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Radiocarbon dating and its applications in Chinese archeology: An overview

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Radiocarbon dating is a well-established chronometric technique that has been widely employed in Chinese archeology since the first radiocarbon laboratory started operating in the Institute of Archaeology at the Chinese Academy of Sciences in 1965. In the three decades of studies that followed, achievements were made in radiocarbon dating, especially in measurement techniques, sample preparation, and the establishment of regional chronological frameworks. There is no doubt that Chinese archeology entered a golden age with the assistance of radiocarbon dating techniques at the beginning of the 2000s. It is, however, also true that compared to Western countries, China has reported far fewer radiocarbon dates than expected. This paper presents an overview of the history of the radiocarbon dating technique and its significant applications in Chinese archeology, focusing on the transition from β-decay counting to accelerator mass spectrometry. Some of the breakthroughs in studies of the Upper Paleolithic, early *Homo sapiens*, neolithization, and the Xia and Shang dynasties are highlighted. We conclude the paper with a brief discussion of future work and research directions that need to be explored.

KEYWORDS

radiocarbon dating, archeology, China, chronology, methodology, applications

1 Introduction

In 1949, the first set of radiocarbon dates was published by Willard Frank Libby and colleagues (Libby et al., 1949). Shortly afterward, radiocarbon dating laboratories were established in many Western countries (Deevey et al., 1965). Radiocarbon dating was considered to be a great revolution in prehistoric archeology in the 20th century (Daniel, 1959), and it "came as a godsend to archeology" (Renfrew, 1976: 53–75). This new technique allowed archeologists to examine archeological remains and associated events with well-delineated chronological frameworks. It contributed significantly to addressing critical concerns in archeological studies such as the chronologies of specific events and the formation of new hypotheses and research paradigms (Kuzmin, 2009).

Radiocarbon (^{14}C) is a radioactive isotope of carbon with a half-life of 5730 years. It is continuously generated in the upper atmosphere by the interaction of ^{14}N with cosmic ray-induced neutrons. Rapidly oxidized in the air, ^{14}C atoms enter the global carbon cycle in the form of $^{14}CO_2$, which plants absorb during photosynthesis. Animals ingest the carbon by eating plants and release a portion through respiration and excretion. When animals die, their exchange of carbon with the biosphere (and eventually the atmosphere) ceases, and the decay of radiocarbon causes the level to decrease with time. When the remaining radiocarbon in a plant or animal sample is determined, the age of the sample can be calculated. Radiocarbon ratios of the analyzed samples indicate the elapsed time since the last exchange of carbon between the sample and the environment (Libby, 1955). Radiocarbon dates are usually reported in uncalibrated years BP (before the present), where BP refers to 1950 AD. Calendar years can be calculated from the uncalibrated year BP using the calibration curve.

China was among the first Asian countries to adopt radiocarbon dating for archeological research. Xia Nai, Director of the Institute of Archaeology of the Chinese Academy of Science (IA-CAS, which in 1977 became the Institute of Archaeology of the Chinese Academy of Social Sciences, or IA-CASS), introduced the radiocarbon dating technique to Chinese archeologists in 1955 (Xia, 1955). In 1965, the first radiocarbon dating laboratory was set up in the IA-CAS, a groundbreaking event in Chinese radiocarbon chronology (Lab of IA-CAS, 1972). More than half a century has passed since the first group of radiocarbon dates was reported in China, and significant progress has been made in the construction of testing facilities and in radiocarbon dating methods, which continued to improve the precision and accuracy of measurements. Tens of thousands of radiocarbon readings have been published in the Old and the New World. The present paper reviews the development of radiocarbon dating methods and their applications in Chinese archeology, especially studies on the Upper Paleolithic and early modern human origins, Neolithization, Neolithic chronology, and the Xia–Shang–Zhou Chronology Project.

2 Developments in radiocarbon dating methods in China

2.1 β-decay counting and advances in radiocarbon dating

After World War II, the application of radioisotopes became widespread in natural sciences, and ^{14}C was used for archeological dating in this context. Prior to the 1960s, Chinese archeology, especially of prehistoric periods, relied strongly on the stratigraphy of archeological sites and the typology of artifacts in inferring the dates. However, the low precision and unreliability of this method often led to controversial conclusions. Realizing the great potential of radiocarbon dating for establishment of more solid and finer chronological frameworks, the IA-CAS hired two nuclear physicists, Qiu Shihua and Cai Lianzhen, and supported them in setting up a radiocarbon dating laboratory at the CAS. The construction began in 1959 and was completed in 1965. Qiu and Cai first ran tests on samples of known ages dating to the Neolithic and Bronze Age in China, and the ^{14}C dates were compatible with the dating results inferred from archeological stratigraphy and pottery typology. The first radiocarbon dating laboratory in China started to produce radiocarbon dates soon afterward (Lab of IA-CAS, 1972; Rudolph, 1973). For the first time, "Chinese prehistory can be placed on an absolute-chronological basis" (Chang, 1973). Other radiocarbon dating laboratories were set up in China in the 1970s (Radiocarbon Lab of the Institute of Geochemistry of the CAS, 1973; Radiocarbon Lab of the Institute of Geology of the CAS, 1974). In 1981, about fifty ^{14}C labs were registered for the first National Conference on ^{14}C; however, most of them were built for geoscience studies (Editorial Group of the First National Conference on ^{14}C, 1984).

The first radiocarbon dating laboratory at the IA-CAS adopted the gas counting technology, which could generate dates up to 40,000 years BP. Over the years, Qiu and others made significant efforts to improve the quality of measurements and achieved this goal by enhancing the facilities, especially the gas-proportional counters, the electronic detectors, high-voltage power supplies, shielding devices, and vacuum systems for sample preparation (Lab of IA-CAS, 1972). In the 1960s, the application of liquid scintillation counting (LSC) technology for measuring ^{14}C was proven successful in radiocarbon dating laboratories of the West (Tamers, 1960). Compared to the gas method, LSC simplified the sample preparation procedures, required a smaller sample size, and ran tests with shorter times and lower background. In 1975, Yuan Sixun and others set up the first LSC radiocarbon dating laboratory at Peking University (Radiocarbon Dating Lab of Archaeology of Peking University, 1976). Subsequently, more radiocarbon dating laboratories in China began using the LSC method, including both new laboratories and ones that had previously used gas-proportional counting facilities (Lab of IA-CASS, 1978; Radiocarbon Dating Lab of Institute of Science and Technology for Cultural Relics Preservation 1978).

Sample preparation was significantly improved in the 1970s, along with the associated devices. In 1965, when acetylene gas was prepared, calcium was used to absorb carbon dioxide extracted from the samples; calcium was replaced by magnesium in the 1970s and by lithium in the early 1980s (Huang et al., 1981). At about the same time, automated testing techniques were used to measure ^{14}C and computers were used for processing the data, which significantly improved the efficiency, the data quality, storage, and retrieval (Lab of IA-CASS, 1983). In the 1990s, small sample sizes (100–250 mg) could be run for radiocarbon dating on LSC devices, which was a great advantage for dating archeological samples where only a small amount of material was available (Zhou et al., 1994).

Beginning in the 1950s, the A.D.1890 tree rings and other early 20th-century wood samples were used as 'modern' reference materials for calibrating radiocarbon dating results around the world. Oxalic acid was adopted internationally as the carbon standard at the 4th International Radiocarbon Conference (Godwin, 1959), and at the 8th International Radiocarbon Conference, sucrose ANU was recognized as the international sub-standard (Polach and Krueger, 1972). As the number of radiocarbon laboratories increased in China, so did the desire for reference materials that could be used to cross-check and validate the radiocarbon dates between different laboratories. A consensus was reached at the National Isotopic Geology Conference held in Guiyang that a modern carbon standard for radiocarbon studies should be used in China. Qiu, the principal investigator, and specialists from Peking University and the Chinese Academy of Sciences, were engaged in the project. In 1977, sucrose refined from beets harvested in Inner Mongolia was announced as the raw material for producing charred sucrose as the modern carbon standard. The $\delta^{13}C$ of charred sucrose is →19.32% ± 0.56 relative to PDB, which is very close to the →19% value of oxalic acid II. The averaged FM (fraction of the modern standard) was 1.362% ± 0.003, suggesting that sucrose and oxalic acid II were very similar (1.3407 ± 0.001) (Mann, 1983; Qiu et al., 1983; Polach, 1989). Charred sucrose was thus approved as the modern carbon reference and national standard, known as the Chinese sugar carbon standard (CSC). Employing the new standard, radiocarbon dating was significantly improved, with simple chemical preparation, no more than 1% residue after burning, and no significant isotopic fractionation (Qiu et al., 1983). Recently, researchers started a project that aimed to make CSC a secondary material for accelerator mass spectrometry (AMS) radiocarbon dating. To achieve this goal, CSC particles were ground into a finer powder that ensured data homogeneity for AMS dating (Xu et al., 2013).

FIGURE 1
First national conference on ^{14}C in China (1981).

On September 15–18, 1981, the First National Conference on ^{14}C dating was held in Beijing. Over 70 participants attended the conference, and more than 40 reports were submitted (Figure 1). The presentations not only focused on archeology and geosciences but also on the most recent advances in radiocarbon dating techniques of China and abroad, especially in sample pretreatment, LSC facilities, error analysis of radiocarbon data, δ^{13}C measurement, and the application of AMS in radiocarbon dating (Editorial Group of the First National Conference on ^{14}C, 1984). In 1982, the 2nd National Conference on ^{14}C dating was held in Nanjing University. The Radiocarbon Chronology Group supervised by the Chinese Association for Quaternary Research was approved and an official announcement was made that the national radiocarbon dating conference would be organized on a regular basis (every 3 years) together with summer schools on radiocarbon dating methodologies. Radiocarbon dating results from different laboratories were also reported at this conference (Li, 2009). The workshops and national conferences significantly improved the theoretical and methodological background of specialists and technicians from different Chinese dating laboratories, which made a significant contribution to China's radiocarbon chronology in the decade that followed.

2.2 Accelerator mass spectrometry (AMS) radiocarbon dating

AMS is a method for measuring radioactive nuclides with long half-lives and to measure ^{14}C as early as in 1977 (Bennett et al., 1977; Muller, 1977; Nelson et al., 1977; Berger, 1979). AMS can directly measure the relative abundance of ^{14}C in a sample, a feature that distinguishes it from conventional methods based on β-decay counting. It not only reduces the test time from several hours to a few minutes but also enables measurements of specimens in small volumes and even at the molecular level, namely, ~1 mg carbon (1/1000 of the β-decay counting method). The successful application of the AMS radiocarbon dating technique was enthusiastically welcomed by researchers in archeology, earth sciences, and biological pharmacy. In 1979, Chen Tiemei introduced this newly developed dating technique to China (Chen, 1979). At the First National Radiocarbon Conference, Cai Lianzhen (Cai, 1984) and Shen Chengde (Shen, 1984) presented an overview of AMS radiocarbon dating and its global applications. At the Fourth National Conference on Radiocarbon, on November 5–9, 1988, five of the 29 papers reported on the AMS radiocarbon dating technique, target preparation, and its applications in archeology (Radiocarbon Dating Society of Chinese Quaternary Research Association, 1990).

The first set of AMS radiocarbon data for Chinese archeological samples was reported in 1989 to support a discussion on the chronology of Shandingdong (Upper Cave) of the Zhoukoudian locality in Beijing (Chen et al., 1989). Several institutions began to set up AMS facilities at about the same time (Zhou and Chen, 2009). Peking University completed a dedicated tandem-based AMS facility in 1992, the Peking University accelerator mass spectroscopy (PKUAMS) laboratory with the financial support of the National Natural Science Foundation of China. The PKUAMS laboratory's spectrometer consisted of an ion source with 20-position sample trays, a fast-switching injection line, a 6-MV EN-tandem accelerator, and a post-acceleration analysis and detection system. The first batch of AMS data, reported in 1993, showed a sensitivity of 10^{-14} with a precision better than 1.7% for a modern sample (Chen et al., 1993). A precision of about 1% and a blank sample background lower than 0.006 MC or 43 Ka were achieved for the graphitization technique with the updated power supply, data acquisition and control system, and the highly intensified Cs sputtering ion source (Guo et al., 1995).

From 1996 to 2000, radiocarbon dating was incorporated into the Xia–Shang–Zhou Chronology project. To achieve a high precision, several key facilities were upgraded to the AMS system of Peking University, including replacing the ion source with a 40-sample NEC MC-SNICS device, a pneumatic sample change system, updated vacuum, injector, computer control and data acquisition systems. The new PKUAMS obtained ^{14}C measurements with a precision of ~0.5% and provided over 200 dates for the Xia-Shang-Zhou archeological chronology project (Guo et al., 2000; Liu et al., 2000). While thousands of samples have been dated using the PKUAMS system, there are many more radiocarbon dates needed in the fields of archeology and earth sciences. To meet this need, a new compact AMS system based on the model 1.5SDH-1 Pelletron accelerator with a maximum terminal voltage of 0.6 MV was purchased from the

National Electrostatics Corporation (NEC), installed in Peking University, and used exclusively for radiocarbon dating. The new system obtained ^{14}C measurements at a precision <0.4% and a background <0.03 pMC, or 65 Ka (Liu et al., 2007). Shortly afterward in 2006 , another 3 MV Tandetron-based AMS system, manufactured by High-Voltage Engineering Europe (HVEE), was installed at the Xi'an Accelerator Mass Spectrometry Center (XAAMS), the joint AMS laboratory of the Institute of Earth Environment, and Xi'an Jiaotong University. The XAAMS is a multi-element system for radiocarbon measurement with a precision of ~0.2% (Zhou et al., 2006). Recently, dozens of AMS facilities were purchased overseas to serve the needs of radiocarbon dating (Wu, 2021), including another 0.6 MV ^{14}C AMS facility manufactured by NEC and installed at the Guangzhou Institute of Geochemistry (CAS) in 2014 (Zhu et al., 2015), and a MICADAS type AMS by ETH Zurich at Lanzhou University.

In China, AMS radiocarbon dating has been applied directly not only on carbonized grains such as rice and soybean but also on plant microfossils such as pollen (Zhang et al., 2021) and phytoliths (Wang and Lu, 1997; Jin et al., 2014; Zuo et al., 2017; Zuo and Wu, 2019). In addition, soil sediments and monomer compounds in pottery residues were also collected for dating (Yuan et al., 1997). The widespread application of AMS radiocarbon dating has significantly revolutionized our understanding of archeological events.

3 Radiocarbon dating applications in Chinese archaeology

3.1 Chronology of the upper Paleolithic and the origin of early *Homo sapiens*

More than 2000 Paleolithic sites have been reported in China, and human fossils have been unearthed from about 80 of them (Ge et al., 2021). Most human fossils from Paleolithic sites were from the late-Middle to the Late Pleistocene, which makes China a core region for studying the evolution of early modern humans (EMHs) and their adaptions to diverse environments (Liu et al., 2016; Gao et al., 2019). Archaeology is a science of time, so dating is one of the most important fulcrums in archeological research. Chronology is the key to understanding human origins and evolution as well as shifting cultural materials. Radiocarbon dating is a well-accepted, scientifically based chronometric method for determining specimen ages up to ~55,000 years old (Hajdas et al., 2021), and it was thus essential for studying the evolution of EMHs and anatomically modern humans (AMH) and related archeological materials during the Upper Paleolithic.

Prior to the introduction of radiocarbon dating techniques, the ages of Paleolithic sites and hominin fossils were largely inferred from the stratigraphy and associated faunal assemblages, which often resulted in disagreements over the chronologies. The situation started to change in 1972, when the radiocarbon laboratory of the IA-CAS (Lab of IA-CAS, 1972) published the first set of ^{14}C data. It included a sample of wood associated with Ziyang No. 1, an EMH skull dated to 7500 ± 130 years BP, using the gas proportional counting method. In 1976, bone collagen was extracted from animal fossil samples at late Pleistocene sites, including Zhiyu in Shanxi, dated to 28,135 ± 1,330 ^{14}C BP, and the Upper Cave of Zhoukoudian in Beijing, dated to 18,340 ± 410 ^{14}C BP, to shed light on the chronology of the Upper Paleolithic sites and EMH fossils (Lab of IA-CASS and Lab of Institute of Vertebrate Paleontology and Paleoanthropology of CAS, 1976).

In the early 1980s, radiocarbon data from more than ten Paleolithic sites were published (IA-CASS, 1983). Although most were consistent with the dates inferred from fossilized faunal assemblages, some remained controversial and were very likely questionable. An Zhimin argued that the problematic dates may have resulted from obscure archeological contexts and taphonomy, although the large error in the β-decay counting method could also be the cause. He suggested that, whenever possible, a single radiocarbon date should not be used because "one date is no date" (An, 1983). This called for greater attention to the sampling strategy and a full understanding of the depositional process. In 1988, a preliminary chronological framework was constructed for the Upper Paleolithic period based on paleoanthropological data including radiocarbon dating, K-Ar dating, uranium series, thermoluminescence (TL), and paleomagnetism (Chen, 1988).

In the late 1980s and early 1990s, the AMS technique was adopted to date Upper Paleolithic samples, which refined the chronological frameworks for archeological and paleoanthropological studies (Yuan et al., 1995). The calculated ages of the Zhoukoudian Upper Cave in Beijing can be used as an example to show how the advances in radiocarbon dating over the decades contributed to a better understanding of the Upper Paleolithic. The Zhoukoudian Upper Cave is well-known for EMH fossils, first unearthed in 1933 and 1934. Three human skulls and fragmented human fossils were discovered in layer 4 in the lower room (Pei, 1933; 1939; Norton and Gao, 2008). Some articulated human fossils colored with red ochre were found , leading to the assumption that the cave was a burial site. No chronometric methods were available at the time the human fossils were discovered, but the excavator suggested an age of Late Pleistocene based on faunal assemblages (Pei, 1940). In the late 1970s, two animal bones from the Upper Cave were dated using LSC, generating radiocarbon dates of 18,340 ± 410 ^{14}C BP (ZK-136-0) and 10,180 ± 360 ^{14}C BP (ZK-136-01)). As sodium hydroxide was not used in collagen extraction, humic acid and other organic carbon compounds may have contributed to the apparently younger ages (Lab of IA-CASS, 1980). In 1989 and 1992, Chen and others prepared 12 bone samples using the acid–alkali–acid (AAA) procedure suggested by the Radiocarbon Accelerator Unit at the University of Oxford and published two groups of AMS ^{14}C data on the Zhoukoudian Upper Cave. Most of the sampled bones from the Lower Room were dated between 29,100 ± 520 ^{14}C BP and 23,700 ± 350 ^{14}C BP, much older than the two LSC ^{14}C dates, (Chen et al., 1989; Chen et al., 1992).

Recently, Li and others reanalyzed the taphonomy and stratigraphic contexts (Li et al., 2018a) and selected 11 bones from the Upper Cave for AMS ^{14}C dating at the Oxford Accelerator Unit, where ultrafiltration was added to the AAA procedure to collect large molecular weight proteins (Bronk Ramsey et al., 2004). Eight of the 11 bone samples yielded dates from 50 ka BP to 34 ka BP. Two samples with clear archeological contexts produced dates of 30,010 ± 360 ^{14}C BP (34,744 cal BP–33,551 cal BP) and 32,800 ± 500 ^{14}C BP (38,376 cal BP–35,825 cal BP). Since the artifacts and ornaments found at the Upper Cave showed similarities to those at Denisova in Siberia, the chronology led some archeologists to argue that the Upper Cave EMHs had made contact with other hominin populations further to the north some 35.0 ka BP (Li et al., 2018a). The hypothesis is consistent with the Tianyuan EMH fossils at the Zhoukoudian

Tianyuan Cave, which were dated to 34,430 ± 510 ^{14}C BP (40,328 ± 816 cal BP) using AMS ^{14}C measurements (Shang et al., 2007; Fu et al., 2013; Yang et al., 2017).

To date, the progress in radiocarbon dating has refreshed our understanding of lithic technology and human behavior during the Upper Paleolithic as well as the interaction among hominin groups at Shuidonggou (Li et al., 2019) and Jinsitai (Li et al., 2018b), for example, and the Paleolithic sites around the Songshan Mountain (Wang and Wang, 2014). A large number of radiocarbon dates have been reported from more than 300 sites, which supports new discussions of EMH evolution and migrations (Wu, 2018; Zhang et al., 2018; Gao et al., 2019), the diversity of lithic industry (Wang, 2019), the introduction and routes of spreading Levallois (Hu et al., 2019), microblade technologies (Yi et al., 2016), and the broad spectrum revolution (Janz, 2016).

3.2 Radiocarbon dating and neolithization

The Neolithic is characterized by some fundamental changes including the use of pottery, food production, and settled village life. These changes are now regarded as long-term processes, to which the term "Neolithization" is often applied. In the Near East, food production preceded the use of pottery. However, the opposite was true in China, where Neolithization occurred in the vast, geographically diverse landscapes (Kuzmin et al., 2009). The extensive radiocarbon dating of prehistoric materials has allowed archeologists to construct a chronological framework for significant changes (e.g., the use of pottery and the shift from hunting–gathering–fishing to subsistence farming) that initiated Neolithization in several regions of mainland China.

Since the 1970s, radiocarbon dating has also been used to investigate the origin of pottery making in China. Sherds of very early pottery vessels have been unearthed from the sites of Xianrendong and Diaotonghuan in Jiangxi Province, Zengpiyan and Miaoyan in Guangxi province (Zhang and Hung, 2012), Yujiagou (Gai and Wei, 1977) and Nanzhuangtou (Baoding Institute of Cultural Relic Management et al., 2010) in Hebei Province, Donghulin (School of Archaeology and Museology of Peking University, et al., 2006) in Beijing City, Houtaomuga (Wang, 2018) and Shuangta (Wang and Duan, 2013) in Jilin Province, and Xiaonanshan (Heilongjiang Institute of Cultural Relics and Archaeology and Raohe County Office of Cultural Relics, 2019) in Heilongjiang Province. It was judged from archeological stratigraphy and pottery typology that many of these sherds arguably dated to the early Neolithic Age (Jiangxi Provincial Committee of Cultural Relics, 1963; Guangxi Team of Cultural Relics and Guilin Management Committee of Cultural Relics, 1976; Jiangxi Provincial Museum, 1976). In the 1970s and 1980s, LSC radiocarbon dating applied to freshwater shells and animal bones associated with sherds reported dates of 8000 ^{14}C BP or earlier. However, contradictory results do sometimes exist between stratigraphy and radiocarbon data. In Xianrendong, for example, freshwater shells (ZK-39) sampled from the upper layer were dated to 10,870 ± 240 ^{14}C BP (Lab of IA-CAS, 1974), which was older than the animal bone (ZK-92-0) from the lower layer with an age of 8575 ± 235 ^{14}C BP (Lab of IA-CAS, 1977). This may be due to the effect of dead carbon in the limestone region. Modern archeological samples including wood, charcoal, grain seeds, shells, and bones have been collected for radiocarbon dating and ^{14}C ages of 1000-2000 years were suggested to offset the freshwater reservoir effect (Radiocarbon Lab of Peking University and Radiocarbon Lab of Institute of Archaeology of Chinese Academy of Social Sciences, 1982).

Beginning in the 1990s, the AMS ^{14}C facility made radiocarbon tests with small sample sizes possible. In 1997, Yuan and colleagues successfully extracted absorbed humic acids and intrinsic carbon of pottery clay from sampled sherds from the Miaoyan and Yuchanyan sites in southern China for AMS radiocarbon dating and published the results. Combined with the radiocarbon dates obtained from charcoal and animal bones, it was confirmed that pottery was used in southern China as early as 16.0 cal ka BP (Yuan et al., 1997). Further radiocarbon dating studies refined the earliest use of pottery at Yuchanyan to ca. 18,300 cal BP to 15,430 cal BP (Boaretto et al., 2009) and up to ca. 20,000 to 19,000 cal BP for Xianrendong (Wu et al., 2012). These dates indicate the widespread use of pottery in southern, northern, and northeastern China from 15,000 to 10,000 BP.

China was also one of the centers for agriculture and animal husbandry. While the middle and lower Yangtze River valley of southern China is home to rice cultivation, northern China is well-known for the domestication of foxtail and common millets (Zhao, 2011). Radiocarbon dating results have suggested that plant cultivation occurred thousands of years after the introduction of pottery. Only a very few early Neolithic sites used pottery as well as cultivated plants and practiced animal husbandry: Donghulin (Zhao et al., 2020), Nanzhuangtou (Hou et al., 2021), and Shangshan (Zhao, 2010). Pre-domesticated rice remains were found at sites such as Xianrendong during the late phase, around 10,000 BP or earlier (Zhang, 2000). Radiocarbon dates and micro- and macro-plant fossils have suggested that rice and millets were cultivated separately in southern and northern China some 10,000 years ago. Rice domestication could have begun. 9400 to 9000 BP at the Shangshan and Hehuashan sites in the lower Yangtze River valley (Zuo et al., 2017), while millet cultivation was securely dated to around 10,000 BP at the Donghulin (Zhao et al., 2020) and Cishan (Lu et al., 2009) sites.

In summary, radiocarbon dating has provided important clues to the Neolithic transition in China. Pottery making began around 20,000 BP in China, preceding agriculture by thousands of years. This sharply distinguishes China from the Near East (Makibayashi, 2014; Kuzmin, 2016), and future investigations including radiocarbon dating studies are necessary to confirm this distinction.

3.3 Chinese Neolithic chronology

The construction of Neolithic chronological frameworks is fundamental to understanding the archeology of cultural systems and their interactions. This has remained a key topic in Chinese archeology since the 1970s. In 1977, Xia Nai proposed a tentative chronological framework for Neolithic China using 129 published radiocarbon data sets (Xia, 1977). By the early 1990s, over two thousand radiocarbon dates had been published, about half of which dealt with the Neolithic Age or before 4,000 BP (IA-CASS, 1992). This substantial amount of radiocarbon data made possible the construction of several regional chronological frameworks (Chang, 1987; An, 1991), which continue to be refined using new radiocarbon dates.

The published radiocarbon data have allowed archeologists to divide Neolithic China into the following proposed categories: early

Neolithic (ca. 15,000 BP - 8500 BP or earlier); middle Neolithic, characterized by the pre-Yangshao cultures (ca. 8500 BP - 6900 BP); late Neolithic, represented by the Yangshao cultures (ca. 6900 BP - 4500 BP); and final Neolithic, represented by the Longshan cultures (ca. 4500 BP-3800 BP) (IA-CASS, 2012; Liu and Chen, 2012). The refinement of chronological frameworks has been carried out for the Yangshao (Zhang et al., 2013) and Longshan cultures in the Central Plains (Zhang, 2021), the Lower Haidai region and the lower Yangtze River valley (Long and Taylor, 2015; Long et al., 2017), as well as the Bronze Age Hexi Corridor (Yang et al., 2019). Chronological studies have also been conducted at the Xichengyi (Zhang et al., 2015) and Xiaozhushan (Zhang et al., 2016) sites.

Radiocarbon dating has substantially contributed to the long-term transdisciplinary project, the Origins of Chinese Civilization. Joint efforts of archeologists and radiocarbon experts over 20 years have revised the Neolithic to early Bronze Age chronology in the Yellow River and Yangtze River valleys. Large settlements and urban centers dating from 5500 BP to 3500 BP, such as Liangzhu, Shijiahe, Taosi, Shimao, and Erlitou, have received close attention in radiocarbon dating projects because they are crucial for the understanding of emergent social complexity as well as the formation of Chinese Civilization (Wang and Zhao, 2022). It is widely agreed that early Chinese civilization can be traced back to 6000 BP to 5500 BP in the Yellow, Yangtze, and West Liao River valleys (Wang and Zhao, 2022). Liangzhu, the earliest capital-level settlement in the lower Yangtze River valley and the earliest state in prehistoric southern China (Renfrew and Liu, 2018), had developed a unique hydraulic system around 5100 years ago (Liu et al., 2017).

The Chinese Civilization Exploration Project entered its fifth phase beginning in November 2020. From 2020 to 2024, radiocarbon dating projects will focus on 13 centralized centers in the Western Liao River, Yellow River, and Yangtze River valleys in the hope of offering a refined chronological foundation for research on the origin of Chinese civilization.

3.4 The Xia-Shang-Zhou chronology project

The Xia–Shang–Zhou Chronology project was commissioned in 1996 and completed in 2000 (Li, 2002). The project aimed to provide a reliable chronology of the Xia, Shang, and Western Zhou dynasties of ancient China, through the collaboration of specialists in archeology, history, astronomy, and radiocarbon dating, which played a decisive role in this project. To achieve high-precision radiocarbon data, the dating team optimized the preparation method for charcoal and bone samples and also improved the analytical precision of LSC to 2-3% and of AMS to 5% by upgrading the associated facilities (Qiu and Cai, 1997; Liu et al., 2000; Yuan et al., 2007). These achievements, combined with sequential sampling and ‘wiggle-matching’ of tree ring dates, allowed researchers to obtain several reliable chronologies.

Combining radiocarbon dates with the records of key events in literature, the project proposed that the reigning years of Western Zhou kings could be placed before the first year of the Gonghe Era (共和元年) or 841 BC and the late Shang kings from Wuding (武丁) to Zhou (纣). A relatively detailed chronology of the early Shang period was proposed along with a chronological framework of the legendary Xia Dynasty (Li, 2002). The project leaders combined radiocarbon dating with research in archeology, history, epigraphy, and astronomy. Data on related dates of historical records, bronze vessel inscriptions, and astronomical phenomena were collected and cross-checked for authenticity before use. Sequential samples from several critical sites, especially burials of the Xia, Shang, and Western Zhou, were obtained for radiocarbon dating by LSC and AMS before adopting Bayesian models (Xia-Shang-Zhou Chronology Project Expert Group, 2022). Taking the Western Zhou period as an example, sequential samples were collected for radiocarbon dating from the cemeteries of Marquis Yan at Lulihe and the Jin State at Qucun of Tianma (天马曲村), which laid the foundation for constructing the chronology of the Western Zhou. While the boundaries were delineated in the Bayesian model, information from bronze inscriptions, historical documents, and astronomical calendars was also considered (Guo Z. et al., 2016). A detailed chronology of the Western Zhou kings before 841 BC in this context was given.

In this way, the project obtained sequential dates and established a final chronological framework of the Xia, Shang, and Western Zhou dynasties. The Xia dynasty was dated from ca. 2070 BC to1600 BC and the Shang from ca. 1600 BC to 1046 BC, aligned with the same reigns of nine kings and the reign years of ten Western Zhou kings from Wu (武) to Li (厉) (Xia-Shang-Zhou Chronology Project Expert Group, 2022). Despite some debate and criticism, the project significantly promoted the development of China’s radiocarbon dating technology, especially the AMS facility of Peking University, and profoundly changed the research paradigm of Chinese archeology. Soon after the completion of the Xia–Shang–Zhou Chronology project, another national project, “The Origins of Chinese Civilization”, was put on the agenda, which has adopted the two fundamental principles of “government support and specialist responsibility” and “multidisciplinary research” since its inception in 2001.

4 Concluding remarks

Over half a century has passed since the first radiocarbon dating laboratory was set up and implemented in the winter of 1965, and significant achievements have been made as described previously. In the 1970s and 1980s, radiocarbon dating became the primary method for dating Chinese archeological discoveries to coordinate them with the infrastructure constructions across mainland China. The advent of radiocarbon dating laboratories occurred at just the right time when Chinese archeology was at the stage of constructing chronologies related to cultural development. Published radiocarbon data helped archeologists establish reliable chronicles of archeological cultures, especially the Neolithic and Bronze Age archeology, in different regions of mainland China. In this case, it would seem that the impact of radiocarbon dating on Chinese archeology was somewhat different from that of the West, where significant changes—the so-called radiocarbon revolution—were triggered by advances in the knowledge of antiquity and study of prehistory (Deniel, 1959).

Since the late 20th century, radiocarbon dating has continuously developed and undergone many revolutions. Advances in the precision of radiocarbon dating measurements and refinements in processing methods for separating and preparing carbon with regard to the specific deposit of interest have made it possible to date a variety of materials in samples weighing as little as tens of micrograms (Bronk Ramsey, 2008; Brock et al., 2010; Synal, 2013; Walker and Xu, 2018). Recent achievements in extracting specific biomarkers from absorbed food residues in pottery vessels have proven to be very helpful in providing clues to the absolute ages of the consumption of specific foodstuffs, pottery utilization, and typochronologies (Casanova et al., 2020). In this case, improvements in sampling calibration methods and programs, as well as new calibration curves, confirm the increased potential for high-resolution chronological studies of archeological events (Reimer et al., 2020; Bronk Ramsey et al., 2021; Reimer, 2021). When comparing advances in radiocarbon dating between China and the West in the past decades, however, we have to recognize that there is a long way to go not only in the methodology of radiocarbon dating but also the breadth and depth of its applications in archeology. In the following section, some potentially fruitful research directions are recommended for future studies.

First, more radiocarbon dating laboratories are needed for archeological research. In recent years, over ten laboratories have been established by universities and institutions for radiocarbon dating, some of which have also purchased AMSs (Wu, 2021). However, most of these laboratories are targeted to the geosciences for measurement services. In contrast, only two laboratories are directly related to archeology, namely, the laboratories of the Institute of Archaeology of the Chinese Academy of Social Sciences and Peking University. This limited number of laboratories and specialists needs to be increased to meet the demands of archeological research for radiocarbon dating in China. Therefore, it is necessary to increase the number of laboratories for archeology, especially graphitization labs, the associated facilities, and trained technicians.

Second, there is still a big gap between China and the West in methodology. Radiocarbon dating in China has gradually developed by learning from the West since the 1960s. It is considered a tool for dating antiquities, and there needs to be more exploration in sample preparation and radiocarbon measurement. Therefore, it is necessary to carry out research on isolating and purifying carbon from traditional archeological materials such as bones, mollusks, charred seeds, wood, and charcoal but also from specific compounds and biomarkers. To constantly improve the quality of graphitization and efficiency and precision of testing, it will be necessary to maintain frequent exchanges with the international radiocarbon dating communities.

Third, close cooperation is desirable between specialists in radiocarbon dating and field archeology to address archeological questions. The success of radiocarbon dating studies depends on the optimization of material sampling. Sampling strategies should be designed to answer specific questions, which calls for cooperation of researchers in laboratories and archeologists in the field to discuss the expected results and possible limitations of the methodology of the dating project. To obtain a refined dataset, Bayesian modeling is often applied with the help of independently available information as the preconditions for the chronology model. As a result, instead of waiting in the laboratories, radiocarbon specialists must be engaged in field work for a deeper understanding of the taphonomy of sampled archeological materials to establish a proper chronological model.

Last, radiocarbon dating research projects of Chinese archeology mainly focus on prehistory and Bronze Age, while only a few publications (e.g., Guo Q. et al., 2016) pay attention to the chronological studies of historical archeological issues. Therefore, well-designed and planned investigations are needed for more detailed specific issues of historic archeology besides prehistoric chronicles.

Author contributions

CX conceived the project, collected and analyzed the literature, and wrote the manuscript.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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