REAPPRAISAL OF CHINESE LOESS PLATEAU STRATIGRAPHIC SEQUENCES OVER THE LAST 30,000 YEARS: PRECURSORS OF AN IMPORTANT HOLOCENE MONSOON CLIMATIC EVENT

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ABSTRACT. Through the establishment of radiocarbon chronozones relating common geological events within lacustrine and eolian sediments from five profiles representative of loess *yuan* (tablelands), river valley and northwest margin features of the Loess Plateau, we propose a series of stratigraphic divisions within the last 30 ka. The focus of this detailed study involves stratigraphic relationships contributing to evidence of Younger Dryas events, with the recognition of cold-dry, cool-wet and cold-dry periods represented within the Heiheze silt, Midiwan peat and Liushuwan eolian sand. The stratigraphic profiles reflect century-scale fluctuations of the East Asian monsoons. The precursor events enable us to place the Pleistocene/Holocene boundary at 10,000 BP.

INTRODUCTION

The late-glacial stratigraphy of North China consists mainly of both lacustrine and eolian sediments. Zheng (1984) made a preliminary stratigraphic subdivision for the Holocene loess. Lei (1992) placed the Q4/Q3 boundary at the interface of S0/L1 with the age of *ca.* 10,000 BP for the southern part of Loess Plateau. Head, Zhou and Zhou (1989), Zhou and An (1991), Zhou, An and Head (1994) and Zhou, Head and Kaihola (1994) established pretreatment procedures for the separation of organics from paleosol and the extraction of wood cellulose, and further proposed a stratigraphic subdivision for Late Pleistocene loess based on reliable radiocarbon dating. However, since the stratigraphic resolution of the studied profile is not good enough, it is difficult to make a detailed study of the transitional stratigraphy from the last glaciation to post glaciation. Also, loess-paleosol ^{14}C dating has been limited by the lack of suitable dating materials. The commonly dated materials have disadvantages: the inorganic carbonate of loess is composed of secondary and debris carbonate that may contain young or old carbon; and the organics from loess-paleosol have been greatly affected by modern plant rootlets and organic translocation, meaning that the ^{14}C ages of all the organic materials must be younger. Further, if organic fractions were separated, the impurities of the organic fractions would result in a low reliability of ^{14}C dating for the loess-paleosol sequences as well. Searching for new dating materials thus seems the only way to improve the ^{14}C dating.

METHODS

The authors extracted pollen concentrates from paleosol (Zhou *et al.* 1997), selected charcoal debris under a microscope, extracted wood cellulose and separated peat fractions for small-sample liquid scintillation counting (LSC) (Zhou, Head and Kaihola 1994), gas proportional counting (GPC) at the University of Washington Quaternary Research Center (Stuiver, Robinson and Yang 1979) and AMS ^{14}C dating (Donahue, Jull and Zebel 1984). Through the comparison of pollen, organic fractions and peat with wood cellulose and charcoal, we should be able to obtain reliable data that are close to true ^{14}C ages and establish a ^{14}C chronozone (detailed ^{14}C methods will not be described here.) On the basis of our study described below combined with field investigations, we propose a subdivision of the Younger Dryas stratigraphy of the Loess Plateau of China in the last 30 ka and demonstrate that although the sedimentation characteristics differ among the typical loess *yuan*

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Proceedings of the 16th International ^{14}C Conference, edited by W. G. Mook and J. van der Plicht
RADIOCARBON, Vol. 40, No. 2, 1998, P. 905–913

(tablelands), river valley areas and the loess/desert transitional belt, their chronozones recording climatic events can still be correlated with one another.

Results

Younger Dryas Stratigraphic Sequences

High-resolution stratigraphic profiles are preserved in the Loess Plateau and its neighboring areas (Fig. 1), which provide a natural laboratory for research. Because of space limitations, we discuss only five representative profiles here.

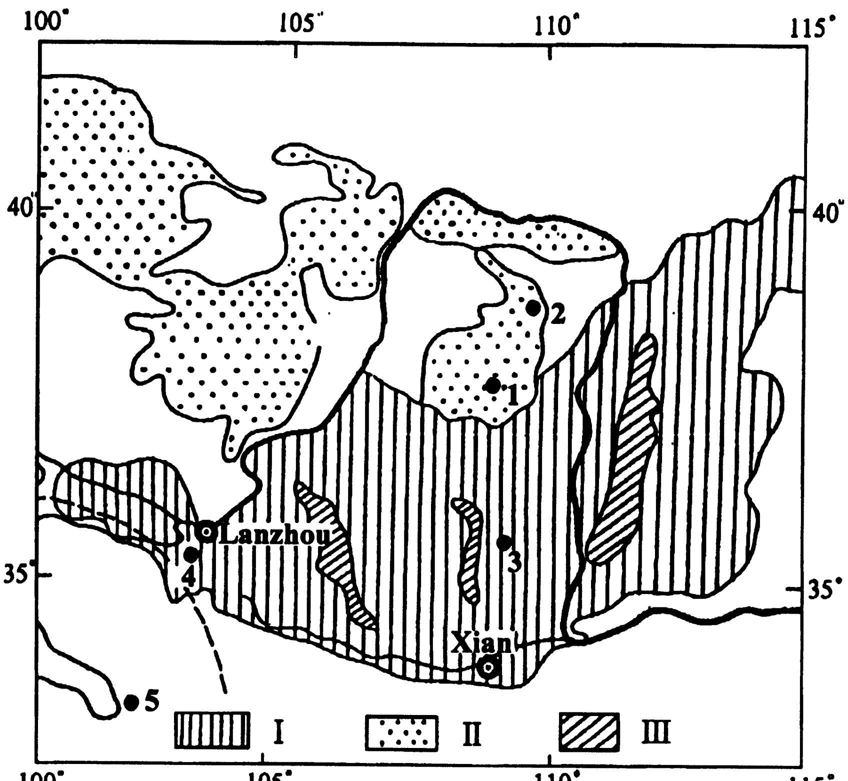

Fig. 1. Map showing the localities for this study. 1.Midiwan in Shaanxi province; 2. Zhengbeitai in Shaanxi Province; 3. Luochuan in Shaanxi Province; 4. Liping in Gansu Province; 5. Wason in Sichuan Province. I. loess, II. sand sheet, III. mountain.

The *Midiwan peat profile* (Zhou *et al.* 1996; 37°39′N, 108°37′E, Fig. 2) is continuous for the last deglaciation and can be regarded as a typical and representative lacustrine profile at the desert/loess transitional belt. During the Younger Dryas interval, the stratigraphy is composed of:

- grayish silt (1020–970 cm depth; AMS ^{14}C ages of debris charcoal from 1018 cm, 993 cm and 973 cm = 11,070 ± 80, 10,760 ± 100 and 10,610 ± 80 BP, respectively),
- grayish-black silty peat (970–900 cm depth, ^{14}C ages by GPC and LSC of wood cellulose from 958 cm = 10,370 ± 70, 10,330 ± 50 BP, respectively),
- yellowish eolian sand with 75 μm average grain size (900–835 cm depth, small-sample LSC ^{14}C age of fine peat fraction is 9750 ± 220 BP).

We termed the silt layer "Heiheze silt", the peat layer "Midiwan peat" and the eolian sand layer "Liushuwan sand".

The detailed proxy data (Zhou *et al.* 1996) show a relatively low *Artemisia*/Chenopodiacea (A/C) ratio and a more positive $\delta^{13}C$ of organic carbon recorded in Heiheze silt between 11,200 and 10,600 BP and in Liushuwan sand between 10,200 and 10,000 BP, indicating the dominance of cold dry winter monsoon climate; whereas from 10,600 to 10,200 BP, a rise in the A/C ratio, elevated pollen values from broad-leaved deciduous trees, *Betula* and aquatic plants, and peaks in *Picea* and *Abies* pollen recorded in peat, all point to cool-humid monsoon climate conditions with increased precipitation and low temperature. Therefore, the Younger Dryas stratigraphy in the East Asian monsoon area is characterized by a sequence of cold-dry, cool-humid and cold-dry conditions.

The *Zhengbeitai loess profile* (38°21'N, 109°42'E) is located at Yuling, Shaanxi province. It is a high-resolution profile developing on the loess ridge of the loess/desert transitional belt. The Younger Dryas stratigraphy consists of:

- upper Malan loess containing a sandy-clay lens (600–540 cm depth, AMS ^{14}C age of pollen concentrate near the bottom = 11,245 ± 85 BP),
- brownish sandy soil (540–500 cm depth, AMS ^{14}C age of pollen concentrate from the top of the layer = 10,270 ± 80 BP), and
- coarse, loose eolian sand (500–370 cm, AMS ^{14}C age of pollen concentrate from the bottom of the overlying paleosol = 9920 ± 90 BP).

Changes in the three sedimentary phases of the profile display a similar record to that of the Midiwan peat stratigraphy. They all indicate the century-scale fluctuations of winter monsoon climate.

The *Liping loess-paleosol profile* (35°33'N, 103°35'E) is located on the second terrace of the Baxie River, a third-order tributary of the Hunghe (Yellow River), Dongxiang, Gansu Province, and can be regarded as a representative of the river valley division of the Loess Plateau. The Younger Dryas stratigraphy of the profile consists of:

- pale yellow loess (485–430 cm depth, AMS ^{14}C age of pollen concentrate from the bottom of the layer =11,040 ± 150 BP),
- blackish-brown paleosol (430–385 cm depth, AMS ^{14}C ages of organic debris from the bottom and top of the layer are 10,610 ± 160 BP and 10,190 ± 150 BP, respectively), and
- pale yellow loess (385–350 cm depth, AMS ^{14}C age of pollen concentrate from the top of the layer is 9880 ± 150 BP).

Between 10,600 and 10,200 BP, a rise in the organic carbon content of paleosol reflected a monsoon climatic condition of increased precipitation (Zhou, Donahue and Jull 1997). ^{14}C dating of the profile and changes in the sedimentary phases are in accordance with those of the Midiwan profile.

The *Luochuan loess-paleosol profile* (Zhou, An and Head 1994; 35°45'N, 109°25'E) is a standard profile in the loess *yuan*. The Upper Malan loess is between 220 and 260 cm depth from the top. Carbonate nodules with a diameter of 5 mm are formed at 250 cm; organic humin from the carbonate nodules has an AMS age of 12,790 ± 720 BP, indicating products of the last deglaciation's warm climatic conditions. A Holocene paleosol complex lies between 220 and 60 cm depth; the AMS ^{14}C age of organic humin near the bottom is 10,420 ± 310 BP. According to the interpolation based on the ^{14}C age and sedimentation rate, Younger Dryas stratigraphy should be located between 230 and 215 cm, but because of the relatively slow sedimentation rate, the Younger Dryas sedimentary record is not obvious.

The *Wason peat profile* (33°05′N, 102°45′E) is located at the northeast margin of the Tibetan Plateau, bordering on the southwestern Loess Plateau; it is a high-resolution and continuous lacustrine profile. The Younger Dryas stratigraphy consists of:

- yellowish-brown muddy silt (670–640 cm depth; plant residue from 670 cm has an AMS ^{14}C age of 10,870 ± 110 BP),
- gray silty mud (640–600 cm depth; wood cellulose from 635 cm has an AMS ^{14}C age of 10,540 ± 100 BP), and
- yellowish silt containing micas (600–583 cm depth; plant residue from 583 cm has an AMS ^{14}C age of 9935 ± 110 BP).

Pollen analysis (Wang *et al.* 1996) shows low values for arborescent pollen percentage and concentration, and an increase of herb percentage from 11,200 to 10,000 BP. But *ca.* 10,600–10,200 BP, pollen concentration and arborescent pollen percentage increased slightly in amplitude, reflecting a cold-dry climate punctuated by a cool-humid phase.

Correlation of Stratigraphic Sequences During the Younger Dryas Interval

During the Younger Dryas interval, the Loess Plateau is characterized by loess interbedding with paleosol (loess-paleosol-loess). The desert/loess transitional belt of the northwestern Loess Plateau and neighboring areas of the southwestern Loess Plateau have a stratigraphic structure of lacustrine sediment intercalating with eolian sand (silt-mud or peat-sand). During the cold period, eolian sand invaded the Loess Plateau to deposit coarse-grained sand or silty loess. During the warm-wet period, lacustrine sediment or paleosol were developed. The correlation of five profiles representing the desert/loess transitional belt, the river valley of the Loess Plateau and the loess *yuan,* respectively, is shown in Figure 2.

During the Younger Dryas glacial stadial (L1LLo) of the last glaciation (L1), the Midiwan profile at the desert/loess transitional belt is characterized by Heiheze silt (11,000–10,600 BP), Midiwan peat (10,600–10,200 BP) and Liushuwan eolian sand (10,200–10,000 BP). In the desert/loess transitional belt (Fig. 2, Zhengbeitai profile) the Younger Dryas interval comprises loess–sandy paleosol–eolian sand stratigraphy on the loess *liang* (ridge). In the river valley of the Loess Plateau, loess-paleosol-loess were deposited during this interval (Fig. 2, Liping profile). These depositions were simultaneous but geomorphologically different. The Luochuan profile in loess *yuan* does not show these three differentiated phases but only loess-paleosol, because of relatively low stratigraphic resolution.

The Younger Dryas stratigraphy in East Asia displays frequent fluctuation of sedimentary phases during the transition from the last glaciation to post glaciation. Pollen, $\delta^{13}C$ and organic carbon content proxies from the Midiwan and Liping profiles indicate that the Younger Dryas of the East Asian monsoon areas was characterized by cold-dry, cool-wet and cold-dry phases. The event of precipitation increase during the mid Younger Dryas (10,600–10,200 BP) was recorded in peat or paleosol stratigraphy, respectively.

Stratigraphic Subdivision of the Loess Plateau and Desert/Loess Transitional Belt in the Last 30 ka

On the basis of ^{14}C chronozones and climatic history reflected by proxies, it is possible to divide the eolian and lacustrine stratigraphy of the Loess Plateau and desert/loess boundary of the last 30 ka into six basic climatic stratigraphic units (Fig. 3). (We make a third-order division of Younger Dryas

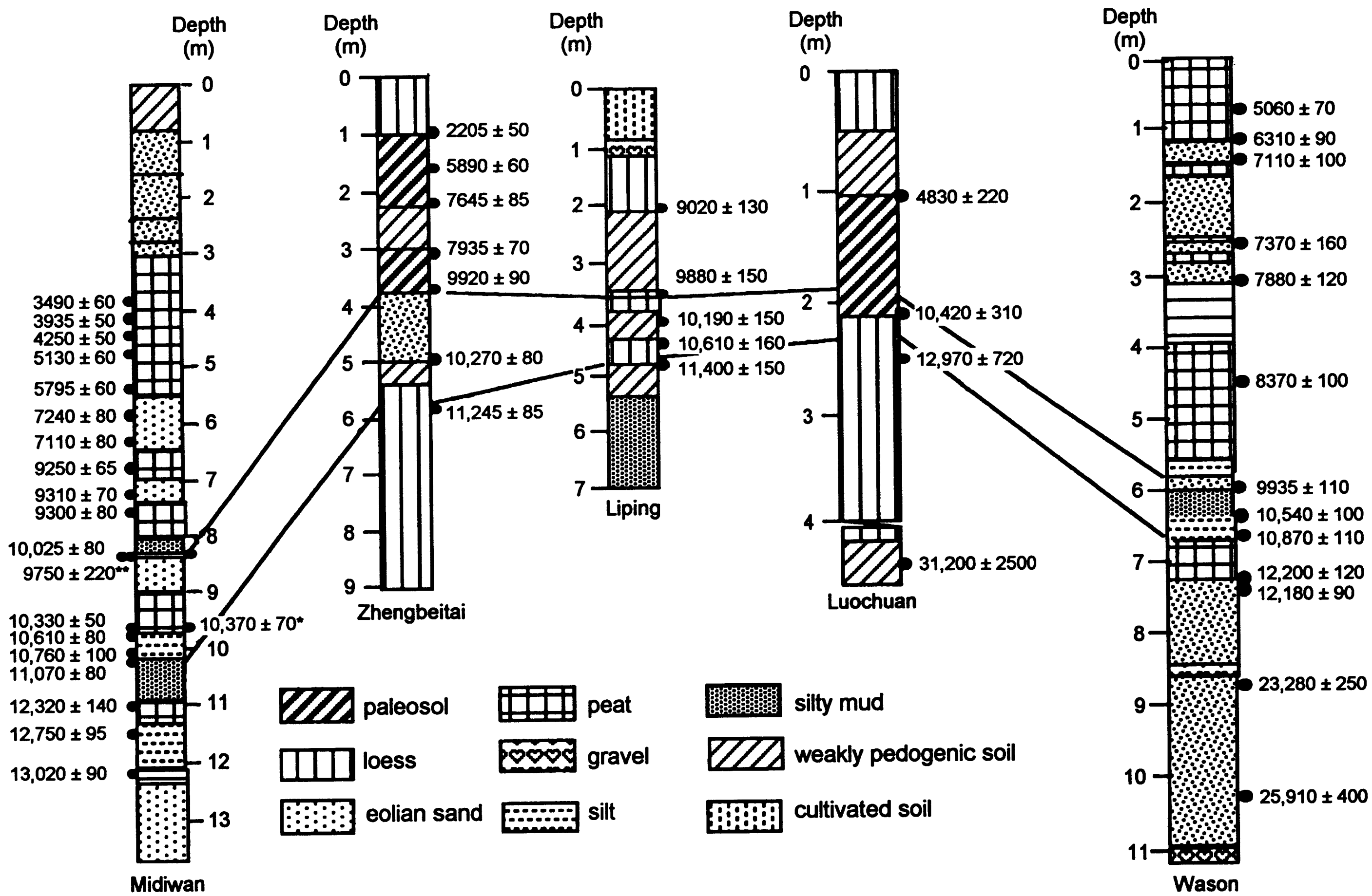

Fig. 2. The correlation of Younger Dryas stratigraphy among the studied profiles in the Loess Plateau and its neighboring area. The ages (BP) are from ^{14}C AMS dating carried out at the NSF-AMS laboratory, University of Arizona, except the ages for the Luochuan profile (from the AMS lab of the Australian National University) and starred ages: * = GPC age, Quaternary Isotope Laboratory, University of Washington; ** = low-level LSC age, State Key Laboratory of Loess and Quaternary Geology, Xi'an, China.

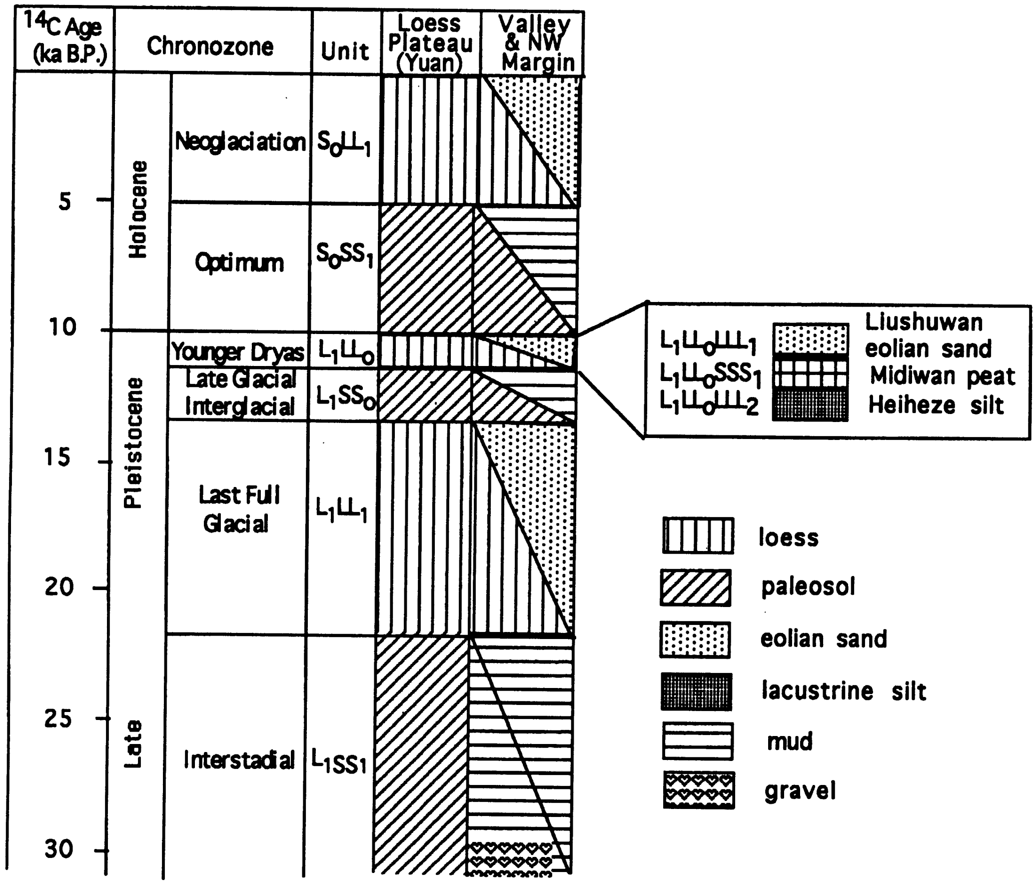

Fig. 3. The stratigraphic division pattern in the Loess Plateau and the desert/loess transitional belt over the past 30,000 years. Younger Dryas stratigraphy is further subdivided into Liushuwan eolian sand, Midiwan peat and Heiheze silt, indicating transition from cold-dry to cool-wet then return to cold-dry monsoon climatic conditions.

stratigraphy according to the standard stratigraphic nomenclature for the Loess Plateau proposed by Kukla and An (1989).) The six units are described from old to young as follows:

1. L_1SS_1, *ca.* 30–22 ka BP, records a cool and humid monsoon climate in the interstadial epoch of the last glacial period. The pollen curve from the Beizhuangcun profile, Shaanxi Province, showed that pollens of *Picea, Abies* and *Pinus* were predominant and the percentage of tree pollen increased during 27–25 ka BP, reflecting a vegetation landscape inlaid with grassland and small patchy woodland. It is estimated that the annual mean temperature was 8.7–12.8°C lower than at present (Sun 1989). Between 27 and 25 ka BP, paleosol was developed in the Loess Plateau and lacustrine/fluvial muds characterized the river valley and northwest margin of the plateau.
2. L_1LL_1, 22–13 ka BP, is the last full glacial period, where the Upper Malan Loess was developed in the loess *yuan* and large quantities of eolian dusts and coarse grain loess were deposited on the northwest margin of the Loess Plateau. Climate was extremely cold and dry; the last glacial maximum occurred by 21–18 ka BP.

3. L_1SS_0, 13–11.2 ka BP, is the late part of last glacial interstadial epoch. In the western Loess Plateau, weakly pedogenic paleosol was developed, although a thin horizon of loess or silt was also intercalated. In the northwest margin of the Loess Plateau, sandy paleosol was developed, and lacustrine sediment was characterized by peat or mud. This clearly marks the mild climate in the Last Glacial period, corresponding to the northwestern European Allerød/Bølling warm period (Berger, Killingley and Vincent 1985).
4. L_1LL_0, 11.2–10 ka BP; glacial climate conditions reappeared within *ca.* 1 ka. The East Asian monsoon climate was characterized by the fluctuations of cold-dry and cold-wet. 11.2–10.6 ka BP ($L_1LL_0LLL_2$) is the major stage of the Younger Dryas, when cold-dry winter monsoons dominated. Heiheze silt was deposited in the lacustrine landscape of the arid/semi-arid transitional belt, while the sand sheet was still characterized by the deposition of eolian sand and the Loess Plateau by loess deposition. 10.6-10.2 ka BP ($L_1LL_0SSS_1$) was a period of monsoon precipitation increase lasting 400 yr. The transitional belt was characterized by development of lacustrine sediment and the Loess Plateau by the development of paleosol. 10.2–10.0 ka BP ($L_1LL_0LLL_1$) was the short period of severe cold and dry winter monsoon climate; eolian sand was widely deposited in the desert/loess transitional belt and loess was deposited in the Loess Plateau. Century-scale fluctuations in monsoon climate indicate a significant variability of East Asian monsoon precipitation and its instability. This may correlate to the sea-surface temperature changes of the Norwegian Sea (Kapuz and Jansen 1992).
5. S_0SS_1, 10–5 ka BP, is the early Holocene, with suitable climate for living organisms. The surface of the loess *yuan* was dominated by luxuriant grassland. A typical paleosol complex was developed. Also, in river valleys, lacustrine sediments were deposited and forest was widely distributed. This period corresponds to the Cishan, Peiligang and Yangshao cultures in China, during which agriculture started in China.
6. S_0LL_1 is the late Holocene Neoglaciation after 5 ka BP, characterized by recent depositions of loess, eolian sand and coarse-grained sediment. Due to the interference of cultivated soil, it is sometimes hard to tell the recent loess from soil. During the Neoglaciation, eolian dusts on the northwest margin of the Loess Plateau moved southward, with dominance of a dry and cold climate, but there were two or three warm and humid fluctuations.

The Pleistocene/Holocene Boundary in Northern China

The location of the Pleistocene/Holocene (P/H) boundary and its onset age has received much attention. In China, K. S. Zhou (1965) placed the start of Holocene at 10,000 BP, based on the obvious increase of linden pollen in the pollen assemblage and the occurrence of broad-leaved deciduous tree pollens. Chou and Cai (1992) suggested that the P/H boundary should be at 11,000 BP. Kong and Du (1980) proposed that 12,000 BP is the boundary of P/H based on the extension of temperate deciduous broad-leaved trees.

Based on the establishment of a ^{14}C chronozone, we propose the following characteristics of an important climatic event of Younger Dryas in China. In the areas influenced by east Asian monsoon climate, the Younger Dryas event was characterized by the fluctuations of monsoon climate; the stratigraphic structure is loess-paleosol-loess (corresponding to Heiheze silt–Midiwan peat–Liushuwan eolian sand). The stratigraphy in the desert/loess transitional belt is silt–peat–eolian sand or silt–sandy paleosol–eolian sand. Soon after the Younger Dryas, an abrupt cooling occurred (YD II, the early Preboreal). Later, S_0 paleosol or peat was developed. The sediments corresponding to YD II were recorded in profiles of Midiwan, Liping and Wason. They are lake silt (800–835 cm), weakly pedogenic loess (345–355 cm) and silt (567–583 cm), respectively. Here, we take the Liushuwan eolian sand layer as the Holocene precursor event record. Therefore, to determine the Holocene boundary from the stratigraphic structure, we should find the stratigraphic record of the precursor event or Younger Dryas event, so that we can correctly determine the Holocene boundary.

The authors believe that the P/H boundary in North China is located at the top of the Liushuwan eolian sand or the top of the loess corresponding to Liushuwan eolian sand. Our ^{14}C age data are shown in Table 1. The P/H ages are *ca.* 10,000 BP, in agreement with the age suggested by the 9th international INQUA Congress (Fairbridge 1973). Obviously, within *ca.* 1 ka of 10,000 BP, northern China and other places in the world experienced the return of a glacial climate, but the event did not have the same characteristics of variation in all regions. The late Younger Dryas cold-dry climate event of 10.2–10.0 ka BP should be regarded as the precursor event of the Holocene arrival in northern China. Thus, the P/H boundary should be determined on the basis of the records in various areas and the climatic conditions they exhibit, combined with ^{14}C dating on the stratum of the precursor event.

TABLE 1. ^{14}C Ages of the Holocene Boundary in North China

Locality	Precursor	Dating materials	^{14}C age (yr BP)
Midiwan	Eolian sand	Debris charcoal	10,025 ± 80
Zhengbeitai	Eolian sand	Pollen concentrates	9920 ± 90
Yangtaomao	Eolian sand	Humin	9645 ± 80
Liping	Loess	Pollen concentrates	9880 ± 150
Baxie	Loess	Humin	9700 ± 150
Luochuan	Loess	Humin	10,420 ± 310
Beizhuangcun	Reworked loess	Humin	9600 ± 170
Wason	Yellow silt	Plant residue	9935 ± 100

ACKNOWLEDGMENTS

This study was supported by the National Science Foundation of China No. 49725308, SSTC, the Chinese Academy of Sciences and the U.S. National Science Foundation and the Quaternary Dating Research Centre of the Australian National University.

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