ridges extending to polar areas (Figures 2.4, 2.5, arrow pointing); triporate type, hexagonal in polar view, with 3 protruding pores and 3 meridional ridges, alternatively arranged (Figure 2.5). Distinct meridional ridge is diagnostic of this subtype in the genus. *S. hainanensis* has similar characteristics to *S. alba*, but pollen size relatively smaller, pollen wall in polar cap thicker, and pore size smaller than *S. alba* (9.49 μm) (Figures 2.4, 2.5). Polar view of *S. gulngai* is triangular, protruding in three sides; meridional ridge short and twisted; pollen wall in polar cap thick, well stratified (Figures 2.4, 2.5).

**Type B (SC=*S. caseolaris*)**

Diagnostic features of *S. caseolaris* pollen grains are exine structurally discontinuous between equatorial and polar regions (Figure 2.4); meridional ridges absent in mesoporium; sexine in polar regions (over polar cap) with a smooth surface but granulate to verrucate elsewhere; triporate type, pore circular to subcircular, prominently protruding; polar cap bow-like, psilate, but nano-striate sculpture under SEM (Mao et al., 2009).

**Type C (SO=*S. ovata*)**

Triporate type, meridional ridge is shorter than types A and B, but weakly developed or absent. Meridional ridge adjacent to polar areas is sharpened, which can be distinguished from *S. hainanensis* and *S. alba*.

**Type D (SAP=*S. apetala*)**

Pollen equatorial view is nearly spheroidal. Pore size is the largest of all pollen of species of *Sonneratia* (ca. 11.9 μm in diameter); triporate type, and pores are circular and prominently protruding. The tectum is continuous over the entire grain, and exine is sculptured with densely distributed granules and small verrucae, which are diagnostic of this type and can be distinguished from other species in the genus.

*Sonneratia alba* has the largest mean size, while *S. ovata* and *S. gulngai* are the smallest (Figure 2.6). The mean size of *S. apetala* shows the closest relationship between polar and equatorial lengths because it is spheroidal in equatorial view (Figure 2.6). These size differences coupled with the presence or absence of a meridional ridge, variations in the stratification of the polar cap, and the sculptural elements of the sexine are all diagnostic features that can be used to distinguish the three species (Figures 2.4, 2.5, 2.6).

3. Pollen key to *Sonneratia*

1. Grains prolate to spheroidal with distinct or indistinct meridional ridge in mesoporium.
2. Grains prolate, with distinct mesoporium ridge, pore less than 10 μm in diameter.
   3. Meridional ridges irregularly rugulate, porate fields large, mean length of polar axis 59.5 μm..........................*Sonneratia alba*
   3. Meridional ridges irregularly rugulate, mean length of polar axis 51.8 μm......................................................*S. hainanensis*
   3. Meridional ridges variable, usually distorted (twisted), tectum granulate to verrucate over entire grain, mean length of polar axis 41.8 μm..................................................................................................................*S. gulngai*
2. Grains prolate to spheroidal, with indistinct mesoporium ridge, tectum granulate, elements somewhat larger and less well defined over polar areas, columellate structure indistinct .................................................................*S. ovata*
2. Grains spheroidal, diameter of pore more than 10 μm, tectum sculptured with ranules and small verrucae over entire surface of grain ............................................................................................................................*S. caseolaris*
2. Grains spheroidal, diameter of pore more than 10 μm, tectum sculptured with ranules and small verrucae over entire surface of grain ............................................................................................................................*S. apetala*
**Figure 2.4** Pollen morphology of *Sonneratia* and interspecific identification keys (modified from Mao et al., 2009)

Type A: SA=S. alba, SG=S. guangar, SHA=S. hainanensis; Type B: SC=S. caseolaris; Type C: SO=S. ovata; Type D: SAP=S. apetala

**Figure 2.5** Diagnostic characters of species of *Sonneratia* pollen under LM: wall structure in the polar caps, outlines in polar and equatorial view, and mesoporium meridional ridges (arrows) (modified from Mao et al., 2012)
Modern distribution and palaeoecological significance of Rhizophoraceae and its identifiable features of pollen morphology

1. Modern distribution and palaeoecological significance

The Rhizophoraceae, otherwise known as the “mangrove family”, consists of 16 genera and around 120 species of trees and shrubs worldwide. Only about 20 species of four genera, the conspicuously viviparous Bruguiera, Ceriops, Kandelia, and Rhizophora, are found exclusively in mangroves. *Rhizophora* is a pantropical genus and a key member of Rhizophoraceae. China is the home of 6 genera and around 13 species plus 1 variety, including 4 species from Carallia and 1 species from Pellacalyx which occur inland. Thus the bulk of the family (4 genera and 8 species plus 1 variety) are considered to be the main taxa of mangroves.

The “Mangrove family” (mainly Bruguiera, Ceriops, Kandelia and Rhizophora) thrive mostly in tropical and subtropical regions as a result of their adaptation strategies, their ecological dynamics being closely linked to changes in sea level. Some genera (e.g., *Rhizophora*) are anemophilous with high pollen productivity, and pollen grains of *Rhizophora* are an important contributor to the organic materials preserved in estuarine and marine sediments. Therefore, pollen analysis of Rhizophoraceae is important for both palaeoecological reconstructions of coastal vegetation and determinations of palaeoenvironment in tropical and subtropical regions according to many publications. Lots of recent studies based on Rhizophoraceae pollen data from surface sediments and Quaternary deposits have highlighted their importance for palaeoenvironmental interpretation. Coupled with fossil pollen of *Sonneratia*, Rhizophoraceae pollen are strong indicators of estuarine or marine settings. Pollen grains of Rhizophoraceae are normally small; nevertheless, some pollen types show distinct morphological characteristics which aid fossil pollen identification. The following section focuses on pollen identification for Rhizophoraceae.

2. Pollen identification for Rhizophoraceae

Generally, the four genera of Rhizophoraceae,
Bruguiera, Ceriops, Kandelia and Rhizophora, have the following morphological features in common: subprolate–oblate spheroidal shape, tricolporate apertures with an equatorially elongated endoaperture, and a sexine that ranges from psilate to finely reticulate (Figure 2.7; Mao et al., 2012).

Yamanoi (2003) keyed out pollen grains produced by these mangrove taxa to genus level based on equatorial views.

According to Yamanoi (2003), the polar axis of the pollen of Bruguiera gymnorrhiza varies from 15 μm to 18 μm, and the sexine of most grains is faintly and irregularly granulate. The polar axis (P) of pollen of B. sexangula is somewhat larger (17 μm <P< 20 μm) than that of B. gymnorrhiza and B. cylindrica (P< 15 μm), and the sexine is psilate to scabrate. Grain size varies interspecifically and may even vary within a species. Some biotic and abiotic factors may also lead to questionable or anomalous size measurements. However, Bruguiera pollen grains are uniformly very small and differences between species of the genus are indistinct. It is, therefore, difficult to distinguish dispersed Quaternary pollen grains attributed to Bruguiera, although we have referred its pollen to two groups in the pollen keys.

Ceriops pollen grains are the smallest in the Rhizophoraceae family. Their endoapertures are indistinct and discontinuous at the equator, and the sexine is scabrate to weakly granulate and finely perforated. However, their morphology overlaps with that of Bruguiera pollen to some extent. It is necessary to examine specimens at high power under an oil-emersion objective in order to distinguish them.

Kandelia pollen grains are a little larger than those of Bruguiera and Ceriops. Coupled with the constricted structure within the colporium noted above, it is possible to distinguish these from the pollen of other genera within the family.

The morphology of Rhizophora pollen has received particular attention because of the evolutionary importance of the parent plants and their palaeogeographical distribution. Muller and Caratini (1977) reported detailed observations on the morphology of the pollen of six species of Rhizophora and reviewed fossil records and possible affinities. They also commented on the wide variation in the shape of the pollen and a variable degree of fusion of the endoapertures, which may be relatively short with an irregular termination or completely fused to form an annular zone. Based on a limited number of diagnostic criteria, they differentiated three groups: A, R. mucronata and R. stylosa; B, R. apiculata, R. lamarckii and R. mangle; C, R. racemosa.

This grouping is quite close to one based on
pollen morphological examination (Mao et al., 2012). *R. apiculata* can be readily distinguished from *R. stylosa* and *R. mucronata* on the basis of its distinctly stratified exine (Figure 2.7) and perforate to perforate–reticulate sculpture over the whole surface of the pollen grain, but sculptures appear more varied under SEM with three main types: perforate, regulate and reticulate (Mao et al., 2008). However, there is some morphological overlap between *R. mucronata* and *R. stylosa*.

3. Pollen key to Rhizophoraceae

1. Pollen grains with continuous endoaperture (zoneoaperture).
   2. Prolate to spheroidal, pollen wall distinctly stratified, sexine sculpture mainly foveolate to foveo-reticulate — *Rhizophora apiculata*
   2. Oblate spheroidal, pollen wall less well stratified, sexine scabrate to slightly granulate to irregularly pitted — *R. stylosa*
   2. Prolate spheroidal, sexine appears to be finely reticulate under LM, but clearly perforated under SEM, endoaperture less distinct — *R. mucronata*

1. Pollen grains with discontinuous endoaperture in mesocolporium.
   2. Polar axis shorter than 18.5 μm.
      3. Endoaperture indistinct and discontinuous, sexine scabrate to weakly granulate under LM, but seems to be finely foveolate under SEM — *Ceriops tagal*
      3. Endoaperture distinct, sexine psilate, scabrate or weakly granulate under LM, scabrate, pitted or finely granulate under SEM — *Bruguiera spp.*
      2. Polar axis longer than 18.5 μm, sexine with a regulate to irregularly foveolate sculpture, endopore often constricted within colporium — *Kandelia obovata*

2.4.3 Photomicrographs and descriptions of morphological features of major Quaternary pollen and spores in south region

2.4.3.1 Photomicrographs for major Quaternary pollen and spores in south region

Due to the high diversity of fossil pollen flora in south region, only a small portion of representative taxa is selected for brief description here (Figures 2.8–2.10) as an aid to the identification of palynomorphs in this region.

2.4.3.2 Descriptions of morphological features for major Quaternary pollen and spores in south region

**Podocarpaceae**

*Dacrydium*, Figure 2.8: 5; South Region Plates 8: 5, 6; 9: 1–3

In China, *Dacrydium* has only one species (*Dacrydium pectinatum*) on Hainan Island, while fossil pollen grains occur in ①Tianyang crater in Leizhou Peninsula (280,000–180,000 a BP); ②Pleistocene-Holocene sediments from Shuidonggang, Dianbai County, Zhanjiang; ③Pearl River Delta (30,000 a BP), Hanjiang River Delta (40,000–25,000 a BP); ④Hong Kong (late Holocene); ⑤Kunming Basin (Pleistocene), Songhua Basin (mid Miocene–Pleistocene), Zhaotong Basin (late Pleistocene), Dali Basin (late Pleistocene); Menghai lacustrine sediments (10,000–30,000 a BP).

*Dacrydium cf. pierrei*

Pollen grains 48.4–52.8 μm in size, body length 37.4–48 μm, height 22–38.5 μm; two poorly developed sacs composed of elongated “small bursa”, encircling distal pole; pollen wall is thick, and sexine has irregularly arranged baculae, perpendicular to outline. Sacs show radiate folds starting from body, with irregular morphology, distinct wave-shaped. The cappa in proximal pole of body is thickened, with comb-shaped structure. Pollen body shows granulate and striate sculpture, and colpus is indistinct.

*Dacrydium cf. pierrei* type can be assigned to
extant *Dacrydium pectinatum*, while the fossil pollen grains are relatively smaller in size (normally smaller than 60 μm), and exine radiate folds in the sacs are less distinct than the extant species. *Dacrydium cf. pierrei* were found in the depression of Beibu Gulf, Xiayang Formation–Wanglougan Formation in Leiqiong, Sanya Formation–Yinggehai Formation in Yinggehai depression, and Zhuhai Formation–low Hanjiang Formation (close to *Dacrydiumites florinii*) in Pearl River estuary depression. Pollen morphology of extant species *Dacrydium elatum* is also close to that of *Daecycarpus nidulum* in Fiji.

**Sonneratiaceae**

*Sonneratia*, Figure 2.10: 5–8; South Region Plates 39: 9–12, 40: 3–18

Extant *Sonneratia* are distributed in Qinglan Harbor (Wenchang) and the southern areas in Hainan Island.

Fossil pollen types of *Sonneratia* were reported beyond its modern latitudinal limits in the southern...
areas in the mainland of China, occurring in the lower Pleistocene stratum in the coastal areas of Guangdong and the Zhanjiang Formation (upper Pleistocene stratum) in Leizhou Peninsula. In general, fossil pollen grains are mainly present in the mid-late stages of the early Pleistocene. Fossil pollen types can generally be assignable to Caseolaris type and Alba type, comparable to two extant pollen of *Sonneratia caseolaris* and *S. alba*. Detailed descriptions and illustrations for *Sonneratia caseolaris* and *S. alba* are presented in the following section to aid fossil identification. The other extant species of *Sonneratia* are poorly represented in the Quaternary sediments (for their pollen keys, see the former section 2.4.2.1).

*Sonneratia caseolaris*, Figure 2.10: 5, 6; South Region Plate 40: 6–8

Pollen grains prolate in equatorial view, triangular in...
polar view, 52.17 (40.84–64.6) μm × 41.20 (31.50–49.94) μm, average P/E ratio 1.27; triporate; exine thickness varies, structurally discontinuous between equatorial and polar regions, thinnest at poles (ca. 2.1 μm), thickest at equator (ca. 2.5 μm); sexine in polar regions (over polar cap) has a smooth surface but is granulate to verrucate elsewhere (dimensions 0.3–1.2 μm), with a mean density 1.6 elements/μm²; pore circular to subcircular, prominently protruding, ca. 7.8 μm in diameter.

**Sonneratia alba**, Figure 2.10: 7, 8; South Region Plate 40: 3–5

Pollen grains prolate in equatorial view, more or less hexagonal in polar view, 59.50 (51.92–68.78) μm × 44.35 (32.13–50.74) μm, average ratio P/E ratio 1.35; with distinct meridional ridges extending to polar areas; triporate; exine ca. 2.4 μm thick, sexine thicker than nexine, psilate except for scattered perforations in polar areas, irregularly granulate to verrucate in mesoporal areas, irregularly granulate to verrucate in mesoporal
areas with a tendency towards rugulate on meridional ridges (dimensions 0.4–1.4 μm), mean density 1.9 elements/μm²; pore circular to subcircular, protruding, ca. 9.5 μm in diameter.

**Rhizophoraceae**

Recent distribution and identification keys to pollen in this family are already presented above in section 2.4.2.2. The fossil records are well documented from the estuarine sediments of south region and marine sediments, with key types of *Rhizophora*, *Kandelia* and *Bruguiera/Ceiops*. *Rhizophora* is easily identifiable comparing to the other genera, followed by *Kandelia* pollen identification. However, *Bruguiera/Ceiops* pollen are very small and difficult to distinguish, and this pollen is insect pollinated, so fossil pollen types are poorly represented in the sediments. Detailed pollen keys to this family are presented in the section 2.4.2.2. Considering the relatively few species in each genus in the family Rhizophoraceae, fossil pollen types at the genus level are very close to those of extant plants; therefore only pollen description for extant plants are presented below, which can also be practical guides to identify fossil pollen types.

*Bruguiera*, Figure 2.7; Figure 2.9: 6; South Region Plate 36: 1–8

*Bruguiera gymnorrhiza*, Figure 2.4; South Region Plate 36: 1–4

Pollen grains oblate to spheroidal, convexly triangular to circular in polar view, 17.9 (15.6–20.8) μm × 20.1 (16.8–22.5) μm; tricolporate; exine ca. 1.3 μm thick, sexine thicker than nexine, sculpture scabrate to weakly granulate under LM, scabrate to pitted under SEM; aperture vestibulate, endopore within colpus very slightly elongated equatorially, dimensions ca. 2.1 × 2.0 μm, length of colpus ca. 10.6 μm.

*Ceriops*

*Ceriops tagal*, South Region Plate 36: 9, 10

Pollen grains oblate to subspheroidal, rounded triangular to subcircular in polar view, 14.9 (13.5–16.2) μm × 13.3 (12.6–14.5) μm; tricolporate; exine ca. 1.2 μm thick, sexine thicker than nexine, sexine scabrate to weakly granulate under LM, but appears to be finely perforated under SEM; aperture vestibulate, endopore equatorially elongated and discontinuous in mesocolporium, dimensions ca. 1.6 μm × 1.2 μm, length of colpus ca. 9.9 μm.

*Kandelia*

*Kandelia obovata*, Figure 2.7; Figure 2.9: 7; South Region Plate 36: 11–13

Pollen grains subprolate to spheroidal, subcircular in polar view, 21.5 (17.2–25.3) μm × 18.2 (16.7–21.5) μm; tricolporate; exine ca. 1 μm thick, tectum perforate, sexine thicker than nexine with a regulate to irregularly foveolate sculpture, but margins of colpi usually psilate; aperture vestibulate, endopore equatorially elongated, dimensions ca. 3.1 μm × 2.3 μm, often constricted within colporium, length of colpus ca. 14.1 μm.

**Rhizophora**

*Rhizophora apiculata*, Figure 2.7; Figure 2.9: 2, 3; South Region Plate 36: 14–17

Pollen grains spheroidal to subspherical, 24.4 (20.0–28.0) μm × 22.6 (19.6–27.8) μm; mostly tricolporate, sometimes tetracolporate; exine ca. 2.2 μm thick, sexine thicker than nexine, sculpture microreticulate to microrugulate under LM, appears more varied under SEM with three main types: perforate, regulate, and reticulate (Mao et al., 2008), but usually perforated to (irregularly) perforate–reticulate; aperture vestibulate with equatorially elongated endoaperture,
dimensions ca. 2.4 μm × 1.4 μm, length of colpus ca. 12.6 μm with finely rugulate membrane.

**Rhizophora stylosa**, Figure 2.7; South Region Plate 36: 18, 19

Pollen grains subprolate, circular to subcircular in polar view, 20.5 (19.9–22.7) μm × 22.4 (21.3–24.7) μm; tricolporate; exine ca. 1.5 μm thick, sexine thicker than nexine, scabrate to slightly granulate under LM, scabrate to slightly granulate to irregularly pitted under SEM; aperture vestibulate, endopore equatorially elongated, dimensions ca. 3.1 μm × 1.6 μm, length of colpus ca. 13.4 μm.

**Rhizophora mucronata**, Figure 2.7; South Region Plate 37: 1‒3

Pollen grains subprolate to spheroidal, outline in polar view subcircular or rounded-triangular, 23.8 (18.7–26.8) μm × 20.4 (16.6–4.4) μm; tricolporate; exine ca. 1.4 μm thick, sexine thicker than nexine, surface appears to be finely reticulate under LM, but clearly perforated under SEM, perforations less numerous over poles and around equator; aperture vestibulate, endopore equatorially elongated, dimensions ca. 3.0 μm × 2.1 μm, length of colpus ca. 15.8 μm.

**Verbenaceae**

**Avicennia**

*Avicennia* is a species that can tolerate high salinity. It is widely distributed from semi-brackish to saline coastal environments and is often a pioneering species in the tidal zone.

Its fossil pollen grains are found in Pleistocene sediments from the Leizhou Peninsula, as well as Holocene sediments on Hainan Island, with good pollen representation.

**Avicennia marina**, Figure 2.9: 4, 5; South Region Plate 44: 1–4

Pollen grain tricolporate, subprolate to spheroidal in equatorial view, subcircular in polar view, 25.5 (23.6–34.8) μm × 28.8 (24.2–35.3) μm; exine ca. 3.0 μm thick, sexine thicker than nexine, sculpture appears reticulate with granular muri under LM, but surface of tectum is seen to be more foveolate under SEM; colpi extend to polar regions, pore large, subcircular (ca. 6.4 μm in maximum diameter), nexine finely granulate in the colpi under both LM and SEM.

**Combretaceae**

**Lumnitzera**

*Lumnitzera* is distributed along the coastline of Hainan Island, with two species in the genus.

Its fossil pollen occurs in the Holocene sediments and surface soils on Hainan Island, quite low representation.

**Lumnitzera racemosa**, South Region Plate 17: 3–6

Pollen grains subprolate to spheroidal, polar outline subcircular-lobate, 28.6 (26.3–31.6) μm × 26.4 (19.3–29.7) μm; heterocolporate (pseudocolpate); exine ca. 2.7 μm thick, sexine thicker than nexine, finely reticulate in equatorial regions, reticulation more strongly developed at the poles under LM, but under SEM the tectum appears more foveolate, fovea larger on the outer parts of the lobes and at the poles; pores within three colpi sub-rectangular, ca. 5.8 μm × 5.4 μm, both colpi and pseudocolpi (non-functioning “false” colpi) ca. 17.4 μm long.

**Lumnitzera littorea**, Figure 2.9: 9; South Region Plate 17: 1, 2

Pollen grains subprolate to spheroidal, polar outline subcircular-lobate, 38.6 (35.2–42.6) μm × 35.2 (25.8–39.4) μm; heterocolporate (pseudocolpate); exine ca. 2.9 μm thick, sexine and nexine similar in thickness, tectum scabrate to foveolate under LM, more obviously finely pitted/foveolate under SEM; pores within three colpi rectangular, with long axis parallel to the equator, ca. 7.0 μm × 2.1 μm, both colpi and pseudocolpi (non-functioning “false” colpi) ca. 15.5 μm long.

**Barringtoniaceae**

**Barringtonia**

*Barringtonia*, an associated species of mangrove, occurs along the coastlines of southern China and southwestern Yunnan. Its fossil pollen grains occur in Holocene sediments and surface soils, with very low representation.
**Barringtonia racemosa**, Figure 2.9: 8; South Region Plate 13: 1–5

Pollen grains prolate, outline circular in polar view, 64.2 (53.2–70.8) μm × 44.6 (40.9–46.4) μm; tricolpate (tri-syncolpate); exine ca. 2.2 μm thick, sexine and nexine of similar thickness, coarsely reticulate adjacent to colpi and in subpolar areas, scabrate to psilate elsewhere; colpi strongly crassimarginate, especially in polar regions, ca. 53.4 μm long.

**Malvaceae**

**Hibiscus**

*Hibiscus*, also an associated species of mangrove, is distributed along the coastlines of southern China, particularly Hainan Island. Its fossil pollen grains occur in Holocene sediments and surface soils, but only rarely.

**Hibiscus tiliaceus**, Figure 2.10: 9; South Region Plate 30: 11

Pollen grains spheroidal, 130.5 (104.2–185.9) μm in diameter; polyporate (pantoporate); exine ca. 5.6 μm thick, sexine thicker than nexine, prominent spines scattered over the surface of tectum, ca. 19.6 μm in length and widely spaced, ca. 19.7 μm apart; spines psilate, elongate-cone shaped, may be slightly bulbous towards the base before becoming constricted, beneath which the perforated tectum is slightly raised; tectum surface also sculptured with scattered granules; pores ca. 13.6 μm in diameter.

**Acrostichaceae**

**Acrostichum**

*Acrostichum* is the only fern in mangrove forest, with two species in the genus. Its fossil spore occurs in Quaternary sediments on Hainan Island with low abundance.

**Acrostichum aureum**, Figure 2.8: 1; South Region Plate 1: 1, 2

Trilete spores, rounded–triangular in polar view, 53.6 (49.0–73.5) μm × 70.2 (64.1–83.1) μm (the length of side×diameter through arm of the trilete suture); exine ca. 3.9 μm thick, sexine thicker than nexine, granulate to verrucate sculpture under LM, granules and small verrucae appear to be somewhat irregular in shape and size under SEM.

**Arecaceae**

**Nypa**

Modern *Nypa* is distributed in Qinglan Harbor and southern Hainan Island, which can be a dominant community in mangrove forest. Its fossil pollen occurs in estuarine and offshore sediments.

**Nypa fruticans**, Figure 2.10: 3; South Region Plate 34: 4, 5

Pollen grains spheroidal, 51.5 (44.3–56.1) μm × 46.9 (36.5–54.3) μm; monocolpate (zonasulcate/annulocolpate); exine ca. 2.5 μm thick, sexine thicker than nexine; echinate, spines ca. 3.6 μm high, widening significantly and commonly appearing somewhat swollen close to their base, ca. 3.4 μm apart; surface of tectum between spines foveolate; mean width of colpus 3.9 μm.

### 2.5 Southwest Region

#### 2.5.1 Types of Quaternary pollen and spores in southwest region

southwest region includes southeastern Xizang, Yunnan, and the most part of Sichuan. This region is mainly influenced by the Southwest Asian monsoon. In our studies of Quaternary pollen analysis in this region during the past several decades, 130 families and 316 genera of Quaternary pollen and spores were found (Table 2.15). We collected the photomicrographs of these pollen and spores, and compiled them into 131 plates in this book. These plates cover 128 families, including 10 families of algae spores, 6 families of bryophyte spores, 23 families of pteridophyte spores, 4 families of gymnosperm pollen, and 85 families of angiosperm pollen. The composition of regional vegetation inferred from fossil pollen and spores in this region has following features. ①Abundant and diverse ferns—most of ferns indicate humid and hot climatic conditions of tropical and subtropical zone. They
are represented by Alphilsa, Athryiopsis, Cibotium, Davallia, Dicksonia, Onychium, Parathelypteris, Plagiogyria, Pteris, Schizaea, and Vittaria. The appearance of all 8 genera of gymnosperm pollen with sacci—they include Abies, Picea, Pinus, Keteleeria, Cedrus, Tsuga, Podocarpus, and Dacrydium. This feature reflects vertical zonation of alpine and subalpine vegetation in subtropical monsoon region. Dacrydium is absent in Yunnan now, and it only grows in mountainous area at elevations of 1100‒1700 m a.s.l. in the Wuzhishan Mountains of Hainan Island; however, its fossils occurred in southern Yunnan at ca. 40 ka BP (Tang and Liu, 1987). A great diversity of Polygonaceae and evergreen oaks. One feature of angiosperm pollen types is the occurrence of a lot of genera of Polygonaceae in this region. Among them, some species of Koenigia are endemic to the mountains in the southeastern part of Xizang, and their fossil pollen grains were first found in the surface soils and the Pleistocene strata there. Another feature of angiosperm pollen types is the occurrence of a variety of evergreen oaks. These evergreen oaks not only include subtropical green broadleaf forest elements such as Castanopsis, Lithocarpus, and Cyclobalanopsis, but also several evergreen sclerophyllous oaks as major elements of evergreen sclerophyllous forest or montane evergreen shrubland, such as Quercus aquifolioides, Q. rehderiana, Q. senescens, Q. gilliana, and Q. pannosa. Unfortunately, currently it is not possible to identify them at the species level under the light microscope.

### Table 2.15  Common Quaternary pollen and spores in southwest region

<table>
<thead>
<tr>
<th>Plant life form</th>
<th>Pollen and spore type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees</td>
<td>Pinus, Quercus, Castanopsis, Lithocarpus, Cyclobalanopsis, Abies, Picea, Keteleeria, Cedrus, Tsuga, Podocarpus, Dacrydium</td>
</tr>
<tr>
<td>Upland herbs</td>
<td>Poaceae, Compositae, Cruciferae, Polygonum</td>
</tr>
<tr>
<td>Hygrophilous and aquatic herbs</td>
<td>Cyperaceae, Typha, Potamogeton, Alisma</td>
</tr>
<tr>
<td>Ferns</td>
<td>Alphilsa, Athryiopsis, Cibotium, Davallia, Dicksonia, Onychium, Parathelypteris, Plagiogyria, Pteris, Schizaea, Vittaria</td>
</tr>
<tr>
<td>Algae</td>
<td>Pediastrum, Zygnema</td>
</tr>
</tbody>
</table>

2.5.2  Identifiable features of major Quaternary pollen and spores in southwest region

2.5.2.1  Plant distribution and pollen features of Pinaceae in southwest region

1. Modern plant distribution of Pinaceae

Quaternary pollen records in southwest region are characterized by the dominance of coniferous pollen represented by Pinus pollen. The average pollen percentages of Pinus pollen generally are more than 30%, and even over 90%. Phytogeographically, the pines that are widely distributed in the Yunnan-Guizhou Plateau are represented by Pinus yunnanensis, P. kesiya var. langbianensis, and P. densata. Ecologically, these species are drought-enduring and thermophilic plants, and their growth is also related to infertile or fertile soil properties. Pinus yunnanensis is an indigenous species in southwest region. It is widely distributed in the vast areas at elevations of 700‒3200 m on the entire Yunnan-Guizhou Plateau. Its distribution area accounts for 29.2% of forests in Yunnan. Additionally, the Hengduan Mountains and southeastern Xizang are the regions widely covered by subalpine dark coniferous forests in China, and these regions are also the formation and diversification center of Picea and Abies species in the world. Picea and Abies plants generally occur in areas at elevations higher than 2600 m. Tsuga trees are generally distributed at the transitional forest zone between mid-montane deciduous broadleaved forest and subalpine coniferous forest. Tsuga chinitensis, T. dumosa, and T. forrestii mainly occur in western Sichuan, northern Yunnan, and southeastern Xizang, respectively (Jiang et al., 1998).

2. Characteristics of Pinaceae pollen

Pollen grains of Pinaceae are usually large in size, ca. 59‒160 μm. They can be classified into three types in terms of the presence of sacci and ropy-ruffles. Pollen type with sacci: this type of pollen includes the pollen of Pinus, Abies, Picea, Cathaya, Cedrus, and Keteleeria. Pollen grains of this type have distinct sacci attached to the two sides of the corpus with distinct boundary.
between sacci and corpus. These saccate pollen grains can be identified into genus level in terms of the size, thickness of cappa, and connection relationship of sacci to corpus. ②Pollen type with ropy-ruffles: ropy-ruffled pollen only includes the pollen of Tsuga. ③Pollen type without sacci and ropy-ruffles: this type of pollen includes the pollen of Larix and Pseudotsuga.

2.5.2.2 Identification key to pollen morphology of Pinaceae

1. Pollen with sacci.

2. Two well-developed sacci attached to the two sides of the corpus, colpus between two sacci in the distal face.

3. Distinct boundary between sacci and corpus; three circles intersected and sacci larger than semicircular in polar view.

4. Exine thick, nexine distinctly thinner than sexine; marginal ridge absent or indistinct; sexine thinning or not thinning near sacci.

5. Cap sculpture ornate; sexine thinning near sacci; 115‒184 μm in size .............................................. Abies

5. Cap sculpture granulate; two sacci slightly upwarping; sexine thinning near sacci; 113‒155 μm in size ............. Keteleeria

5. Cap sculpture granulate – striate; sexine not thinning near sacci; 63‒82 μm in size .................................. Cathaya

4. Exine thin, sexine as thick as nexine; marginal ridge distinct or indistinct, cap sculpture granulate-striate...... Pinus, Pseudolarix

3. Indistinct difference between sacci and corpus in equatorial view; sacci itself indistinct; no marginal ridge.

4. Sacci semicircle in polar view, sexine gradually thinning near sacci in proximal face ...................................... Picea

4. Sacci larger than semicircle in polar view; sexine not thinning near sacci .............................................. Cedrus

2. Saccus indistinct, annular, surrounding the corpus, difficult to distinguish it from the corpus; corpus sculpture coarsely vermiculate, sometimes echinate; inaperturate .......................................................... Tsuga

1. Pollen grain spheroidal; no sacci, sexine psilate; inaperturate ........................................................................ Larix

2.5.3 Descriptions of morphological features for major pollen and spores in southwest region

2.5.3.1 Photomicrographs of common pollen and spores in southwest region

A great diversity of pollen types occur in southwest region. Here 11 pollen and spore types are selected as their representatives (see Figure 2.11).

2.5.3.2 Descriptions of morphological features of major pollen and spores in southwest region

**Sinopteridaceae**

**Onychium**, Figure 2.11: 1; Southwest Region Plates 38: 1‒10, 39: 1‒8

Spores radially symmetric; obtusely or circularly triangular in polar view, oval, super semicircular or flabellate in equatorial view; Polar axis 28.3‒52 μm, equatorial axis 45‒90 μm; trilete, laesurae thin and narrow with or without margin, margin regular or irregular, almost to the equator in laesura length; perispore thin and non-transparent, surface granulate, and easily dropped down after processing; exine 2.5‒10.8 μm in thickness, distinctly layered; exine surface verrucate, verrucae bigger and more distinct in distal face than proximal face, with or without connected base; exine with thickened equatorial flange along the equator; spores of some species with 1‒2 bead-like or band-like sculpture rings except equatorial flange; spores of individual species without equatorial flange.

**Modern distribution** Fern; distributed in tropical and subtropical Asia, central South America, and Africa; centered in Yunnan and Sichuan provinces, north to the Qinling Mountain, west to southern Himalaya, and east to eastern China and Taiwan Province; also found in Japan.

**Fossil distribution** Quaternary strata in Yunnan-Guizhou Plateau and northwest Yunnan.

**Cyatheaceae**

**Alsophila**, Figure 2.11: 2; Southwest Region Plate 14: 1‒11

Spores tetrahedral, radially symmetric; obtusely or
circularly triangular in polar view, three sides indented, sometimes straight or convex; semicircular or super semicircular in equatorial view; polar axis 23.0‒38.4 μm, equatorial axis 38.4‒53.8 μm (excluding perisporium); trilete, laesurae almost to the equator in length, infrequently ca. 3/4 radius of spores, with somewhat thickening lip-like margin; perisporium semi-transparent or non-transparent, adherent to exine, surface granulate, spiny or striate; exine 1.7‒5.1 μm in thickness, mostly 2.1‒3.8 μm; exine distinctly layered, surface psilate; sexine sometimes thickened or upwarping in triangular areas; spores of some species with exine contracting inward in proximal triangular area to make triangle protruding.

**Modern distribution**  Tree fern with or without vertical trunk; mainly distributed in tropical humid regions, also distributed in Chile, New Zealand, and South Africa.

![Figure 2.11 Photomicrographs of common pollen and spores in southwest region](image)

**Fossil distribution** Quaternary strata in Xishuangbanna of Southern Yunnan-Guizhou Plateau.

**Polygonaceae**

*Koenigia*, Figure 2.11: 4; Southwest Region Plate 110: 1–28

Pollen grain spherical; contour circular, 17.0‒28.9 μm in diameter (including spine); diverse apertures, 7–8-colpi arranging in meridional orientation; mostly 12-pores (or colpi), pores rectangular, colpus-like, 3‒5 μm × 1 μm in size, with cubic margin; seldom pantoporate, 20‒30 pores, circular, 1 μm in diameter (this is a key feature for dividing pollen grains of this genus into three pollen types); exine 1.5‒2.0 μm in thickness (excluding echini), sexine slightly thicker than nexine or almost equal thicknesses; columellae indistinct; exine surface echinate, echinus with sharp end, 0.8‒3.0 μm in length, 0.8‒1.3 μm in diameter, distance between two adjacent echini 0.5‒3.0 μm; exine among echini with fine echinus-foveola or granulum-foveola. Among pollen grains of Polygonaceae, distinctly echinate exine is the key feature to distinguish *Koenigia* pollen from pollen of other genera of this family.

**Modern distribution** Annual herb; distributed in mountainous area of southeastern Xizang.

**Fossil distribution** Quaternary strata in southeastern Xizang.

**Ericaceae**

*Rhododendron*, Figure 2.11: 3; Southwest Region Plate 89: 10–13

Pollen grains tetrahedral and cruciate tetrad; few irregular; 3-colporate, colpi with thickened margins; exine 2-layered, sexine as thick as nexine; surface sculpture extremely finely reticulate.

**Modern distribution** Shrub, infrequently tree; ca. 800 species distributed in northern temperate zone; ca. 650 species in China, in all provinces except Xinjiang, mostly in Southwest and western China; well-known ornamental plants in the world.

**Fossil distribution** Quaternary strata in western Sichuan, Yunnan-Guizhou Plateau, and Hengduan mountains.

**Meliaceae**

*Melia*, Figure 2.11: 8; Southwest Region Plate 101: 20

Pollen grains prolate or spheroidal; polar axis 40‒50 μm; 4-colporate, rarely 3- or 5-colporate; exine 2-layered, sexine thicker than nexine; exine surface finely and densely granulate.

**Modern distribution** Tree or shrub; distributed in tropical and subtropical regions of Southwest and East China.

**Fossil distribution** Quaternary strata in southern Yunnan-Guizhou Plateau.

**Pinaceae**

*Abies*, Figure 2.11: 12; Southwest Region Plate 43: 1–6

Pollen grains with distinct and well-developed sacci; relatively deep concave angle between sacci and cap at proximal base; 115‒185 μm in length; in polar view, corpus and two sacci like three intersected circles, corpus elliptic, sacci larger than semicircular, normally corpus wider than sacci; cap exine 2-layered, sexine extremely thickened, nexine very thin, about 1/4–1/3 of exine in thickness; orante sculpture on the cap formed by bent and branched lines; boundary between cap and ventral area (distal face) not as distinct as *Pinus* pollen; marginal ridge indistinct or absent; sexine thinning near the proximal base, where sexine almost as thick as nexine; sacci with obvious reticula with finer lumina than *Pinus* pollen.

**Modern distribution** Tree; about 19 species and 3 variants in China; distributed in North, Northwest, and Southwest China as well as high mountains in Zhejiang and Taiwan; often forming pure forest and becoming available wood resources; some species as the major elements for regeneration; most of them usually growing in high mountains with high precipitation and cool-wet climatic conditions as cold- and shade-tolerant trees.

**Fossil distribution** Quaternary strata in mountains in southeastern Xizang, western Sichuan, and northwestern Yunnan.

*Cedrus deodara*, Figure 2.11: 10; Southwest Region Plate 45: 1‒4

Pollen grains with sacci attached to two sides of corpus; 76–118 μm in length with an average of 97 μm;
corpus 46–70 μm in length with an average of 60 μm, and 50–76 μm in height with an average of 64 μm; sacci small, with marginal ridge; sexine thick; cap surface granulate; boundary between sacci and cap indistinct; exine in distal face indistinctly granulate; sacci reticulate with bent and discontinuous muri and irregular lumina.

Comments Cedrus pollen is similar to Picea pollen in equatorial view, however, the sacci of Cedrus pollen are larger than semi-circular in polar view, which is distinct from Picea pollen. In addition, the thickness of sexine does not change at the connecting part between corpus and sacci in the proximal face, which is also different from Picea pollen.

Modern distribution Evergreen conifer; distributed in western Himalaya Mountains and Xizang.

Fossil distribution Quaternary strata in western Sichuan, northwestern Yunnan, and southeastern Xizang.

Tsuga dumosa, Figure 2.11: 9; Southwest Region Plate 67: 1–1

Pollen grains spheroidal, 63–111 μm in diameter; circular in proximal view, concave in distal view sometimes when pollen grains getting dried, biconvex lens shape in lateral view; exine surface coarsely vermiculate, with echini among sculptures under microscope at high magnification (×600); exine distinctly layered, with thin nexine and thick sexine; saccus extremely undeveloped, surrounding the corpus as an annulus ring in polar view, with irregular rugulae; saccus with sculptures the same as those on the corpus, difficult to distinguish it from the corpus under optical section; inaperturate.

Modern distribution Tree; distributed as pure hemlock forest or as an element of mixed coniferous forest, in alpine regions at elevations of 2300–3500 m in southern Xizang, Northwest and Northeast Yunnan, as well as Jingdong region of western Yunnan, Southwest Sichuan, upper reaches of Minjiang River, and along Dadu River, Qingyi River, and Mabian River; also distributed in India, Nepal, Bhutan, and Burma.

Fossil distribution Quaternary strata in mountainous regions of Yunnan and western Sichuan.

Podocarpaceae

Podocarpus, Figure 2.11: 11; Southwest Region Plate 68: 4–6

Pollen grains with two large and distinct sacci; sacci attached to the two sides of the corpus, distinct from corpus; some species with three sacci; outline of saccus larger than corpus and semi-circular in polar view; sacci coarsely reticulate, reticula with connected or discontinuous muri, muri with sparse granula seen under microscope at ×300 magnification; pollen grains oval in lateral view; exine thin and 2-layered, indistinctly and finely granulate; pollen grains psilate in distal face, indistinct boundary between proximal and distal faces, with a distal colpus; Podocarpus pollen distinct from other saccate pollen in terms of size, exine thickness, sexine structure, and size and structure of sacci.

Modern distribution Evergreen tree or shrub; distributed in provinces south of the Yangtze River.

Fossil distribution Quaternary strata in the Xishuangbanna area of southern Yunnan.
Plates and Descriptions of Quaternary Pollen and Spores in Different Regions of China
Northwest Region

Plates 1, 2
Gleicheniaceae
Hemionitidaceae
Lycopodiaceae
Osmundaceae
Polypodiaceae
Pteridaceae
Selaginellaceae

Plates 3, 4
(Cont.) Selaginellaceae
Cupressaceae
Ephedraceae

Plates 5–10
(Cont.) Ephedraceae
Ginkgoaceae
Pinaceae

Plates 11–14
Amaranthaceae
Anacardiaceae
Aquifoliaceae
Araliaceae
Betulaceae
Boraginaceae
Campanulaceae

Plates 15, 16
(Cont.) Campanulaceae
Caprifoliaceae
Caryophyllaceae

Plates 18–20
(Cont.) Caryophyllaceae
Celastraceae
Chenopodiaceae

Plates 21–29
Compositae

Plates 30, 31
(Cont.) Compositae
Crassulaceae
Cruciferae
Cucurbitaceae
Cyperaceae

Plates 32, 33
(Cont.) Cyperaceae
Elaeagnaceae
Euphorbiaceae

Plates 34, 35
Eupteleaceae
Fagaceae
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Plate 36
Geraniaceae

Plates 37–39
Hamamelidaceae
Juglandaceae
Labiatae

Plates 40–42
(Cont.) Labiatae
Leguminosae
Liliaceae
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Plates 43–45
(Cont.) Malvaceae
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Plates 46–50
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Polygonaceae
Ranunculaceae

Plate 53
(Cont.) Ranunculaceae
Rhamnaceae
Rosaceae

Plates 54–56
(Cont.) Rosaceae
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Rutaceae
Salicaceae

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Sapindaceae
Scrophulariaceae
Simaroubaceae
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Thymelaeaceae

Plates 59–61
Tiliaceae
Typhaceae
Ulmaceae
Umbelliferae
Valerianaceae

Plates 62, 63
Vitaceae
Zygophyllaceae
**Chenopodiaceae**: 1–20. *Chenopodium* (5–8, Xinjiang; 16, 17. Qaidam Basin, Qinghai)
**Cruciferae:** 1. Cardaria; 2, 3. Cardaria draba; 4, 5. Hesperis; 6, 7. Megacarpaea; **Cucurbitaceae:** 8. Cucurbita moschata; **Cyperaceae:** 9–13. Carex (1. Tianshan, Xinjiang; 2, 3, 8. Qaidam Basin, Qinghai; 4, 5. Gansu)
Plate 35

Plumbaginaceae: 1–6. *Limonium* (Barkol, Xinjiang)
Poaceae: 1–5. *Zea* (Shaanxi)
Poaceae: 1–5. *Zea* (Shaanxi)

**Rhamnaceae:** 13–15. *Rhamnus*;

<table>
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<th>North Region</th>
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</table>

**Plates 1, 2**
- Hydrodictyaceae
- Phthanioperidiniaceae

**Plate 3**
- Scenedsmaceae
- Chlorophyta
- Acritarchs

**Plate 4**
- Ricciaceae

**Plate 5**
- Dennstaediaceae
- Gleicheniaceae
- Hemionitidaceae

**Plate 6**
- Hymenophyllaceae
- Lycopodiaceae
- Parkeriaceae

**Plates 7–9**
- Polypodiaceae
- Selaginellaceae
- Sinopteridaceae
- Cupressaceae
- Ephedraceae

**Plates 10–24**
- (cont.) Ephedraceae
- Pinaceae
- Podocarpaceae

**Plate 25**
- Aceraceae
- Actinidiaceae
- Alismataceae
- Amaranthaceae
- Apocynaceae
- Aquifoliaceae
- Araliaceae

**Plates 26–28**
- Balsaminaceae
- Berberidaceae
- Betulaceae

**Plates 29–30**
- Caprifoliaceae
- Campanulaceae
- Caryophyllaceae
- Celastraceae
- Chenopodiaceae
- Compositae

**Plates 31–37**
- (cont.) Compositae

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- Convolvulaceae
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- Ericaceae
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**Plates 53–56**
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**Plates 59, 60**
- Saxifragaceae
- Scrophulariaceae
- Solanaceae
- Sparganiaceae
- Sterculiaceae
- Tamaricaceae
- Tiliaceae
- Typhaceae

**Plates 61, 62**
- Ulmaceae
- Umbelliferae

**Plate 63**
- Valerianaceae
- Violaceae
- Zygophyllaceae
**Pinaceae**: 1–7. *Pinus* (1, 2. Jingpo Lake, Heilongjiang; 4, 5, 7. Alxa Youqi, Inner Mongolia)
**Pinaceae**: 1–7. *Pinus* (Jalai Nur, Inner Mongolia)
Pinaceae: 1–5. Tsuga (1, 1a. Jingpo Lake, Heilongjiang)
Compositae: 1, 1a. Acroptilon repens; 2–15. Artemisia
Cyperaceae: 1–8. *Cyperus* (1, 4, 7, 8, Hebei)
(15. Jingpo Lake, Heilongjiang)
**Saxifragaceae:** 1–7. *Saxifraga*; **Scrophulariaceae:** 8, 9. *Mazus japonicas*; **Pedicularis:** **Solanaceae:** 11, 12. *Solanum*; 13, 14. *S. nigrum*; **Sparganiaceae:** 15, 16. *Sparganium*; **Sterculiaceae:** 17, 18. *Firmiana simplex*; **Tamaricaceae:** 19–25. *Tamarix*; **Tiliaceae:** 26, 27. *Tilia* (8, 9, 13, 14. Hebei; 26. Jingpo Lake, Heilongjiang)
(2–4. Yushe, Shanxi)
## Southeast Region

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<td>Spiniferitaceae</td>
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<th>Plates 24</th>
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<td>(cont.) Pinaceae</td>
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<td>Acritarchs</td>
<td>Podocarpaceae</td>
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