The earliest hydraulic enterprise in China, 5,100 years ago

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Abstract

Here we present one of the world's oldest examples of large scale and formalized water management, in the case of the Liangzhu culture of the Yangtze Delta, dated at 5,300–4,300 years cal B.P. The Liangzhu culture represented a peak of early cultural and social development pre-dating the historically recorded Chinese dynasties, hence this study reveals more about the ancient origins of hydraulic engineering as a core element of social, political, and economic developments. Archaeological surveys and excavations now can portray the impressive extent and structure of dams, levees, ditches, and other landscape-transforming features, supporting the ancient city of Liangzhu, with an estimated size of about 300 ha. The results indicate an enormous collective undertaking, with unprecedented evidence for understanding how the city, economy, and society of Liangzhu functioned and developed at such a large scale. Concurrent with the evidence of technological achievements and economic success, a unique relationship between ritual order and social power is seen in the renowned jade objects in Liangzhu elite burials, thus expanding our view beyond the practicalities of water management and rice farming.

Significance

The recently excavated Liangzhu hydraulic system in the Yangtze Delta has pushed back the date of formalized water engineering in China to ca. 5,100 years ago. The results are unprecedented in learning about the timing, structure, and function of a large-scale complex of dams, levees, ditches, and other water-controlling features in ancient China. Together with the well excavated remains of Liangzhu city and its rice fields, the new findings represent one of the largest efforts of hydraulic landscape engineering in the ancient world.

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Introduction

The Liangzhu case may be considered among the many agrarian societies of Asia strongly influenced by monsoonal rainfall patterns. While the predictable monsoon rains in principle could sustain abundant wetland rice fields and other farmlands, too much dependency on such a system could prove devastating whenever the monsoon events occur earlier, later, lighter, or heavier. At the Liangzhu center and elsewhere in the world, such as South Asia and Mesopotamia, populations grew increasingly dense and socially complicated while taking advantage of the monsoonal rains, yet eventually many of these cities were rendered unsustainable and were abandoned, as evidently occurred at Liangzhu by 4300-4200 years B.P.. Among the challenges for the people of Liangzhu and other Asian monsoon-region farming societies, middle to late Holocene aridification involved numerous short-term fluctuations of precipitation with potentially profound consequences, notably well illustrated at archaeological sites of South Asia (1). Some societies were resilient to periodic droughts and other stressful events by diversifying their crops and developing other mechanisms, as revealed by investigations of ancient Indus agricultural systems (2). Other population centers were abandoned during or after years of drought, sometimes followed by catastrophic floods. Archaeologists, historians, geographers, and others have noticed the key role of water management technology in the development of food production systems (3-4) and political complexities worldwide. Wittfogel was among the first explicitly to propose a formal 'hydraulic hypothesis' (5), wherein the elites of Asian polities used water-control systems as a means to force their populations into labor against their own best interests, in essence creating despotic regimes in a model that he termed 'Oriental despotism.' This hypothesis has been elaborated and challenged by diverse scholars in their research of hydraulic systems across time and space (6-9), but it remains central in conceptualizing the interactive dynamics of social power, economic production, and landscape transformation. Helms (10) reported a late fourth millennium BC water supply system of reservoirs, pools, dams, canals, and conduits that supported extravagant societal growth in the arid setting of an early Bronze Age walled town of Jawa in Jordan. Though initially disputed, Helms' early dating of c. 5,600 B.P. now has been widely accepted (11). Slightly later but perhaps better defined water systems can be found in Early Dynastic Mesopotamia at 4,900-4,350 B.P., characterized by lengthy and branching canals throughout the urban and rural landscapes. Their advantages in navigation as well as irrigation and other functions significantly shaped the urban development of ancient Mesopotamia (12-13).

The 5100-year-old water management system at Liangzhu may further alter our concepts of how and why water-control complexes originated and developed. Here we highlight the new discoveries of the Liangzhu hydraulic system as a means to re-evaluate the classic hypotheses of the functional links among water management, farming economy, and political control that largely had been based on different examples in the Near East and Mesopotamia (6, 8, 12-13). Among other concerns, a narrow interpretation of Wittfogel's 'hydraulic hypothesis' as a technological phenomenon would disregard the potentially diverse pathways to power through ritual performance and religious ceremony of water management now strongly documented in Southeast Asian societies (7, 9). Accordingly, the Liangzhu archaeological findings reveal elaborate burial practice and other rituals, hinting at the religious beliefs concurrent with the development of the large-scale city, hydraulic system, and rice farming complex. In fact, Liangzhu was distinguished in Chinese archaeology primarily by its exquisite jade artifacts with meticulously carved motifs buried in elite graves (14).

Crucial for understanding the role of water management in Liangzhu at 5,300-4,300 years B.P., the site was situated in a naturally watery setting of low-elevation marshlands bordering the Yangtze Delta (Fig. 1*A*). A steady rise in post-glacial sea level reached its peak around 6,500 cal B.P. (15). As it is known today, the Yangtze Delta thereafter formed with a steady supply of marine deposits coupled with river-transported sedimentation (16). During the time of the Liangzhu site occupation, however, the low-lying landforms mostly were inundated, and they were habitats for hydrophilic and salt-tolerant vegetation (17). In the sedimentary layers beneath and pre-dating the Liangzhu settlement, deep marine deposits of grayish clay suggest that the area was estuarine marshes before the Liangzhu period (18). During the archaeologically defined Liangzhu period, people made use of the hillslopes and other elevated terrain, while they transformed the swampy lowlands into an inhabited landscape of artificial mounds, walls, and other man-made features. A fuller picture of the large-scale artificial transformation now has been possible with archaeological discoveries of the ancient water management system and farmlands. Perhaps akin to the speed and scale of construction projects in modern-day China, ancient Liangzhu emerged as a radical creation (Fig. 1*B* and Fig. S1), prompting unprecedented social and economic change.

Defining the Liangzhu Hydraulic Landscape

Our studies in 2009-13 confirmed and expanded on earlier reports of water-control features at Liangzhu, now understood as comprised of numerous inter-related components covering several dozens of hectares. Some of those constructions still are functional today (Fig. 2*C* and Figs. S2 and S3). Perhaps most impressive were the high and low dams, and the Tangshan levees at the basal slopes of Tianmu Mountain (Fig. 1*B* and Table S1). The high dams were built in the spots of low ground between isolated hilly formations, in total retaining several large reservoirs at the foot of the mountain. The Tangshan levees extend for at least 5 km, and they are 20-50 m in width and 2-7 m in height. In the middle section of the levees, two parallel dikes formed a ditch-like structure. These dikes may have allowed storage of water prior to being released into the redistribution outlets. Several artificial mounds were constructed to the east of Tangshan, separated by a hill running along the north-south direction. According to our excavations at the dams of Liyushan, Laohuling and Mifenglong (Fig. S4), the low dams were built on swampy lands. The excavations revealed a bottom layer of iron-depleted whitish clay, caused by long-term inundation and leaching in water. Atop this light clay layer, people had posed bundles of grayish clay wrapped by grass leaves resembling 'sand bags' (Fig. 3*A*), arranged as an artificial layering before the main body of the dams was constructed by another layering of piles of pure yellowish clay (Figs. S4 and S7). Bundles of the yellowish clay as well had been wrapped by grass leaves in apparent ‘sand bags,’ for instance as seen in the walls of the Laohuling and Liyushan dams (Fig. 2*D* and Fig. S7).

Superimposed over the Laohuling dam, our excavation found a Late Liangzhu period ditch dated to 4,800-4,300 cal B.P.. The superimposed ordering suggests that the Laohuling dam had been constructed prior to the Late Liangzhu period. Similarly, atop the Tangshan levees, a jade and stone workshop and several elite burials were dated to the Late Liangzhu period, thus indicating an older age for the Tangshan levees. The chronological sequence of the features has been refined by direct AMS radiocarbon dating of the annual grassy plants used in the ‘sand bags’ and charcoal found inside 10 dams and one levee. Most of the dating results from the high dams cluster at 5,200-4,800 cal B.P., whereas most of the dates from the low dams and the levees cluster at 5,000-4,800 cal B.P.. These dates verify an Early Liangzhu association defined by pottery typology. The dating of the dams and levees prior to 4,800 years B.P. reveals that these features most likely existed prior to the construction of most of Liangzhu city dated at 4,900-4,600 cal B.P. (19). According to the newest results, the high dams were built first, followed by the construction of the low dams and the levees. The dates from the low dams are particularly tightly concentrated, indicating that the low dams were built within a narrow window of time. The high dams of Ganggongling, Laohuling and Zhoujiafan were built at slightly different times, but the dams of Qiuwu, Shiwu and Mifenglong yielded dating results consistently around 4,900 cal B.P., close to the age of the low dams and the Tangshan levees. Several outlier dates (e.g., Laohuling-BA120588 and Liyushan-BA120581) suggest a later period of reconstruction for certain dams or groups of dams. A number of spatial groupings can be ascertained in the overall mapped distribution (Fig. 1*B*), likely reflecting separate construction projects. Nevertheless, the piecemeal construction activities all functioned toward a coherent whole, suggestive of a central planning.

To the south and southeast of the hydraulic complex, earthen walls enclosed the city of Liangzhu in an area of about 300 ha (ca. 1.9 km*1.7 km). This early urban center was made with much the same architectural and engineering sophistication as seen in the water-controlling system, for instance as employed for designing and building the large-scale artificial platforms, walls, and many other features (Fig. 1*B*). In the middle of the city, the Mojiaoshan palatial compound covered an artificial trapezoidal mound of enormous size, about 30 ha. Atop this mound, three smaller-sized palace foundations included the Damojiaoshan mound with parts up to 15 m high, as well as the Xiaomojiaoshan and Wuguishan mounds. Our excavations revealed some of the construction techniques in and around the Mojiaoshan palatial compound. A layer of grayish clay 8 m thick was piled up horizontally, and the edge was covered by another layer of 2-3 m of yellowish clay. Among the three artificial mounds was a plaza of 7 ha, built by sandy sediments removed from elsewhere (Fig. S1). To the southwest of Mojiaoshan, an excavation next to the river exposed an ancient bamboo surface and standing wooden stakes with mortise-and-tenon joints in well preserved condition (Fig. 2*B*).

Both inside and surrounding the city, natural river channels were augmented by a network of artificial moats, ditches, and canals, in total measuring about 30 km in length (Figs. S5 and

S6A). Eight water gates facilitated control of key points in the city's water network. In addition to the moats along the walls, 51 ancient river channels and artificial ditches so far have been documented. In some of those features, clay had been bundled into 'sand bags' identical to those used in the dams. In particular at the Zhongjiagang canal (Fig. S6A), our excavation showed that the canal had been consolidated by piles of 'sand bags' (Fig. S7C). Next to the river system outside the city, excavations uncovered two exceptional wooden constructions of the Bianjiashan Pier and the Meirendi Bank (Fig. 4).

Logistic Planning and Operation of the Liangzhu Hydraulic System

The immensity and internal complexity of the hydraulic system and city at Liangzhu undoubtedly required advanced planning, design, and logistics in construction, operation, and continual maintenance. The labor expended on each dam, canal, or other feature can be calculated numerically in terms of the person hours needed to move the volume (m^3) of earth for each construction, with further consideration for the tasks of initial source material removal, transportation to the desired destination, and final positioning into the construction outcome. Complexities in design and operation, however, tend to be more qualitative than quantitative, although they can be estimated or inferred through the numbers of functional features, levels of hierarchy in houses and burial goods, and awareness of the how the hydraulic enterprise related with the religious, political, and other aspects of ancient Liangzhu.

We estimated that 3,000 people worked for nearly eight years to move approximately 2.88 million m^3 of earth when building the ancient dams at Liangzhu (Table S1). The late phase construction of the Tangshan levees and the low dams was of a significantly larger scale than the early phase construction of the high dams (Table S1). This indicates that after the initial push to build the high dams, there was also a drawn out process to accumulate more labor and other resources to expand the hydraulic system. More numerous laborers and specialized tools could have increased the pace of construction. On the other hand, the total calendar time may have been elongated due to the availability of most people only for a few months per year during the seasons when they were free from agricultural work. In any case, a multi-year undertaking may have accommodated incremental stages or phases of operation in ever-growing capacity, and perhaps the site complex would have continued to expand if not for its eventual abandonment. Our labor estimate was based on a number of assumptions, and varying results may follow different information about the hours needed for the individual work tasks. In our calculation, we assumed that people used hand-held stone tools and simple carrying equipment, without the aid of draft animals or specialized devices. We next assumed that a single person could be employed in one of three possible 'assembly line' tasks of digging, transporting, or re-piling the clay or other earthen material. For each such task, we estimated that one person could be responsible for handling 1 m^3 of material per day, given 8-10 working hours per day. These parameters were comparable with the results of an experimental study with the clays in the same region (20), and they were more conservative than the independent estimates for building the ancient walled towns in other parts of China (21-24) and Mesopotamia (25).

The requisite labor force numbered in the thousands, thus prompting questions about how the people were recruited and how they were organized. The workers most likely were among the population residing at Liangzhu, which reached 22,900-34,350 at its peak, according to the density of archaeological features (Table S3 and Fig. S5). In a rice-farming settlement such as at Liangzhu, however, most people were unavailable for construction work except for a few months per year, and some may have been unwilling or unsuitable for the labor. As a unified undertaking, the hydraulic enterprise brought benefits of supporting the rice farmlands and ability to feed the city's population as a whole. Archaeobotanical studies have confirmed the dominant role of rice in the local diet. A storage pit of 0.06-0.07 ha at eastern Mojiaoshan contained 10,000-15,000 kg of preserved rice, and it may have held more when full (Fig. 3*B*). Furthermore, the paddy fields at Maoshan increased in size dramatically from less than 30-40 m^2 in the early phase (4,900-4,600 cal B.P.) to 0.1 ha or up to 0.2 ha in the later phase (4,600-4,300 cal B.P.). The later phase saw the application of manuring, burning, and frequent draining actions (26), as the region's hydrology was becoming wetter (27).

With the ability to control vast reservoirs and redirect water into specifically targeted locations and at any desired time, the unprecedented Liangzhu hydraulic system profoundly affected the surrounding natural and economic landscape. It formed a 1,300 ha protective screen to the north and northwest of the city, and it influenced a total of 10,000 ha. The storage volume of the high and low reservoirs would have been about 14.98 and 50.72 million m^3, respectively (Table S4), forever altering the hydrology of the surrounding landscape while rendering the water itself into a controllable commodity and symbol of power. The sprawling network of channels and canals functioned along with strategically positioned gates, piers, and other constructions in support of the rice-farming economy, transport of goods and people, trade partnerships, and other goals. The waterways allowed several economic advantages that we are just now beginning to trace. For instance, our petrological and experimental studies confirmed that the stones used in the base of the Liangzhu city walls (Fig. 2*A*) were quarried from the nearby mountains in the north and transported downstream into the city through the water system (28). In principle, key access points such as gates and piers could be controlled as pathways to power.

Conclusion

The excavated findings at Liangzhu now can allow a re-evaluation of Wittfogel's 'hydraulic hypothesis' and related notions of the role of water management in social and political systems (5-9). The 5100-year-old Liangzhu case demonstrates the link between an enormous hydraulic operation and a densely populated urban center with an intensive rice-farming economy, very different from other studies of surface-visible water temples, cisterns, and irrigation features (7, 29-30). The scale of landscape transformation at Liangzhu indeed was unparalleled in its era, thereby opening a window into how such a system originated and developed largely in isolation, rather than as part of an expanding economic enterprise or empire.

The artificial control of water at Liangzhu enabled an unprecedented scale of rice farming and support of thousands of people within the city's sphere of influence, but furthermore it represented an opportunity to consolidate political power. This political aspect cannot be observed directly in an ancient archaeological context without written records, yet it can be inferred through the numbers of functional elements in the Liangzhu hydraulic landscape, the scale and complexity of labor organization, and associated religious beliefs potentially reflecting social order and political authority. A labor force of thousands of people must have been organized in divisions and possible subdivisions by a central authority and likely an organizational hierarchy. Such a hierarchy would consist of authority figures, city planners, and others. According to the differential treatment of burials with a range of burial goods, some individuals could be viewed as elites with access to extravagant wealth, while others showed lesser degrees of status. This pattern reveals that the people of ancient Liangzhu adhered to a social hierarchy, even though we cannot reconstruct the precise social or political categories and relationships at this time.

The heavily engineered landscape of Liangzhu encompassed the inner city, outer circle, hydraulic system, and network of waterways, as well as the economic production areas that provided resources to support the center. Outside this core area, numerous small-scale settlements probably were subordinate to the center through specialized product manufacture and trade, for instance involving the high quality of distinctive Liangzhu style jade objects (14). These core-periphery relations could be viewed as reflecting an early development of urbanism (31), in some ways similar to the functioning of a territorial state polity (24, 32). Regardless of however the political structure may be classified at Liangzhu, it can be recognized as having involved complex operations and organized management of multiple technological and economic components at a scale that was otherwise unknown in its time.

The ultimate decline and abandonment of Liangzhu can be linked to the burial of the site beneath 1 m of light yellowish clayey deposits (Figs. S6*B* and *C*). This widespread clayey horizon represents massive flooding in the region, possibly occurring in multiple events starting around 4,200 years B.P. or shortly thereafter. Excavations have shown scattered instances of *in situ* Liangzhu artifacts embedded inside this clayey horizon, indicative of limited occupation at some locations until eventually even these small-scale efforts were no longer sustainable by ca. 3,800 cal B.P.. In this regard, some of the highest mounds and largest river channels may have continued to function in limited capacity after the flooding. Even today, the Qiuwu dam is used for many purposes by the local community (Fig. S3), although these later contexts have not involved the full operation of the ancient hydraulic system. While continuing studies will reveal more details about Liangzhu's ancient hydraulic engineering landscape, our findings so far illustrate a vivid material example of relevance to the global urgency of developing sustainable water systems that can survive through changing climate and increasing population density. The Liangzhu case was successful at an impressive scale for some centuries, yet eventually it could not be sustained through a period of environmental catastrophe. In this regard, more knowledge about the operational capacity and internal maintenance requirements of ancient Liangzhu can help to overcome current and future management crises in modern systems.

Methods and materials

One of the high dams, the Ganggongling dam, was found accidently by local farmers when they were digging earth from a small 'hill'. This important clue led to the discovery of several high dams that still stand today, including the Laohuling, Zhoujiafan, Qiuwu, and Shiwu dams. The low dams were recognized by careful examination of the Remote Sensing data, assisted by the analysis of high-resolution Corona and Google Earth images and coring survey data. On the ground, cores were taken from the suspected dams identified by the satellite images. Once confirmed by careful examining and comparing the coring sediments, more cores were taken both vertically and horizontally along the dams. More than 500 cores have been taken and examined to date.

ARCGIS and Digital Elevation Model (DEM) technologies were applied in order to reconstruct precise elevations at different points of the dams. The resulting data were used to calculate the storage volumes of the reservoirs formed by these dams based on the principle that water flows from higher to lower ground. A small drone was used for photographing and digital measurement during the excavations. The information was used to reconstruct the excavation areas in 3D.

Remains of annual grassy plants and bamboo were collected from the dams during excavations and coring surveys. They were sent to the laboratory at the School of Archaeology and Museology, Peking University, for AMS dating. The dates were calibrated using the OxCal online software OxCal v4.3.2 using the IntCal13 atmospheric curve (33) and 5568 yr half-life (table S2).

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Fig. 1 Geographic location of the Liangzhu site complex and distribution of important sites

(A) The studied area, as indicated by the red rectangular, is situated to the south of Taihu Lake and the Yangtze Delta, with the Qiantang River located to its south. (B) DEM map of the Liangzhu site complex, with locations of important discoveries mentioned in the text. 1. Tangshan Levee; 2. Shizishan dam; 3. Liyushan dam; 4. Guanshan dam; 5. Wutongnong dam; 6. Ganggongling dam; 7. Laohuling dam; 8. Zhoujiafan dam; 9. Qiuwu dam; 10. Shiwu dam; 11. Mifengnong dam; 12. Mojiaoshan mound; 13: Southern section of the Inner city walls; 14. Southern limit of outer city walls; 15: Meirendi; 16. Bianjiashan. The inner city walls form a near rounded-shaped circle (note the ‘water gates’ as indicated by the gaps), while the outer city walls are distributed discontinuously. The

Meirendi (15) and Bianjiashan (16) were parts of the outer city walls.

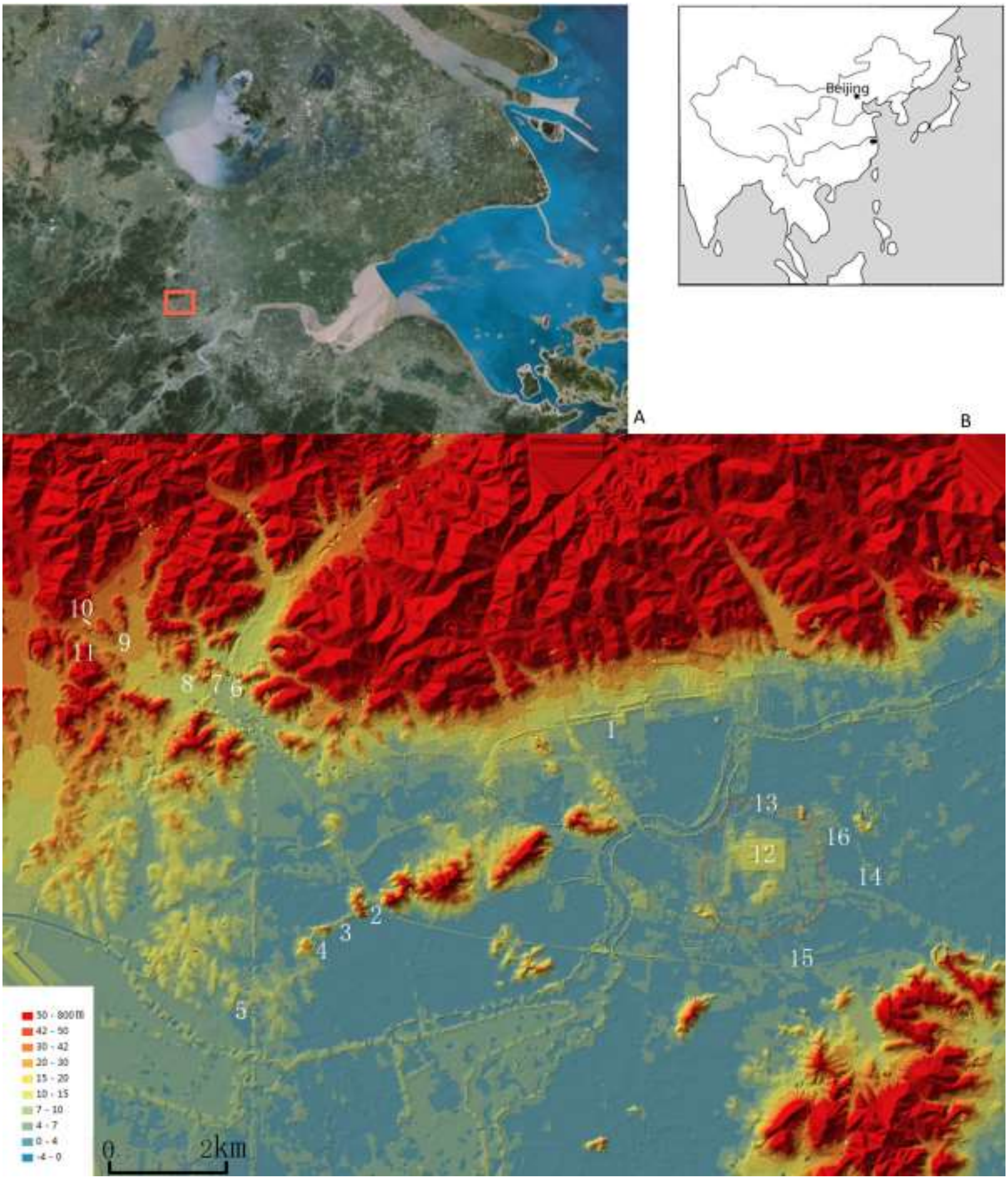


Fig. 2 Structures of some of the key sites at the Liangzhu City

(A) Excavation of the rock base of the Liangzhu city walls. The walls were built on a layer of rock, which was taken from the nearby mountains as confirmed by our petrological study *(14)*. This 40-60 m rock base was overlain by pure yellowish clay. Some well-preserved sections are currently about 4 m in height and 20-150 m in width. (B) The wooden and bamboo structure with mortise-and-tenon joints located next to Mojiaoshan. (C) Preservation of dams 9-11 (arrows) as shown in Fig. 1B. (D) Cross-section of the Laohuling dam, note the shapes of the so-called ‘sand bags’ still clearly visible on the section.

A

B

Fig. 3 The ‘sand bags’ and floated rice remains

(A) One example of the well-preserved ‘sand bags’, with the knots still clearly visible, the grass plants used are *Triarrhena lutarioriparia*. (B) A small proportion of rice remains discovered from the storage pit excavated at eastern Mojiaoshan, depth of the boxes around 10 cm.

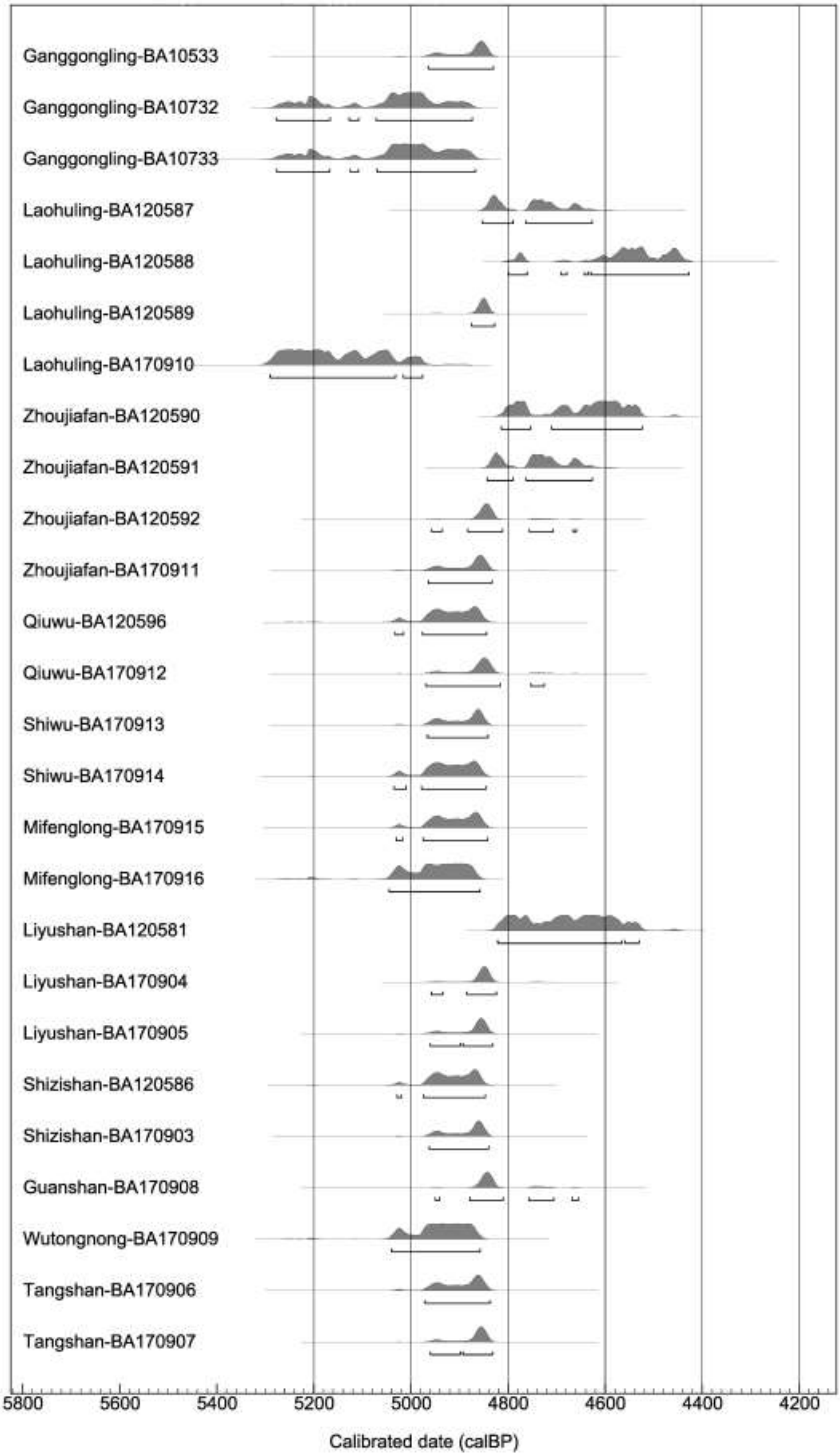
Fig. 4 Excavations of Meirendi and Bianjiashan

(A) Structure of the Meirendi bank with wooden planks still standing upright. Three logs of wood sleepers were placed in south-north direction at the bottom, overlain by three pieces of beams in east-west direction, and on top of which were the standing wooden planks. (B) The Bianjiashan pier, wooden stakes still were preserved, forming a T shape.

A

B

Fig. 5 Calibrated 14C dates using the OxCal online software (OxCal v4.3.2) and the IntCal atmospheric curve (33)



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Zhoujiafan-BA170911
Qiuwu-BA120596
Qiuwu-BA170912
Shiwu-BA170913
Shiwu-BA170914
Mifenglong-BA170915
Mifenglong-BA170916
Liyushan-BA120581
Liyushan-BA170904
Liyushan-BA170905
Shizishan-BA120586
Shizishan-BA170903
Guanshan-BA170908
Wutongnong-BA170909
Tangshan-BA170906
Tangshan-BA170907
5800
5600
5400
5200
5000
4800
4600
4400
4200
Calibrated date (calBP)