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ORIGINAL PAPER

Phytolith evidence for early agriculture in the East Liao River Basin, Northeast China

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Abstract

We present the results of the analysis of phytoliths, grain size and organic matter content ($LOI_{550℃}$), and AMS ^{14}C dating of sedimentary profiles and individual archaeological samples from the Changshan site in Jilin Province, Northeast (NE) China. Our aim was to elucidate the origins of agriculture in the East Liao River Basin. The results indicate that there were two intervals during which prehistoric culture flourished at the Changshan site: ~ 6,500–5,600 cal years BP in the Neolithic, and ~ 3,700–2,750 cal years BP in the Bronze Age. Abundant η-type husk phytoliths from common millet and a few Ω-type husk phytoliths from foxtail millet found at the Changshan site provide direct evidence for prehistoric agriculture during these two periods. Prehistoric agriculture was practiced together with hunting and fishing, which were part of a multi-subsistence strategy. The relatively warm and wet climate during ~ 6,500–5,600 cal years BP and ~ 3,700–2,750 cal years BP promoted the prosperity of the local culture, together with cultural interchange, and the climatic conditions also encouraged the dispersal of early agriculture in the East Liao River Basin. In addition, archaeological excavations have shown that there was frequent interchange and interaction among prehistoric cultures in NE China, and we hypothesize that the Liao River Basin was the main routeway for cultural interchange and the dispersal of prehistoric agriculture in NE China.

Keywords East Liao River Basin · Changshan site · Prehistoric agriculture · Phytoliths · Archaeological evidence

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Introduction

Northeast (NE) China is one of the most important regions in China for the modern cultivation of corn, soybean, rice and other crops (Cheng and Zhang 2005). Both the origin of agricultural domestication and sedentism in the region can be traced back ~ 8,000 years ago (Yu 1985; Guo et al. 1993; Yi 1993; Tao et al. 2011; Shelach-Lavi et al. 2019; Zhao 2014, 2019). It is regarded as one of the areas of origins of dry farming, characterized by the domestication and cultivation of common millet (*Panicum miliaceum*) and foxtail millet (*Setaria italica*) (Liu et al. 2015). The results of archaeological excavations have shown that early agriculture in NE China was mainly practiced in the West Liao River Basin and the Lower Liao River Basin, both located in the southern part of NE China (Yi 1993; Liu et al. 2012). In contrast, the prehistoric economy of the northern part of NE China (the East Liao River Basin, Nenjiang River Basin, Songhua River Basin and Heilongjiang River Basin) was for a long time thought to be dominated by fishing and hunting and there have been few prehistoric agricultural discoveries

(Zhao 2006, 2007). In general, the spatio-temporal pattern of agriculture in NE China, from prehistoric times to the modern period, shows a pronounced difference between the northern and southern parts of the region. Diversified prehistoric subsistence strategies were adopted in the northern and southern parts of NE China, which differed from the modern agriculturally based economy. Thus, an important question arises regarding the reasons for the disparity in this prehistoric spatio-temporal pattern, and specifically which factors were responsible for the limited practice of prehistoric agriculture in the northern part of NE China. Notably, there is archaeological evidence for the occurrence of exchanges between prehistoric cultural areas in the northern and southern parts of NE China (Zhao 2011a; Wu 2011; Zhao 2016; Duan 2018; Lin 2018; Wang 2019). However, it remains unclear why this prehistoric cultural exchange failed to promote the dispersal of prehistoric agriculture from the south to the north in NE China, and how it modified the subsistence strategy of prehistoric humans in the north.

Carbonized seeds and plant remains from archaeological excavations can directly reflect the plant-utilization strategies of prehistoric humans. However, previous research paid little attention to the remains of crop plants, due to the absence of prehistoric farm implements in the northern part of NE China. Recently, however, the emergence and widespread use of new methods, such as phytolith and starch grain analysis, have promoted significant developments in archaeobotanical research. As a consequence, great progress has been made in the study of the origin, domestication and dispersal of rice, millet and other crops (Piperno and Stothert 2003; Itzstein-Davey et al. 2007; Lu et al. 2009a; Yang et al. 2012; Wu et al. 2014; Ball et al. 2016; Luo et al. 2016, 2019; Hilbert et al. 2017; He et al. 2017). For example, it has proven possible to distinguish and quantify the occurrence of millet (common millet and foxtail millet) and their ancestral weed plants from archaeological sites using phytolith analysis (Lu et al. 2009b; Zhang et al. 2010, 2018, 2019; Weisskopf and Lee 2016).

Although the multiplicity and redundancy of phytoliths are problematic, phytolith analysis has great advantages for distinguishing the Poaceae, especially several common cereals. Given the advantages of phytolith analysis in the identification of crops at archaeological sites, and in order to study prehistoric agricultural dispersal and cultivation in the East Liao River Basin, we applied the method at the Changshan site in the East Liao River Basin, which is adjacent to the region where crop plants were domesticated. Combined with archaeological excavations at the Changshan site in 2016 and 2017, our aims were as follows: (i) to provide chronological evidence of the prehistoric period at the Changshan site; (ii) to obtain direct evidence for prehistoric agriculture practiced at the site; (iii) to determine the climatic conditions within which prehistoric agriculture was practiced; and (iv) to determine the possible dispersal route of prehistoric agriculture in NE China. Overall, it was hoped that the study would provide a reference for understanding prehistoric human-environmental interactions in NE China.

Study area and archaeological sites

The Changshan site, which was discovered in 1983, is situated in the northwestern part of Changshan village, in Lishu County in Jilin Province (43° 44′ 30.1″ N, 124° 25′ 45.7″ E). The site is located on a long and narrow sand dune on the first terrace in the middle reaches of the East Liao River, with a maximum height ~ 10 m above the first terrace, and ~ 1 km from the East Liao River. The site was jointly excavated in 2016 and 2017 by the Research Center for Chinese Frontier Archaeology of Jilin University, the Jilin Province Archaeology and Cultural Relics Institute, the Siping Cultural Relics Management Committee Office and the Lishu County Cultural Relics Administration. Remains of the Bronze Age and the Liao and Jin dynasties were excavated in 2016 (Lin et al. 2018), and Neolithic remains were excavated in 2017; they included 23 houses, 10 tombs, 299 ash pits and 10 ditches. In addition to the houses, tombs, ash pits, ditches, pottery sherds, stone tools, jade artefacts and clay figurines which were excavated, the Changshan site also yielded a large number of freshwater fish bones, bivalve shells and a few pieces of turtle shells along with mammal and bird remains (the zooarchaeological results have not yet been published). Overall, the Changshan site represents four archaeological occupations according to the characteristic of the remains, which are dated to the Neolithic, the Bronze Age, the Liao and Jin dynasties and the Qing dynasty.

The Changshan site is located in the middle reaches of the East Liao River. Regulated by the East Asian Monsoon (EAM), the regional climate exhibits significant seasonal variability. The mean annual temperature (MAT) is ~ 6.73 ℃, with a maximum temperature of the 23.8 ℃ in July and a minimum temperature of − 14.2 ℃ in January. Precipitation is concentrated in summer (June, July and August) and represents 69% of the annual total. The mean annual precipitation (MAP) is ~ 488 mm, and the precipitation is delivered mainly by the East Asian Summer Monsoon (EASM) (Gujiazi meteorological station for 1981–2010, National Meteorological Information Center, http://data.cma.cn) (Fig. 1). Regulated by the East Asian Winter Monsoon (EAWM), the region experiences long cold winters with strong winds. The Changshan site is located near the Song-Liao watershed, with an elevation of ~ 155 m a.s.l., and the sand dune on which it is located is the eastern extension of the edge of the Horqin Sandy Land.

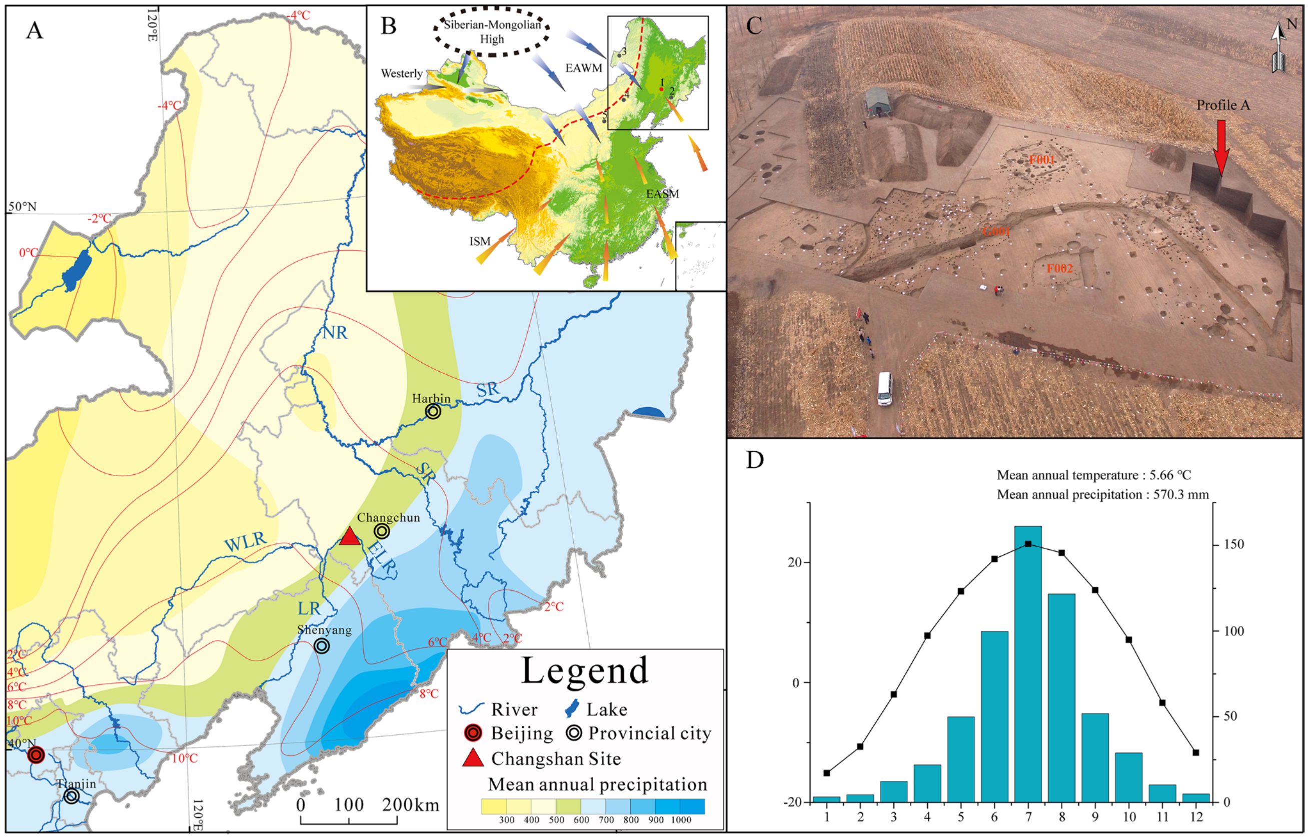

Fig. 1 **A** Location of the studied area in NE China and the spatial distribution of precipitation and temperature. **B** Modern trajectories of the East Asian summer and winter monsoon winds. **C** Photos of the excavation area. **D** Annual distribution of temperature and precipitation at Gujiazi meteorological station

Materials and methods

Sampling

Lithology of the studied profiles

In October 2017, a 4.1-m-long archaeological profile (profile A) was excavated from the northeastern part of the core of the excavation area, and a 2.8-m-long naturally exposed profile (profile B), with less evidence of human disturbance, was selected at a site some 200 m away, in the southeastern part of the excavation area. The lithology of profile A is as follows: 0–30 cm, ploughed layer consisting of grey fine sand with numerous plant roots; 30–75 cm, yellow fine sand, gradual lower boundary; 75–110 cm, black brown paleosol; 110–160 cm, yellow fine sand, gradual lower boundary; 160–215 cm, black brown cultural layer, containing numerous clam shells, fish bones, mammal bones and pottery fragments, gradual lower boundary; 215–300 cm, yellow fine sand; and 300 cm-base, black brown paleosol. Eighty-two samples were collected from the profile, at 5-cm intervals.

The lithology of profile B is as follows: 0–65 cm, yellow fine sand with numerous plant roots. Below 65 cm, the yellow fine sand is gradually mixed with occasional small pebbles. Within the intervals of 90–110 cm and 140–175 cm, the yellow fine sand gradually becomes a black brown paleosol. The intervals of 110–140 cm and 175–230 cm are mainly yellow fine sand. Below 230 cm, the yellow fine sand is mixed with greyish-white fine sand. Fifty-six samples were collected from the profile at 5-cm intervals.

Specimens from 5 levels of profile A and 4 levels of profile B were selected for AMS ^{14}C dating based on the sedimentary characteristics of the profiles and the archaeological stratigraphy. The dating was conducted at the State Key Laboratory of Organic Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China.

Relic samples

Sixty-five archaeological samples were collected for phytolith analysis and AMS ^{14}C dating. Phytolith analysis was performed on 52 of the 65 samples for which chronological information was available. Twenty-four of the 65 samples (12 from ash pits, 7 from hearths, 3 from ditches, 1 from a dwelling place, and 1 from a pillar hole) were used for AMS ^{14}C dating. There were 11 samples for which both phytolith analysis and AMS ^{14}C dating were conducted.

Laboratory analyses

Phytolith extraction

Phytoliths were extracted using the standard procedures for sediment samples (Piperno 1988; Wang and Lu 1992). First, carbonate was removed from ~ 20 g of sample with 10% HCl, and then organic matter was removed with concentrated H_2O_2, after washing with distilled water. To calculate phytolith concentrations, *Lycopodium* spores (27,560 spores/tablet) were added to each sample, followed by centrifuging three times at 2,500 revs/min for 10 min. Flotation of phytoliths was conducted with a $ZnBr_2$ solution with a specific gravity of 2.38. After washing with distilled water, samples were dehydrated with anhydrous ethanol and fixed on a microscope slide with Canada balsam. Finally, the slides were examined at × 600 magnification with an OLYMPUS BX53 biomicroscope, and more than 300 phytoliths were counted per slide. A total of 68,088 phytoliths, diatoms and sponge spicules were counted and identified. The concentrations of phytoliths and diatoms were calculated based on the number of *Lycopodium* spores, as follows:

$$a = \frac{b \times 27560}{c \times d}$$

Here, a is the concentration of phytoliths/diatoms, b is the counted number of phytoliths/diatoms, c is the counted number of *Lycopodium* spores, and d is the sample weight.

Organic matter content ($LOI_{550℃}$) and grain size analysis

The organic matter content of the samples from profile A was measured using weight loss-on-ignition (LOI). The samples were first homogenized using a pestle and mortar. Samples of 10–15 g weight were then heated to 105 °C for 24 h to constant weight and then combusted at 550 °C for ~ 6 h to constant weight; the weight at 550 ℃ ($LOI_{550℃}$) was then calculated.

The grain size distributions of the samples from profile A were also measured. Samples were pretreated by sequentially adding ~ 5–10 ml of 10% HCl and 10% H_2O_2 to remove carbonate and organic matter, respectively. The treated samples were rinsed 3–4 times with deionized water until they were pH neutral. Finally, the samples were dispersed by adding 10 ml of 0.05 mol/L sodium hexametaphosphate $(NaPO_3)_6$ solution followed by ultrasonication for 10 min. The grain size distributions were measured using a Microtrac S3500 laser grain size analyser with a measurement range of 0.02–2,000 μm.

Results

Chronology

Specimens from 5 levels of profile A, 4 levels of profile B and 24 archaeological samples were selected for AMS ^{14}C dating (Tables 1 and 2), based on the sedimentary features of the profiles and the archaeological stratigraphy. The 33 radiocarbon ages were calibrated to calendar years before present (1950) using the IntCal13 calibration curve (Reimer et al. 2009).

As shown in Fig. 2, only the Bronze Age cultural layer is contained within the profile A, and its age range is 3,172–3,386 cal years BP. The 24 dates from the archaeological samples were selected in order to

Table 1 Results of radiocarbon dating of samples from the profile A and profile B at the Changshan site

Laboratory code	Sample code	Depth interval (cm)	Sample type	Conventional radiocarbon age (BP)	Calibrated date (2σ range) (Cal BP)
NENUR10468	CSZR-15	70–75	Organic matter	1965 ± 40	1995–1825
NENUR10469	CSZR-32	155–160	Organic matter	4230 ± 50	4870–4584
NENUR10470	CSZR-44	215–220	Organic matter	5300 ± 60	6266–5935
NENUR10471	CSZR-55	270–275	Organic matter	6920 ± 70	7928–7622
NENUR10472	CSRW-20	95–100	Organic matter	2855 ± 40	3137–2859
NENUR10474	CSRW-34	165–170	Organic matter	3090 ± 40	3386–3182
NENUR10475	CSRW-45	220–225	Organic matter	3080 ± 45	3384–3172
NENUR10476	CSRW-55	270–275	Organic matter	4095 ± 45	4820–4443
NENUR10477	CSRW-75	370–375	Organic matter	4210 ± 45	4855–4586

Table 2 Results of radiocarbon dating of samples from the archaeological samples at the Changshan site

Laboratory code	Sample code	Sample type	Conventional radiocarbon age (yr BP)	Calibrated date (2σ range) (cal years BP)
NENUR10442	F001Z002③	Charcoal	5020 ± 60	5907–5623
NENUR10443	F001Z008③	Charcoal	5020 ± 50	5900–5654
NENUR10444	F001G001①	Charcoal	5210 ± 60	6182–5768
NENUR10446	F002Z001①	Charcoal	7970 ± 80	9014–8602
NENUR10447	F005Z001③	Charcoal	4480 ± 60	5310–4887
NENUR10449	F009①	Charcoal	4935 ± 50	5857–5588
NENUR10450	F010Z001③	Charcoal	5350 ± 60	6281–5993
NENUR10451	F011Z003①	Charcoal	5170 ± 60	6175–5746
NENUR10452	F014H001①	Charcoal	4495 ± 50	5309–4974
NENUR10453	F015Z001①	Charcoal	285 ± 35	460–156
NENUR10454	F016D041①	Charcoal	5270 ± 60	6201–5918
NENUR10456	G001②	Charcoal	2870 ± 40	3142–2872
NENUR10457	G001③	Charcoal	5640 ± 60	6562–6298
NENUR10459	H043①	Organic matter	3395 ± 45	3825–3497
NENUR10460	H076①	Charcoal	4945 ± 50	5875–5590
NENUR10461	H076②	Charcoal	5010 ± 50	5900–5645
NENUR10463	H113①	Charcoal	5290 ± 60	6263–5927
NENUR10464	H132③	Charcoal	1115 ± 40	1173–935
NENUR10465	F001H021①	Charcoal	5350 ± 60	6281–5993
NENUR10466	H223③	Charcoal	4940 ± 50	5862–5588
NENUR10467	H226①	Charcoal	4965 ± 50	5887–5596
NENUR10556	H152②	Ash	1080 ± 35	1059–931
NENUR10557	H250	Organic matter	2745 ± 35	2925–2764
NENUR10560	F001H007①	Ash	3820 ± 35	4405–4091

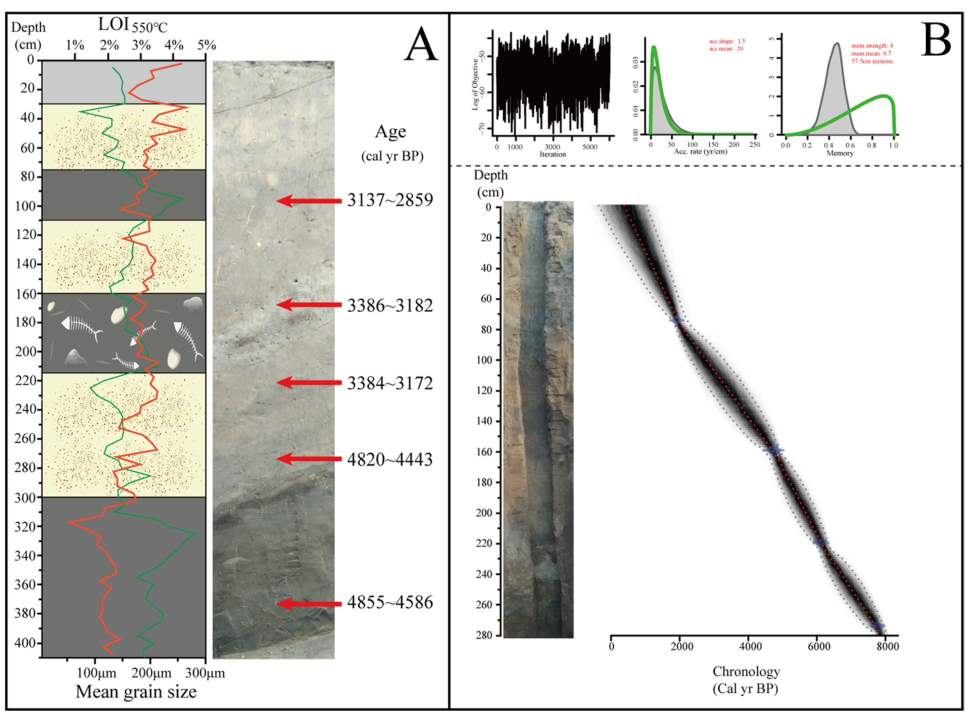

Fig. 2 Sedimentary characteristics of the archaeological profile (**A**) and the age-depth model for the natural profile (**B**). The red and green lines respectively show profiles of mean grain size and organic matter content (LOI_{550}℃) in the archaeological profile. The red arrows indicate the calibrated date of radiocarbon ages, and the grey-shaded area represents the 95% confidence intervals of the age-depth model

establish an archaeological chronology (Fig. 3) using the OxCal 4.3 program (Ramsey 2009). The summed probabilities graph, which combines 2 dates of the cultural layer from the profile A and 24 dates of the archaeological samples, was drawn using CALIB 7.04 program (Stuiver et al. 2020). As shown in Fig. 3, the summed probabilities for 26 dates show a cluster of age within two main intervals: ~6,500–5,600 cal years BP and ~3,700–2,750 cal years BP, in the prehistoric period.

An age-depth model of the profile B (Fig. 2) was generated using Bayesian analysis implemented with the Bacon 2.2 program (R version 3.6.2) (Blaauw and Christen 2011). During the process, millions of Markov Chain Monte Carlo (MCMC) iterations were conducted to estimate the sediment accumulation rate for each part of the sections. Thereby, it was possible to eliminate the influence of anomalous data and to construct a reliable age-depth model. The results showed that the number of iterations of the corresponding years exceeded 5,000, which indicates that a reliable chronological framework had been obtained. The sedimentation accumulation rate parameters conformed to the gamma distribution, and the number of samples included in the sedimentation rate at a specific depth accorded with the beta distribution. Based on the AMS ^{14}C ages and the age-depth models, the profile B represents a continuous sedimentary sequence for the interval of 7,724–396 cal years BP. The surface of profile B is not modern due to erosion caused by modern agricultural activity.

Phytolith and diatoms in profile A

A total of 33,043 phytoliths were identified in the profile A samples, and they were classified into morphotypes according to previous studies (Wang and Lu 1992; Madella et al. 2005; Lu et al. 2009a, b). A stratigraphic diagram of the phytolith assemblages for profile A is presented in Fig. 4. The phytolith types include short cell phytoliths (saddle, rondel, bilobate, cylindrical polylobate, cross, trapeziform sinuate); long cell phytoliths (elongate psilate, elongate tabular, elongate attenuate, elongate echinate, elongate granulate); hair cell phytoliths (prickle, lanceolate, hair); bulliform cell phytoliths (cuneiform and cubic); millet phytoliths (η-type husk phytolith from common millet and Ω-type husk phytolith from foxtail millet); and other types (blocky irregular, tabular irregular, square, epidermal phytolith, silicified stomata, tracheid, sclereid, carinate) (Figs. 5 and 6). The phytolith concentration of the profile is high (mean of 168,706 grains/g), especially within the intervals of ~160–225 cm (~3,172–3,386 cal years BP) and ~300–410 cm (~4,586–4,855 cal years BP).

The saddle, rondel, bilobate and trapeziform sinuate types amongst the short cell phytoliths are present at high

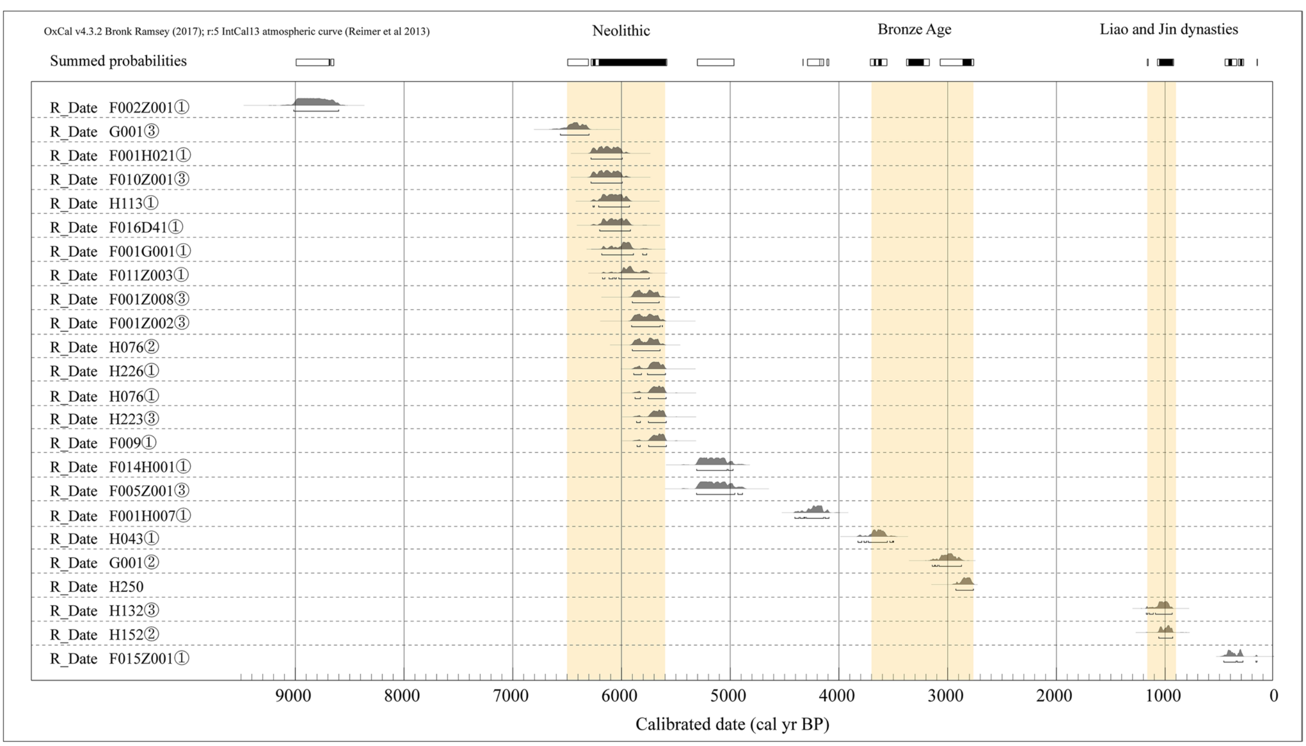

Fig. 3 Calibrated radiocarbon dates (OxCal v4.3.2) for the Changshan archaeological samples (detailed data are shown in Table 2). The orange rectangles represent the three main occupation periods of the Changshan site

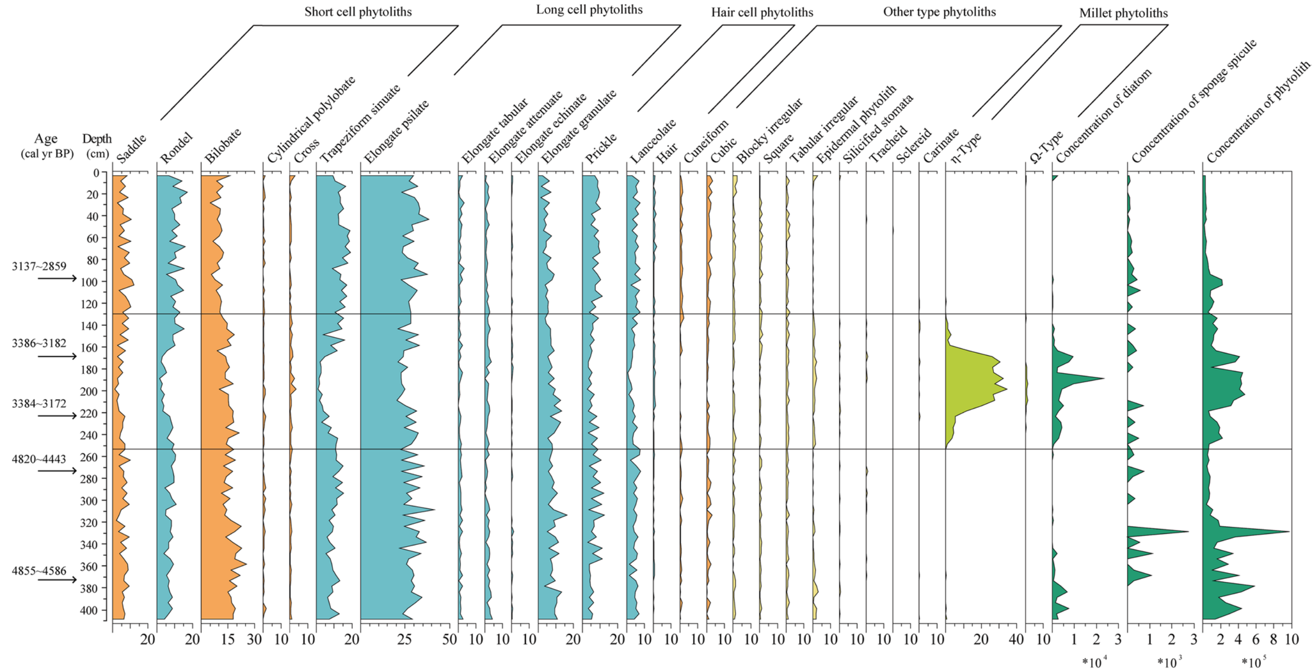

Fig. 4 Phytolith diagram for profile A

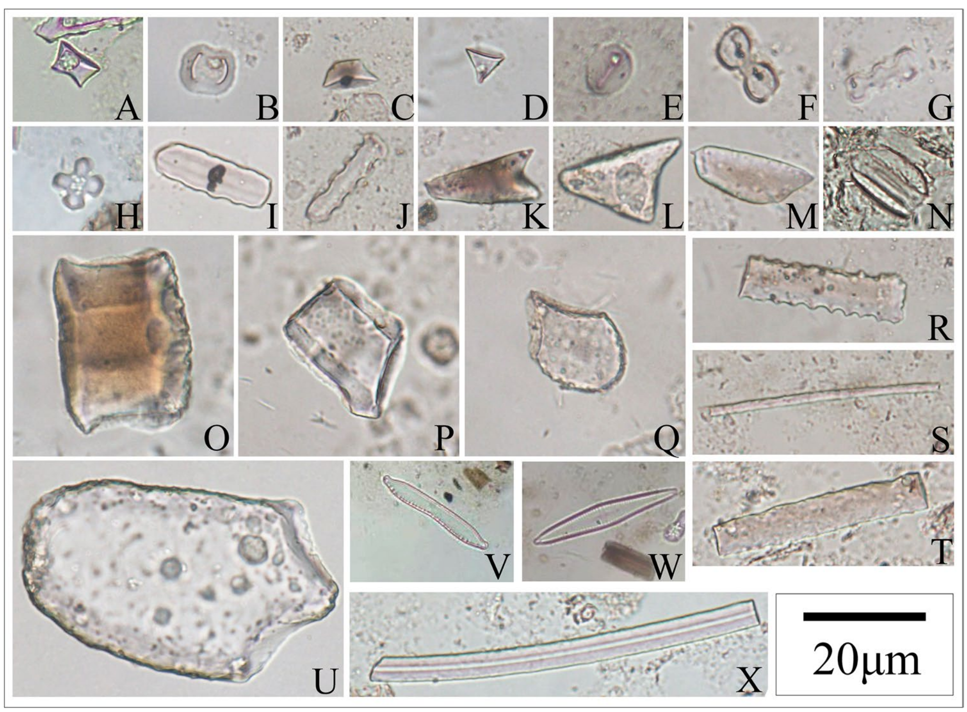

Fig. 5 Microphotographs of phytoliths and diatoms found during the study. (**A** and **B**) Saddle; (**C**-**E**) Rondel; (**F**) bilobate; (**G**) cylindrical polylobate; (**H**) cross; (**I** and **J**) trapeziform sinuate; (**K**–**M**) lanceolate; (**N**) silicified stomata; (**O**) cubic; (**P**) blocky irregular; (**Q** and **U**) cuneiform; (**R**) elongate granulate; (**S**) elongate attenuate; (**T**) elongate psilate; (**V** and **W**) diatom; (**X**) sponge spicule

frequencies (6.1%, 8.2%, 14.4% and 10.4%, respectively). Long cell phytoliths mainly consist of elongate psilate and elongate granulate types, and the corresponding percentages are 28.3% and 7.4%, respectively. Hair cell phytoliths are dominated by prickle and lanceolate types (6.7% and 4.7%). Other phytolith types are present at a low level, with percentages < 2%. Notably, the η-type husk phytolith from common millet (*Panicum miliaceum*) is relatively abundant and concentrated in the middle of the profile (~ 3,172–3,386 cal years BP), and it occurs sporadically at ~ 410–370 cm (~ 4,586–4,855 cal years BP). The percentages of the η-type husk phytolith increase gradually

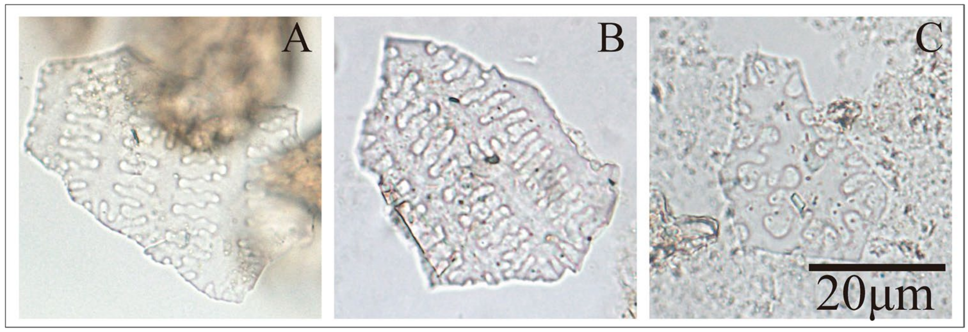

Fig. 6 Microphotographs of millet phytoliths found during the study. (**A** and **B**) η-type husk phytolith from common millet (*Panicum miliaceum*); (**C**) Ω-type husk phytolith from foxtail millet (*Setaria italica*)

at 250 cm, and then rapidly above 225 cm, and reaching a maximum (34.5%) at 200 cm (3,386–3,172 cal years BP). The percentages then decrease sharply above 165 cm and the η-type husk phytolith disappeared at 130 cm. In addition, the Ω-type husk phytolith from foxtail millet (*Setaria italica*) is sporadically distributed within the interval of 250–135 cm (~4,443–3,137 cal years BP).

Two hundred fifty-two diatoms and 49 sponge spicules were identified while identifying the phytoliths (Hu and Wei 2006; Liu 2010). The major diatom types are *Navicula radiosa*, *Navicula cryptocephala* and *Hantzschia amphioxys* (Fig. 5). The mean diatom concentration is 1,658 valves/g, and the peak concentration (23,210 valves/g) occurs at 190 cm (3,172–3,386 cal years BP). The profile can be divided into two intervals according to the diatom concentrations. The first interval is 410–345 cm (~4,586–4,855 cal years BP), and the second is 265–145 cm (~4,443–3,137 cal years BP). Notably, the variations in diatom concentration are synchronous with those of the percentages of the η-type husk phytolith, which can potentially be explained by the appearance of agricultural irrigation at the Changshan site.

Phytoliths in archaeological samples

A total of 12,801 phytoliths were identified from 52 archaeological samples. A total of 1,968 η-type husk phytoliths from common millet (*Panicum miliaceum*) were identified in 39 of the 52 samples, and only 9 Ω-type husk phytoliths from foxtail millet (*Setaria italica*) were identified (Fig. 7). In addition, the results for 10 of the 52 samples with high concentrations of η-type husk phytoliths (exceeding 10,000 pieces/g) and 22 of the 52 samples with a high ratio of η-type husk phytoliths to other phytoliths (exceeding 0.1) are shown in Fig. 7. The archaeological samples can be divided into three periods based on AMS ^{14}C dating

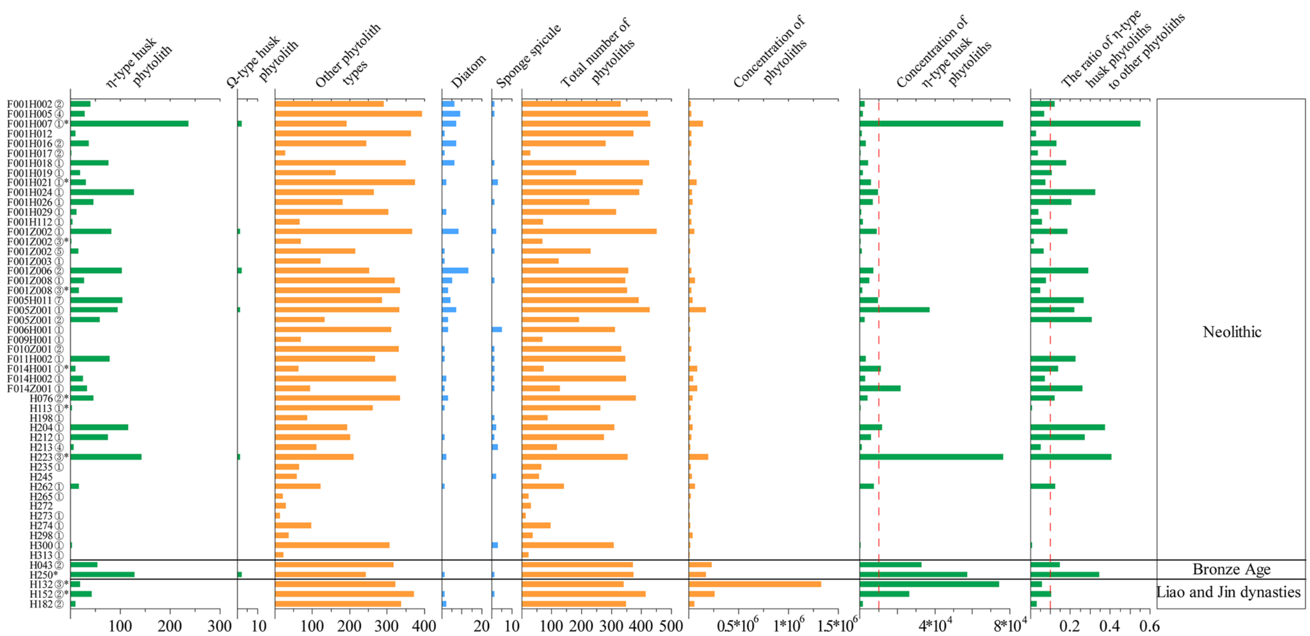

Fig. 7 Phytolith diagram for the archaeological samples. In the sample number, 'F' represents a house, 'H' represents an ash pit, 'Z' represents a hearth; the circled number represents the layer and '*' represents the radiocarbon age

and archaeological stratigraphy: (i) Neolithic (19 ash pits from house nos. F001, F005, F006, F009, F011 and F014, 11 hearths from house nos. F001, F005, F010 and F014, 17 ash pits independent of houses); (ii) Bronze Age (2 ash pits independent of houses); (iii) the Liao and Jin dynasties (3 ash pits independent of houses). The η-type husk phytolith has been identified in 34 Neolithic and all 5 Bronze Age and Liao and Jin dynasties archaeological samples. Only 5 Neolithic and a Bronze Age archaeological samples contained Ω-type husk phytolith. Furthermore, the Neolithic samples H223③ and F001H007①, and Bronze Age sample H250, contained high concentrations of η-type husk phytoliths and high ratios of η-type husk phytoliths to other phytoliths (> 50,000 pieces/g and > 0.3, respectively). Samples F001H007①, H223③ and H132③ have comparatively high concentrations of η-type husk phytoliths (76,315 pieces/g, 76,483 pieces/g and 74,105 pieces/g, respectively). Notably, sample F001H021①, dated to 5993–6281 cal years BP, was determined to contain 30 η-type husk phytoliths, and is the earliest sample containing millet phytolith.

Organic matter content (LOI$_{550℃}$) and grain size distributions of the profile A

The LOI$_{550℃}$ values of profile A reflect the fluctuations in the organic matter content (Fig. 2A). The profile indicates that the organic content is generally low throughout the profile, with a range of 1.2–4.7% and mean of ~ 2.8%. The profile can be divided into seven intervals according to the variations in lithology and organic matter content: three intervals with high values (75–110 cm, 160–215 cm and 300–410 cm, with respective values of 3.5%, 2.9% and 3.4%); three intervals with low values (30–75 cm, 110–160 cm and 215–300 cm, with respective values of 2.1%, 2.6% and 2.3%); and the plough layer (0–30 cm, 2.4%).

Variations in the mean grain size of the profile A (Fig. 2A) reflect changes in the sedimentary environment. Most of the samples consist of fine sand (125–250 μm), with a few samples consisting of very fine sand (63–125 μm) (Wentworth 1922). Notably, the mean grain size is negatively correlated with the LOI$_{550℃}$ curve, except for within the cultural layer.

Phytolith content of profile B

A total of 21,602 phytoliths were identified in the profile B samples, and the corresponding phytolith diagram is shown in Fig. 8. The phytolith types within the profile are short cell phytoliths (saddle, rondel, bilobate, cylindrical polylobate, cross, trapeziform sinuate); long cell phytoliths (elongate psilate, elongate tabular, elongate attenuate, elongate echinate, elongate granulate); hair cell phytoliths (prickle, lanceolate, hair); and other types (cuneiform, cubic, blocky irregular, square, tabular irregular, epidermal phytolith, silicified stomata, tracheid, sclereid) (Fig. 5).

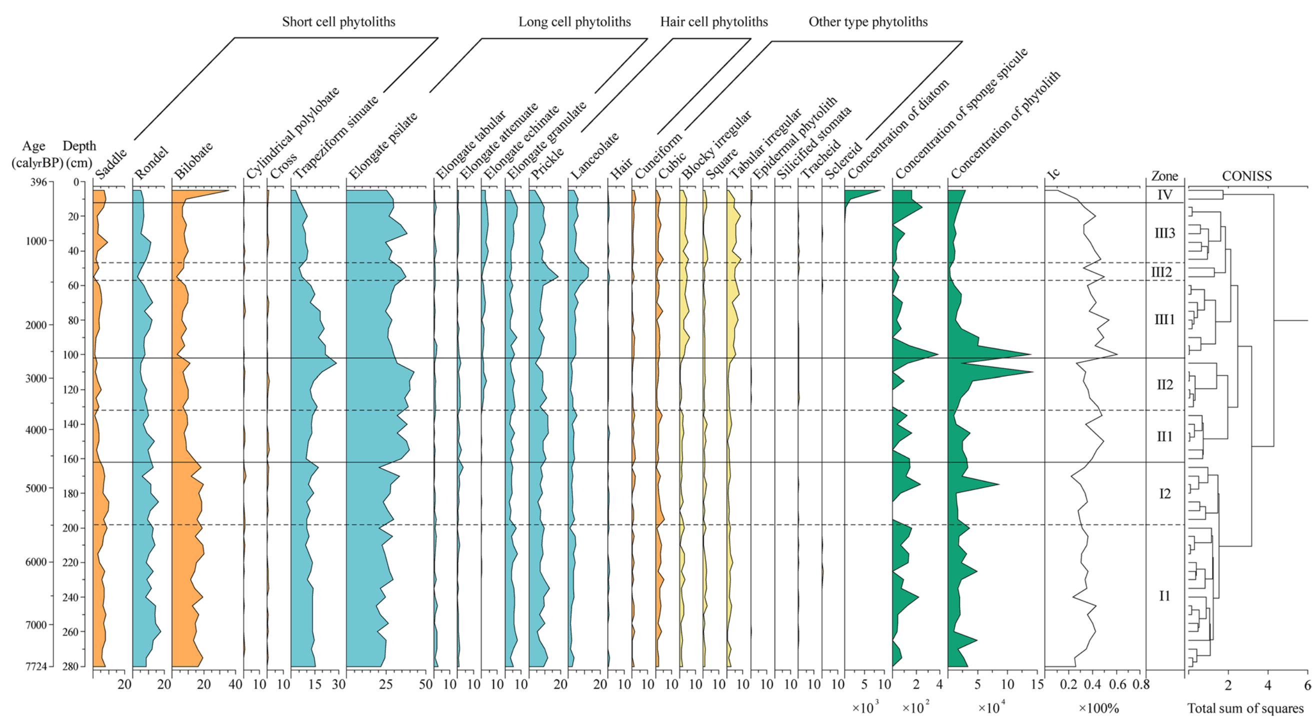

Fig. 8 Phytolith diagram for profile B

The saddle, rondel, bilobate and trapeziform sinuate types within the short cell phytolith category are relatively abundant (5.1%, 9.7%, 12.1% and 12.9%, respectively), as are the elongate psilate and elongate granulate types within the long cell phytoliths category (29.0% and 4.9%, respectively). Hair cell phytoliths are dominated by prickle and lanceolate (8.9% and 3.8%, respectively), while the other types are poorly represented. The application of cluster analysis enables the phytolith assemblages to be divided into four zones and seven subzones (Fig. 8). With reference to previous studies (Twiss 1992; Bremond et al. 2008) and the phytolith assemblages within profile B, we calculated the Ic index (climatic index) in order to reconstruct the paleoenvironment of the Changshan site. The Ic index is calculated as follows:

$$Ic = \frac{\text{Rondel} + \text{Trapeziform}}{\text{Rondel} + \text{Trapeziform} + \text{Saddle} + \text{Cross} + \text{Bilobate}} \times 100\%$$

A high Ic value represents a cooler climate and a low value a warmer climate.

Discussion

Chronological evidence of the prehistoric period at the Changshan site

An early archaeological survey of the East Liao River Basin reported the discovery of numerous archaeological remains of the Neolithic and the Bronze Age near the Changshan site (Lin et al. 2018). Jin (1992) divided the Neolithic remains of the Changshan site into two periods, 6,000–5,500 years BP and ~ 5,000 years BP, based on an analysis of pottery sherds. Zhao and Yu (2016) summarized the results of previous excavations and proposed that the age range of the Neolithic remains at the Changshan site was ~ 6,500–6,000 years BP, which is roughly synchronous with the Late Lower Zuojiashan culture and the Early Hongshan culture (Table 3). The results of an archaeological excavation in 2016 (Lin et al. 2018) also indicated that the age range of the Neolithic remains at the Changshan site was ~ 6,000–5,000 years BP. However, there is much conjecture regarding the age of the Bronze Age remains from the Changshan site; the results of

Table 3 Archaeological culture in NE China

NRB&WSNP			The remains of Xiaolaha Phase I Group A		The Type of Bashan in Haminmangha Culture		Angangxi Culture		Baijinbao Culture
SRB	Early Lower Zuojiashan Culture	Middle Lower Zuojiashan Culture	Late Lower Zuojiashan Culture		Early Upper Zuojiashan Culture	Late Upper Zuojiashan Culture			Xituanshan Culture
LLRB	Early Lower Xinle Culture	Late Lower Xinle Culture	Early Hongshan Culture	Middle Hongshan Culture	Late Hongshan Culture	Early Pianbaozi Culture	Late Pianbaozi Culture	Gaotaishan Culture	
WLRB	Xinglongwa Culture	Zhaobaogou Culture and Fuhe Culture	Early Hongshan Culture	The phase of Xishuiquan in Hongshan Culture and The Early Xiaoheyan Culture	The phase of Dongshanzui in Hongshan Culture and The Early Xiaoheyan Culture	Late Xiaoheyan Culture		Lower Xiajiadian Culture	Upper Xiajiadian Culture
ELRB			Changshan site Neolithic remains					Changshan site Bronze Age remains	
	Early	**Middle**	**Late**	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**
	Phase I			**Phase II**		**Phase III**		**Bronze Age**	
	Neolithic Age								

Modified from Zhao (2004a). *NRB&WSNP*, the Nenjiang River Basin and the Western Songnen Plain; *SRB*, the Songhua River Basin; *LLRB*, the Lower Liao River Basin; *WLRB*, the West Liao River Basin; *ELRB*, the East Liao River Basin an archaeological excavation in 2017 indicated that the age was ~ 3,000 years BP. In summary, based on the evidence from the archaeological excavations and without reference to absolute dating, the ages of the occupation phases of the Changshan site are ~ 6,500–5,000 years BP and ~ 3,000 years BP.

Our independent chronology for the Changshan site is based on 26 AMS radiocarbon dates for 24 individual archaeological samples and 2 samples from the cultural layer of the profile A, which were obtained in 2017. As shown in Fig. 3, the summed probabilities of 26 dates are clustered within two main intervals of ~ 6,500–5,600 cal years BP and ~ 3,700–2,750 cal years BP, in the prehistoric period, representing two main occupation phases at the Changshan site. Furthermore, there are 4 samples that fell outside of these two periods, which may indicate a transitory occupation. In summary, based on chronological evidence and the archaeological stratigraphy, we infer that there were two intervals during which prehistoric societies flourished at the Changshan site, during ~ 6,500–5,600 cal years BP and ~ 3,700–2,750 cal years BP. This provides a chronological framework for a study of the process of prehistoric agricultural dispersal and the climatic context at the Changshan site.

Direct evidence for prehistoric agriculture at the Changshan site

Carbonized seeds, prehistoric farm implements and macro- and microscopic remains recovered from archaeological site are considered as direct evidence of agriculture. Evidence from Neolithic sites throughout China indicates that a critical phase in the domestication of prehistoric agriculture, both in north and south China, occurred at ~ 8,000 years BP (Xia 2012). A large amount of carbonized domesticated crop remains, identified as rice, foxtail millet, broomcorn millet and soybean, were recovered, together with many prehistoric farm implements dating to this period (Liu and Chen 2012). In the southern part of NE China, carbonized domesticated millet remains were recovered by flotation from the Xinglonggou site in Inner Mongolia (Zhao 2004b), from the Xinle site and Tachiyingzi site in Liaoning (Yu 1985; Shelach-Lavi et al. 2019), and from the Weijiawopeng site in Inner Mongolia (Sun and Zhao 2013). At the Zhahai site in Liaoning (Dian and Xin 1994) and the Baiyinchanghan site in Inner Mongolia (Guo et al. 1993), starch grains of foxtail millet and broomcorn millet were recovered from the stone tools such as grinding slabs, grinding stones, stone knives and stone shovels, which were excavated in the two sites, but no carbonized crop remains (Wu 2015; Tao et al. 2011). In conclusion, a large amount of evidence indicates that the primary subsistence strategy in the southern part of NE China was hunting and gathering, and millet domestication began to occur at ~ 8,000 years BP. However, in the northern part of NE China, archaeologists and historians have long considered that fishing and hunting dominated the prehistoric economy due to the rarity of carbonized seeds and prehistoric farm implements found at archaeological sites (Zhao 2006, 2007).

No prehistoric farm implements and carbonized seeds were found during excavations at the Changshan site during 2016 and 2017. However, abundant η-type husk phytoliths from common millet and a few Ω-type husk phytoliths from foxtail millet were found in 39 of the 52 individual archaeological samples, and 24 of the samples had concentrations of η-type husk phytolith > 10,000 pieces/g or ratios of η-type husk phytoliths to other phytoliths > 0.1. In addition, Zhang et al. (2010) identified 2,892 ± 701 η-type husk phytoliths from per common millet. In the present study, we found more than 3 grains of common millet per gram of soil in 10 archaeological samples (Fig. 7), with the highest value of ~ 26 grains/g in sample H223③. Therefore, we conclude that the prehistoric inhabitants of the Changshan site began to cultivate common millet as a dietary carbohydrate supplement as early as 6,281 years ago, while for some reason, foxtail millet was only cultivated at a very low level. In addition, a large number of η-type husk phytoliths from common millet were found in the cultural layer (dated to 3,172–3,386 cal years BP) of profile A, along with occasional Ω-type husk phytoliths and diatoms, which further supports our conclusion that the subsistence strategy of prehistoric humans at the Changshan site involved the cultivation of common millet and foxtail millet as early as 6,281 cal years BP, along with hunting and fishing, and that a multi-component subsistence strategy continued during 3,700–2,750 cal years BP.

Unlike foxtail millet, common millet is well adapted to a wide range of soil and climatic conditions. It is a relatively short-season crop and requires only a small amount of water during the growing season; it grows further north (up to 54°N) than the other millets and is also well adapted to plateau conditions and high elevations (Matz 1986). The Changshan site is located on a long and narrow dune, which is the eastern extension of the edge of the Horqin Sandy Land. The $LOI_{550℃}$ and grain size distributions of profile A indicated that in the cultural layer the sediments are fine sand (125–250 μm) and the organic matter content is relatively low (mean $LOI_{550℃}$ value of 2.9%). These soil conditions are more suited to the cultivation of common millet than foxtail millet, especially during the prehistoric period with lower productivity. It appears that during the prehistoric period, common millet was more suited to the northward dispersal of its cultivation, which explains why more common millet husk phytoliths were identified at the Changshan site.

Climatic conditions associated with prehistoric agriculture at the Changshan site

The nature of the relationship between climate and prehistoric agriculture will always be a controversial. It is undeniable that climate change played an important role in the origin and dispersal of prehistoric agriculture, although the details, together with the precise role of climate change, remain unclear (Guo et al. 2016; Lu 2017). Recent research has shown that the process of plant domestication lagged behind sedentism and progressed slowly during the wet period in the NE China (Shelach-Lavi et al. 2019). It can be seen that in NE China, climatic conditions had some degree of influence on human settlement patterns and plant domestication during the early Neolithic.

The variation of the phytolith-based Ic index in profile B at the Changshan site (Fig. 9a) indicates that the climate in the East Liao River Basin was unstable with pronounced

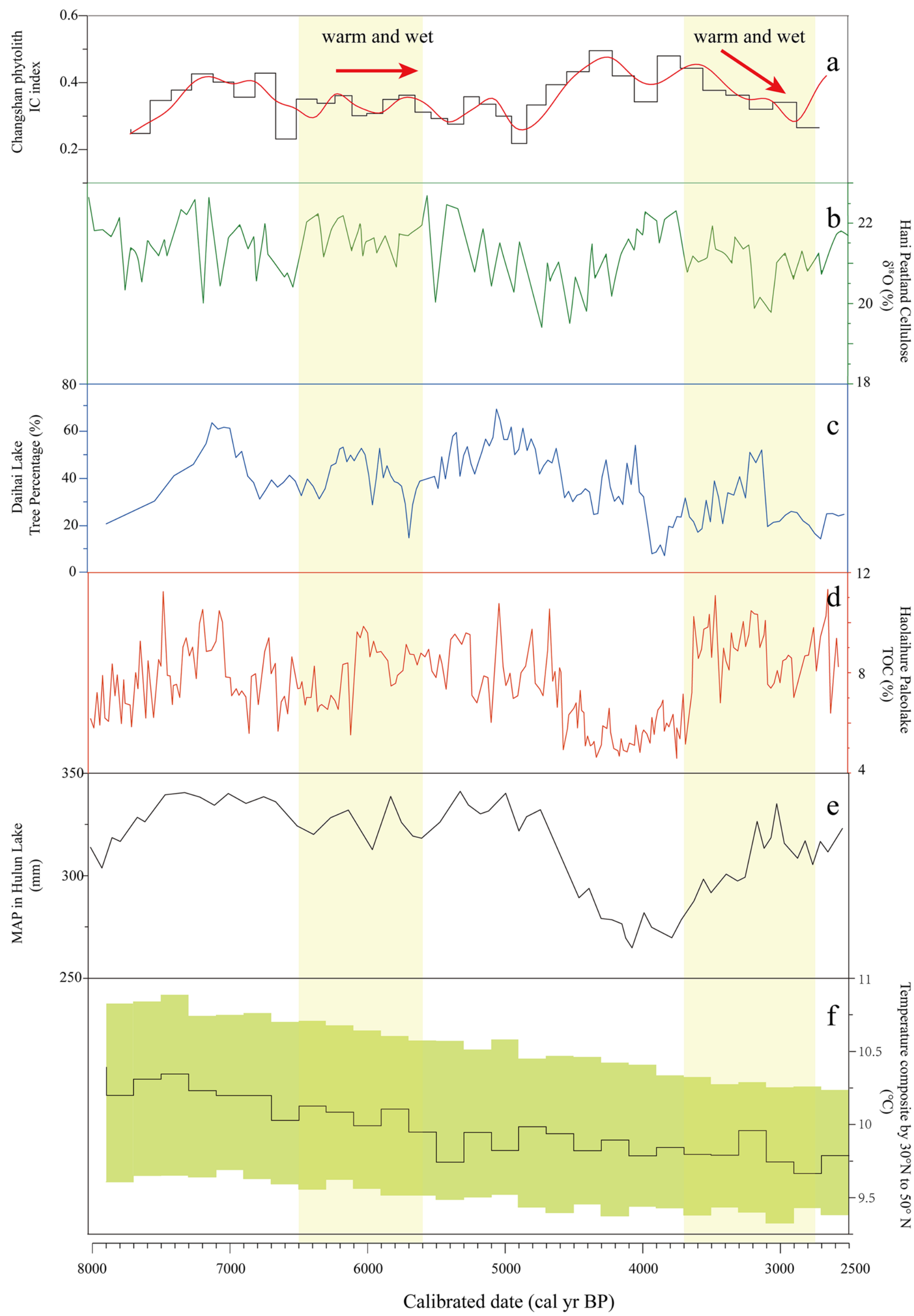

Fig. 9 Comparisons natural profile phytolith Ic index for the Changshan site with other regional palaeoclimatic records from NE China. **a** Changshan phytolith Ic index; (**b**) the cellulose ^{18}O record of the Hani peatland in the Changbai Mountains; (**c**) tree pollen percentages at Daihai Lake; (**d**) total organic carbon (TOC) content at Haolaihure paleolake; (**e**) mean annual precipitation (MAP) at Hulun Lake; (**f**) temperature composites for 30–50° N

fluctuations during 7,724–2,500 cal years BP. The Ic values are lower during 7,724–5,000 cal years BP, indicating a warm climate, and the index fluctuates substantially during 5,000–2,500 cal years BP, indicating substantial climatic change. However, the Ic index decreases during ~ 3,700–2,750 cal years BP, indicating climatic warming. Combining the Ic record with the chronological evidence, we conclude that the climate of the Changshan site was warm during ~ 6,500–5,600 cal years BP, which promoted the cultivation of crop plants and the dispersal of prehistoric agriculture in the region. During ~ 3,700–2,750 cal years BP, following a long interval of relatively low temperatures, a further climatic warming occurred at the site, which further encouraged the expansion of prehistoric agriculture in the area.

The variation of the Ic index within profile B is consistent with independent palaeoclimatic records for the region. Shi et al. (1992) concluded that the warmest phase of the Holocene in the Chinese mainland was during 8,500–3,000 years BP, based mainly on pollen studies. In the cellulose $\delta^{18}O$ record of the Hani peatland in the Changbai Mountains in the eastern part of NE China (Hong et al. 2009), intervals exceeding the mean value of the profile (21‰) occurred during at ~ 6,500–5,600 cal years BP and during ~ 3,700–3,200 cal years BP (Fig. 9b), suggesting a climate that was warmer than that of today. Notably, after ~ 3,200 years BP, there was an interval of almost 200 years of relatively low temperature. However, this may be the result of the use of different climate proxies at different locations, together with chronological uncertainties. In addition, Daihai Lake (Wen et al. 2017), Haolaihure paleolake (Liu et al. 2018) and Hulun Lake (Wen et al. 2010) are on the edge of the monsoon zone and sensitive to precipitation fluctuations. Records of tree pollen percentages at Daihai Lake (Fig. 9c), total organic carbon (TOC) content at Haolaihure paleolake (Fig. 9d), and of mean annual precipitation (MAP) at Hulun Lake (Fig. 9e) indicate a warm climate with increased precipitation during ~ 6,500–5,600 cal years BP and during ~ 3,700–2,750 cal years BP. Routson et al. (2019) used global Holocene paleoenvironmental reconstructions to produce a synthesized climate record for midlatitude regions. The results show that temperature composites for the region of 30° N to 50° N reached a maximum at 8,000 years BP, which was followed by climatic cooling. It can be seen from Fig. 9f that the climate was relatively warm during the two intervals of ~ 6,500–5,600 cal years BP and ~ 3,300–3,100 cal years BP.

In summary, the climate during ~ 6,500–5,600 cal years BP and during ~ 3,700–2,750 cal years BP was relatively warm and wet, which promoted the increased prosperity of prehistoric societies, cultural interchange, and favoured the dispersal of prehistoric agriculture in the East Liao River Basin.

Possible routeway of prehistoric agricultural dispersal in NE China

The advancement and development of human civilisation was inextricably linked to the natural environment, and it is generally accepted that favourable climatic conditions were an important contributing factor to the development and flourishing of ancient cultures (Dong et al. 2017a). It has also been argued that the domestication and diffusion of crop in prehistory contributed to the development and flourishing of ancient culture and even gave birth to civilization (Liu 2004; Weisdorf 2005; Hosoya et al. 2010). In the Early Neolithic, several centres of agricultural origin began to emerge in Eurasia, with wheat and barley domesticated in Western Asia (Zeder 2008; Zohary et al. 2012; Riehl et al. 2013), while millet and rice were domesticated in China in the Yellow River (some scholars believe that the West Liao River basin in the NE China was also one of the places where millet originated) and the Yangtze River basin, respectively (Lu 2017; Zhao 2019). The subsequent Middle Neolithic was a key period of agricultural domestication and diffusion (Mannion 1999), with wheat crops spreading in wave-like pattern from the eastern coast of the Mediterranean throughout Europe (Bocquet-Appel et al. 2012; Colledge et al. 2013; Dong et al. 2017b) and millet and rice spreading in various degrees to surrounding regions (He et al. 2017; Lu 2017). The diffusion of prehistoric agriculture contributed to a significant increase in the size of populations (Shennan et al. 2013; Stevens and Fuller 2017; Wang et al. 2014; Dong et al. 2020), which facilitated the emergence of social complexity (Underhill 2013). In the Yellow River basin of China, the Yangshao culture (~ 7,000–5,000 years BP) represents the flourishing of Neolithic farming villages (Liu and Chen 2012), which was a critical timespan in the establishment of sedentary farming societies and the emergence of social complexity (Li et al. 2021). In the West Liao River basin, the Hongshan culture (~ 6,500–5,000 years BP) was the first complex society to develop in NE China, and the agricultural economy was considered to be its most important subsistence strategies (Liu and Chen 2012). During the Middle Neolithic, cereals experienced a shift from the beginning of domestication to large-scale cultivation, the emergence of sedentary patterns, an increase in population and settlement density, which facilitated the development of a division of labour and a complex society, and more frequent exchanges and trade across regions, facilitating the circulation and diffusion of artefacts and cereals.

The scale of human activities in NE China expanded rapidly in the Middle Neolithic, more than 30 prehistoric cultures have been identified in different periods, and most regions have representative Neolithic cultures (Table 3) (Zhao 2004a; Wang 2019). In general, pottery vessels were decorated with 'Z' (之) motifs (Nelson 2003), which are

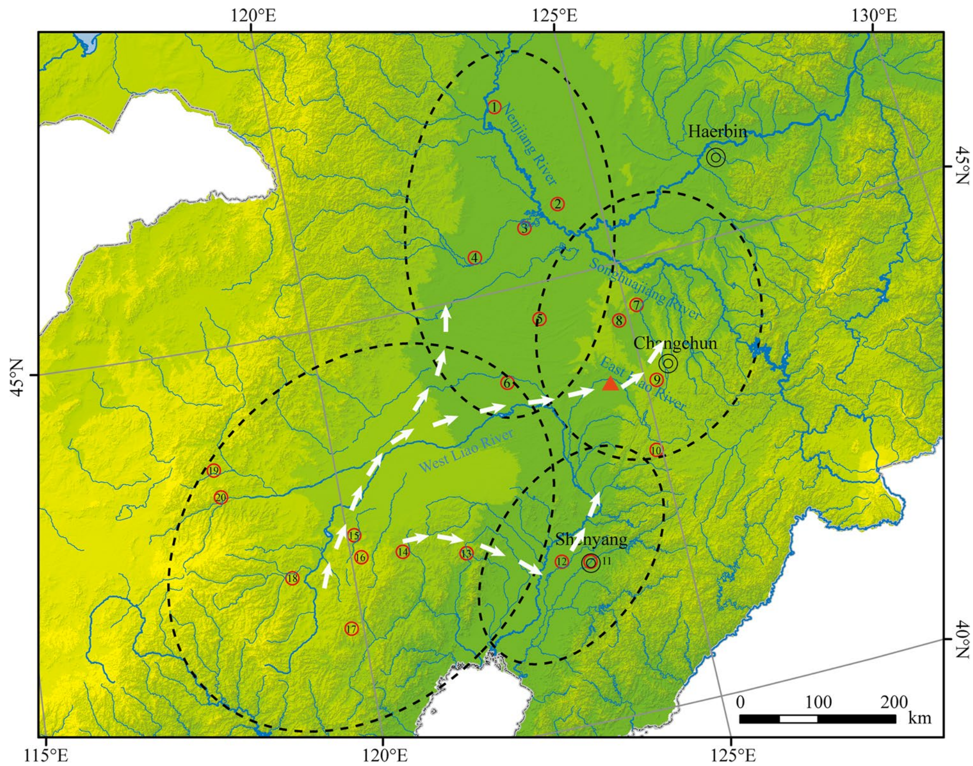

Fig. 10 Distribution of archaeological sites and archaeological cultural areas in NE China. The areas enclosed by the dotted black line are archaeological cultural areas (Table 3). Red circles represent archaeological sites (1, Aang'angxi site; 2, Xiaolaha site; 3, Houtaomuga site; 4, Shuangta site; 5, Yaojingzi site; 6, Haminmangha site; 7, Zuojiashan site; 8, Yuanbaogou site; 9, Xingshan site; 10, Xiduanliangshan site; 11, Xinle site; 12, Pianbuzi site; 13, Zhahai site; 14, Xionglongwa site; 15, Xiaohexi site; 16, Zhaobaogou site; 17, Niuheliang site; 18, Hongshan site; 19, Shuiquan site; 20, Baiyinchanghan site). The thick white lines with arrows represent the possible routeway for the dispersal of prehistoric agriculture

regarded as a unique regional decorative motif in NE China during the Neolithic, and which played an iconic role in the cultural evolution of the region. The earliest 'Z' (之) motifs appeared in the Xinglongwa culture and were then inherited and expanded as far north as the Zuojiashan culture in the Songhua River Basin (Duan 2018; Zhao 2011a, b; Wang 2019). In addition to the 'Z' (之) motif on pottery vessels, research on jade (Wu and Jiang 2011) and polychrome pottery (Zhao and Ren 2016) also demonstrates the occurrence of frequent cultural exchanges between the prehistoric cultures of NE China. Moreover, the flat and open terrain in the middle of NE China also promoted interregional interactions.

An archaeological survey of the Changshan site in 1983 and an archaeological excavation in 2016 unearthed numerous pottery vessels decorated with 'Z' (之) motifs. Archaeologists have determined that the Changshan Neolithic culture belongs to the same cultural type as the first phase of the Xiduanliangshan site, and that they both belong to the Late Lower Zuojiashan culture (Jin 1992; Lin et al. 2018). In addition, stone tools and polychrome pottery fragments excavated in 2016 were also influenced by the Hongshan culture from the West Liao River Basin (Lin et al. 2018). In conclusion, archaeological excavations have demonstrated that there was the frequent interchange and interaction of prehistoric cultures in NE China, and that the culture of the Changshan site was mainly influenced by the Late Lower Zuojiashan culture in the eastern part, and the Hongshan culture in the western part of the region. Therefore, we hypothesized that the prehistoric Liao River Basin, including the East Liao River, the West Liao River and the Lower Liao River, formed part of an important routeway of culture interchange between several cultural areas and may also have been a routeway for the dispersal of prehistoric agriculture (Fig. 10).

The Changshan site, in the middle and lower reaches of the East Liao River and adjacent to the confluence of the East Liao River and West Liao River, is located on the edge of a major archaeological cultural area. It was influenced by various prehistoric cultures, especially the Hongshan culture from the West Liao River. Therefore, the Neolithic remains of the Changshan site belong to the Late Lower Zuojiashan culture under the influence of the Hongshan culture. Due to its geographical location, the Changshan site was an early recipient of agricultural dispersal from the West Liao River Basin. Supported by the abundant water resources of the East Liao River, prehistoric cultivation became an important part of the subsistence strategy of the prehistoric inhabitants of the Changshan site.

Conclusions

Our analyses of the chronology, phytoliths, grain size distributions and organic matter content ($LOI_{550℃}$) of a profile from the Changshan site in NE China reveals evidence of the appearance of prehistoric agriculture in the East Liao River Basin. The results suggest that there were two intervals during which prehistoric culture flourished at the site: during ~ 6,500–5,600 cal years BP in the Neolithic, and during ~ 3,700–2,750 cal years BP in the Bronze Age. Abundant η-type husk phytoliths from common millet and occasional Ω-type husk phytoliths from foxtail millet were found at the site, and they provide direct evidence for prehistoric agriculture practice during these two periods. Prehistorical agriculture was practiced together with hunting and fishing, which were part of a multi-subsistence strategy which continued during these two periods. The climate during the two periods was warm and wet, which promoted the prosperity of the regional culture together with cultural interchange, and it also encouraged the dispersal of prehistoric agriculture in the East Liao River Basin. In addition, archaeological excavations demonstrate that there was frequent cultural interchange and interactions among the prehistoric cultures in NE China. We propose that cultural interchange and the dispersal routeway of prehistoric agriculture in NE China were based in the Liao River Basin.

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