

GEODIVERSITY AND CULTURAL DIVERSITY: CURRENT PUBLIC ISSUES IN PHYSICAL SCIENCE



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Geodiversity and Cultural Diversity: Current Public Issues in Physical Science (PHY SCI 107)



Likwan Cheng

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CHAPTER OVERVIEW

1: Perspective - Geodiversity Breeds Cultural Diversity

1.1: Reading/Media

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1.1: Reading/Media

Perspective - Geodiversity Breeds Cultural Diversity

By Likwan Cheng

Holocene climate change—the long, winding period of warming following the Last Glacial Maximum some 12,000 years before the present (BP)—coincided in time with the transition of human society from foragers to farmers and then to urban settlers. As this climatic shift swept across the globe, it transformed geological landscapes in every corner of Earth, driving human adaptations in various ways. It was in this precarious environment and through such geological forces that the world's earliest cultures took shape.

In the Nile river valley of North Africa, a previous high-water swamp too wet for habitation gradually gave way to a harsh, equally inhospitable arid desert. Between these two extremes, a period of climate moderation once emerged. Seizing the moment, human settlers migrated toward the Nile valley. With fertile soils on the floodplains and efficient river transportation, the early Egyptians built a thriving civilization around 5,000 BP. On boat travel on the Nile, they admired the elegant hills lining the horizon and were inspired to build spiritual monuments emulating their geometry and scale. Millenniums later, the Egyptian pyramids stood above a transformed landscape as a testament to the early civilization while continued aridification had swept away the settlements below and buried the river branch that had once transported the building stones in sand.



Figure 1.1.1: Decorated jar with boat scene, ca. 3,300-3,100 BCE. Clay pottery. The decoration painted on this jar shows two multioared boats traveling through riverbanks lined with trees and aloe bushes. Rows of hills line along the river bank. The Nile river was ancient Egypt's primary means of transportation. (Cleveland Museum of Art.)

On the Yangtze river delta in East Asia, the Holocene climate shift drove a monumental transformation of a different kind. Faced with a watery landscape created by fluvial floods from the melting of upstream glaciers, early humans turned challenge into opportunity. With fire and flood management, they cleared out coastal swamps to construct the first paddy fields for rice cultivation as early as 7,700 BP. Once wandering foragers who hunted animals and gathered wild rice in the lower Yangtze basin, they were now on a trajectory to become farmers through the domestication of rice, and with further hydraulic advances by 5,100 BP, urban settlers of a complex society. But the early Chinese proved to fare no better than the early Egyptians. As the Holocene warming continued, the rising sea inundated their farms and collapsed the nascent civilization. History would ultimately vindicate these early pioneers, as the rice farming they championed would become the subsistence foundation of the forthcoming agricultural Chinese society, lasting for five millennia.



Figure 1.1.2: Rice farming in ancient China. Continuous narrative painting depicting scenes of farmers planting seedlings in rice fields. Qing dynasty (1644-1911 CE). (National Palace Museum, Taipei.)

In Mesopotamia, today's Middle East, the Holocene climate change led to far-reaching development in yet another dimension. As the pluvial phase of the early Holocene gave way to the progressively drying periods of middle Holocene, the region's two famed rivers, Tigris and Euphrates, changed course, exposing fine river-laid clays on the alluvial plain between them. Aridification transformed natural, rain-fed agriculture to managed irrigation and accelerated the transition to an urban society. The demand for administrative and economic recordkeeping led to the innovation of pictographic notations scripted on tablets of the river clays. Soon, these notations evolved into the world's first written language. When baked, the tablets became as resistant to weathering as rock, carrying their messages millenniums into the future. "Through them," the twentieth-century archaeologist Edward Chiera wrote, "we can follow changes in religious beliefs, economic conditions, and customs in daily life. In fact, through them we can...resurrect the old civilizations in the minutest details." (Chiera, 1938)



Figure 1.1.3: A cuneiform clay tablet from ancient Mesopotamia. (Institute for the Study of Ancient Cultures, University of Chicago.)

These historical episodes are among the eight episodes of ancient geology and cultural development with water-related themes to be explored in this book. Spanning five millenniums and crossing five continents, these episodes include crucial discoveries made in the first quarter of the twenty-first century. Read alone, each episode showcases how geology shaped human cultural development in a monumental way, as exemplified above in spiritual monuments, subsistence agriculture, and written language. Read comparatively, the episodes further reveal how nuanced variations in geological contexts triggered corresponding variations in cultural responses. For example, the Amazonian culture developed drainage networks on forest savannas to cultivate maize, while the Chinese culture developed hydraulic systems on the Yangtze delta to cultivate rice. Similarly, the Maya used volcanic silicates to filter water to keep it clean over time, while the Romans used volcanic ash to build aqueducts to transmit water over distance. Geological variations were tied to variations in human cultural development. In both monumental and nuanced ways, Earth's geodiversity shaped the world's human cultural diversity.

Geodiversity to the physical world is the conceptual equivalent of biodiversity to the living world. Having first emerged in the academic literature in the 1990s, the term geodiversity in the conventional view refers to Earth's geological variations, including materials (minerals and rocks), geomorphology (landforms and topography), and geological processes (climates and climate change). Geodiversity and biodiversity together make up the diversity of nature. Now, at the beginning of the second quarter of the

twenty-first century, scholars are seeking a more expansive and integrative view of geodiversity, one that connects to Earth's other spheres. Among these is the connection to humans and human cultures. Scholars have pointed out that "geodiversity shaped the history and development of human societies since their earliest days" and that, conversely, "the role of current and past human activities in shaping geofeatures has been documented for centuries." ([Scammacca and Bétard, 2026](#)) To the human society, geological scarcity mirrors ecological fragility. Just as cultural diversity helps maintain Earth's biodiversity ([Cheng, 2012](#)), it also helps maintain Earth's geodiversity.

The entangled histories of Earth's geological transformation and human cultural development are fascinating and educational. But this vast record of past millennia is not yet fully accessible. Buried below thick sedimentation and hidden by dense vegetation, human-modified landscapes and embedded cultural artefacts that attest to the stories of the past are not readily in view. But twenty-first century technologies are changing this. At the landscape scale, new aerial sensing technologies, such as LIDAR, or light detection and ranging technology, can map large areas of Earth's surface in infrared light and digitally remove covering materials to unveil the hidden topography below. At the microscopic scale, refined instrumentations, such as advanced X-ray imaging, now allow scientists to probe minerals and rocks in tiny grains with atomic-scale resolution and chemical sensitivity. These new technologies are joining traditional excavation to make new discoveries.

What these discoveries transpire are ancient stories presented in a new light or told for the first time, often leading to revised or newly established views. The indigenous settlement in Amazonia discovered under forest canopy that was once thought nonexistent and the self-healing ancient Roman concrete created through natural mineral-water reactions that outlasts modern steel-reinforced concrete by millennia in longevity are revelations of past and present biases due for correction or improvement. How the stories are presented also matters. The twentieth-century historian Arnold J. Toynbee argued that human stories of the past may be presented in three ways—as history, science, or fiction—and the choice is to be judged on the ground of the quantity and quality of data at hand ([Toynbee, 1957](#)). The educational endeavor through a limited number of episodes demands an objective presentation of facts (history) rather than a forum for speculation (fiction) or generalization (science). And objective storytelling is best done through the words of the scholars who made the discoveries, as excerpts from original scholarly texts. With this approach, we will undertake our exploration.

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CHAPTER OVERVIEW

2: Maize Monoculture on Drained Savannas in Pre-Hispanic Amazonia, 700 BP

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2.1: Reading/Media



The Bolivian Amazon. On the seasonally flooded forest-savanna landscape in Bolivian Amazon, the ancient Casarabe culture (500–1400 CE) developed water drainage and storage infrastructure to cultivate maize monoculture. (Photo by [Dirk Embert](#)/WWF. Wikimedia.)

Maize Monoculture on Drained Savannas in Pre-Hispanic Amazonia, 700 BP

Excerpts from "[Lidar reveals pre-Hispanic low-density urbanism in the Bolivian Amazon](#)" by H. Prümers, C. Betancourt, J. Iriarte, *et al. Nature* 606, 325–328 (2022). CC BY

Excerpts from "[Maize monoculture supported pre-Columbian urbanism in southwestern Amazonia](#)" by U. Lombardo, L. Hilbert, M. Bentley, *et al. Nature* 639, 119–123 (2025). CC BY 4.0

The Casarabe culture of Amazonia

Excerpt (Prümers et al.): Archaeological remains of agrarian-based, low-density urbanism have been reported to exist beneath the tropical forests of Southeast Asia, Sri Lanka and Central America. However, beyond some large interconnected settlements in southern Amazonia, there has been no such evidence for pre-Hispanic Amazonia. Here we present lidar data of sites belonging to the Casarabe culture (around AD 500 to AD 1,400) in the Llanos de Mojos savannah–forest mosaic, southwest Amazonia, revealing the presence of two remarkably large sites (147 ha and 315 ha) in a dense four-tiered settlement system. The Casarabe culture area, as far as known today, spans approximately 4,500 km², with one of the large settlement sites controlling an area of approximately 500 km². The civic-ceremonial architecture of these large settlement sites includes stepped platforms, on top of which lie U-shaped structures, rectangular platform mounds and conical pyramids (which are up to 22 m tall). The large settlement sites are surrounded by ranked concentric polygonal banks and represent central nodes that are connected to lower-ranked sites by straight, raised causeways that stretch over several kilometres. Massive water-management infrastructure, composed of canals and reservoirs,

complete the settlement system in an anthropogenically modified landscape. Our results indicate that the Casarabe-culture settlement pattern represents a type of tropical low-density urbanism that has not previously been described in Amazonia.

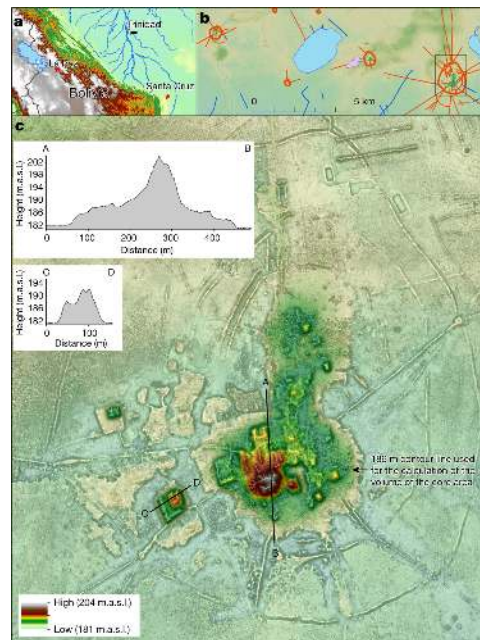


Figure 2.1.1: **a**, Occupation of the Cotoca lidar area. **b**, Sites and major archaeological features revealed by lidar in the Cotoca area. **c**, Lidar image of the large settlement site Cotoca with cross sections A–B and C–D. m.a.s.l., metres above sea level. (From Prümers et al. 2022.)

Subsistence food cultivation of the Casarabe culture

Excerpt (Lombardo et al.): The Casarabe culture (500–1400 CE), spreading over roughly 4,500 km² of the monumental mounds region of the Llanos de Moxos, Bolivia, is one of the clearest examples of urbanism in pre-Columbian (pre-1492 CE) Amazonia. It exhibits a four-tier hierarchical settlement pattern, with hundreds of monumental mounds interconnected by canals and causeways. Despite archaeological evidence indicating that maize was cultivated by this society, it is unknown whether it was the staple crop and which type of agricultural farming system was used to support this urban-scale society. Here, we address this issue by integration of remote sensing, field survey and microbotanical analyses, which shows that the Casarabe culture invested heavily in landscape engineering, constructing a complex system of drainage canals (to drain excess water during the rainy season) and newly documented savannah farm ponds (to retain water in the dry season). Phytolith analyses of 178 samples from 18 soil profiles in drained fields, farm ponds and forested settings record the singular and ubiquitous presence of maize (*Zea mays*) in pre-Columbian fields and farm ponds, and an absence of evidence for agricultural practices in the forest. Collectively, our findings show how the Casarabe culture managed the savannah landscape for intensive year-round maize monoculture that probably sustained its relatively large population. Our results have implications for how we conceive agricultural systems in Amazonia, and show an example of a Neolithic-like, grain-based agrarian economy in the Amazon.

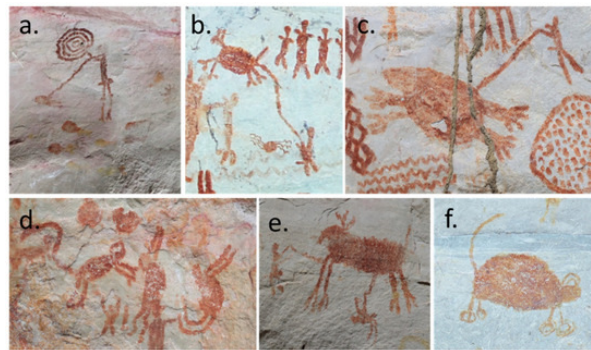


Figure 2.1.2: Ancient Amazon rock art. Figurative images from the Late Pleistocene show (a) fishing and (b,c,e) hunting as way of life. But whether Amazonians had developed the subsistence agriculture of a complex society in the Holocene has not been previously revealed. (From Hampson et al. [Arts 13, 135, 2024](#).)

The role of grain agriculture as the subsistence base of prehistoric complex societies in both the Old and New World has been a matter of sustained debate for many decades. In Mesoamerica, the earliest evidence of maize as a staple crop dates to 4,000 calendar years before the present. The timing and nature of maize's role as the staple crop of Andean civilizations, as seen in early historical accounts, is controversial. In Amazonia it is well established, from both archaeological and palaeoecological data, that maize has been cultivated since at least 6,850 calendar years before the present; however, to date there is no evidence of it being a staple crop. Most societies had mixed economies relying on multiple cultigens. Roosevelt proposes that the rise of social complexity in the Amazon was based on maize agriculture. However, current archaeological evidence has not been conclusive of maize cultivation being the staple crop of complex societies of the Amazon. Current archaeobotanical and palaeoecological data from Late Holocene complex societies in Amazonia indicate polyculture (mixed-cropping) agroforestry, not maize monoculture, as the basis of a subsistence economy.

Recent archaeological research has revealed evidence for low-density urbanism, social complexity and large populations in the Andean foothills of the Upano River region of Ecuador, and in the monumental mounds region (MMR) in the seasonally flooded savannahs of the Bolivian Amazon. Here in the MMR, the Casarabe people built hundreds of monumental mounds interconnected by canals and causeways across a flat forest-savannah mosaic landscape dominated by seasonally flooded savannahs, with forests restricted to non-flooded palaeo-river levées. Whereas drained fields and terraces, built on extremely fertile volcanic soils, were clearly integral to low-density agrarian urbanism of the Upano region, the type of farming system needed to sustain the Casarabe culture is still unknown. It has been proposed that the construction of drainage canals permitted cultivation of the relatively fertile sediments of the seasonally flooded savannahs of the MMR without the need for deforestation. However, no agricultural fields or other food production systems have hitherto been found in connection with such canals, leaving unanswered the question of how the Casarabe people managed to feed its relatively large population. To address this issue, we combine remote-sensing imagery with a programme of coring, test pits, radiocarbon dating and pollen and phytolith analyses on both seasonally flooded savannahs and forest.

We have identified two unreported and complementary agrotechnologies in the savannahs of the MMR: dense drainage networks and artificial farm ponds (Fig. 2.1.3), in which different portions of a savannah (Fig. 2.1.3, top left inset), or different savannahs within the same area (Fig. 2.1.3, bottom right inset), have been heavily modified—into either intricate arrangements of canals or clusters of circular depressions.

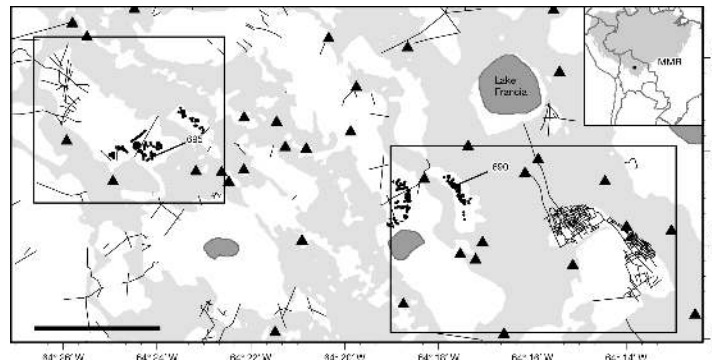


Figure 2.1.3: Triangles represent monumental mounds; black dots, ponds; thin black lines, canals; light grey areas, forest; white areas, savannah; and dark grey areas, lakes. Inset top left, the northern side of a savanna is crisscrossed by canals but the southern side is dotted with ponds. Inset bottom right, one savanna (to the east) has been modified by the excavation of a densely packed network of drainage canals, and two other savannas, to the west, are dotted with ponds; in the former, the network of canals drains into Lake Francia located about 4 km to the north. 690 and 695 indicate the locations of the two farm ponds sampled for this study. Inset top right, boundaries of Amazonia and the image of World Countries Generalized provided by ESRI under the ArcGIS Pro license. Scale bar, 5 km. Credit: European Commission JRC. (From Lombardo et al. 2025)

Hydraulic modification of the savanna landscape

The drainage network

In one of the savannas under study (Fig. 2.1.4), the small canals converge into larger canals that drain the whole savanna toward Lake Francia to the north. We identified three orders of drainage canals: the first order (1 in Fig. 2.1.4b), the smallest, are around 4 m wide and 25 cm deep, the second order (2 in Fig. 2.1.4) are around 8 m wide and 70 cm deep and the main canal (third order) that drains into the lake is 14 m wide and 1.8 m deep (3 in Fig. 2.1.4), becoming 3.2 m deep about 1.5 km before reaching the lake. Overall, the drainage network drains towards the north, becoming ever deeper with respect to the general topography. Several stratigraphic profiles of the canals show that the original depth of the canal network was around 80 cm deeper than at present for the second-order canals (see profiles 667 and 671) and around 45 cm deeper for the first-order canals (for example, profile 674). The drainage network is associated with circular elevated platforms roughly 50 cm in height, resembling pre-Columbian forest islands, and with small mounds of around 2–3 m in diameter. The elevated platforms are surrounded by deep canals (profiles 666 and 677).

Soil cores were collected from several locations both inside the canals and between them. Phytolith analysis shows a high abundance of phytoliths derived from the cob glumes and leaves of *Zea mays* in almost all canal soil profiles, with sporadic presence of *Cucurbita* spp. (666 and 677), *Manihot* sp. (677), *Calathea* sp. (674) and *Lagenaria* sp. (667) phytoliths. We cannot exclude the possibility that *Cucurbita* was cultivated in greater amounts than implied by the phytolith assemblage, because some domesticated *Cucurbita* varieties may lack scalloped phytoliths.

The majority of *Oryza* phytoliths are concentrated in the upper levels of all the profiles. Most upper-level glume phytoliths were from domesticated plants, whereas those from lower levels in the soil profiles (30–50 cm depth) were classified as wild species. These results are not surprising, because some of these fields are currently being used to grow modern Asian rice. The low production of diagnostic wavy-top rondel phytoliths in maize and the high abundance of these, relative to the sporadic presence of phytoliths of other cultivars, indicate that maize was by far the principal cultivar in these savannas. We attribute the absence of maize phytoliths in the uppermost 20–25 cm of the canal soil profiles to sedimentary fill from adjacent fields over recent decades or centuries—an inference corroborated by our soil phytolith data from fields between the canals. Here, maize phytoliths appear in only one of the three profiles, suggesting that the cultivated area is likely to have been established along the canals, probably on elevated rims that have since eroded into the canals. It is probable that, while in use, the original depth of the canals was maintained by their periodic re-excavation and redistribution of canal sediment fill along the canal margins, where maize was then planted, mimicking what has been proposed for raised-field agriculture in other regions of the Llanos de Moxos.

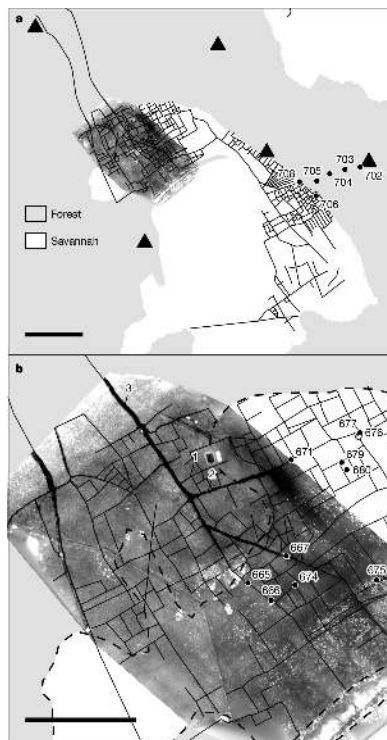


Figure 2.1.4: **a**, The complete drainage network. Numbered dots indicate the location of phytolith profiles. **b**, Detail of the digital elevation model of the northern part of the drainage network. Dashed lines represent the forest-savannah boundary, showing that a great deal of the drainage network is presently covered by forest. Scale bars, 1 km (**a**), 500m (**b**). (From Lombardo et al. 2025.)

The forest

Forest in the study region grows on elevated surfaces, mostly fluvial levees, that remain above the water level during the rainy season. Four soil profiles were dug and sampled across the forest, along a transect from the savannah to a large 15-ha monumental mound, to reveal to what extent the forest was cleared for agriculture. No charcoal or any other evidence of fire was visible in any of the profiles. Phytolith profiles are all similar and do not show any obvious stratigraphic change, apart from a slight reduction in Arecaceae (palms) and an increase in Poaceae (grass) phytoliths, which could indicate a slight opening of the forest canopy. No cultivar phytoliths were found in any of the profiles. Although our data cannot show the extent to which the forest was used for agroforestry, wood harvesting, hunting or cultivation of medicinal plants, the absence of charcoal does show that slash-and-burn agriculture did not take place here.

The clusters of farm ponds

A large portion of the savannahs in the MMR contains clusters of circular depressions of 10–100 m in diameter. They are often connected, either by canals or directly by adjacency. These ponds are similar to natural depressions called *gilgais*, an Aboriginal Australian name for water holes, that form in vertisols because of repeated expansion and contractions of the clay. To understand their genesis and use, we sampled two ponds in two different savannahs. Profiles 690 and 689 were excavated and cored, respectively, in a large pond of roughly 100 m in diameter, with its central depression about 60 cm below the surroundings. Profile 695 was excavated in a pond of roughly 30 m in diameter, and with a central depression currently 40 cm below the surrounding savannah. Pond profile 690 exhibits a very irregular, sharp contact between the organic sediment fill and the grey, inorganic clay below, and shows no evidence of shear surfaces (slickensides), suggesting that the pond was excavated and is not a *gilgai*. The anthropogenic origin of these depressions is further supported by their size, which is far larger than the 15–20-m-diameter *gilgais*, and by their clustered linear distribution. Sediment profiles from both ponds show the continuous presence of maize phytoliths and pollen throughout, with phytoliths of *Cucurbita* sp. present in only two adjacent samples in profile 690 at around 40 cm depth, and a pollen grain of *Manihot* at approximately 50 cm depth. No other cultivars were detected. The chronology of pond profile 690 indicates that this system was in use around 1250–1550 calendar years CE.

Today, the majority of these ponds hold water for most of the year, maintaining wet soil until the very end of the dry season. If this hydrological balance is representative of the past, these ponds would have provided sufficient water for maize cultivation around

their margins throughout the dry season. This is not dissimilar to the *k'hochas* in the Bolivian altiplano, where yields are up to four times higher than for regional rainfed production. Similar pond-based farming systems have been described in Bangladesh and India, where ponds provide an integrated production system that includes fish farming, poultry and cultivation of pond dykes. A very similar system could have been in place in the MMR, where swamp eels (*Synbranchus marmoratus*) were an important part of the diet of the Casarabe culture; the Muscovy duck (*Cairina moschata*), the only known domesticated animal in the Amazon, was probably kept. Bones of *S. marmoratus* were found in pond 695 at a depth of 70 cm. During the dry season, these farm ponds would have served as 'watering holes', attracting game.

Water management for intense farming

The combination of these two types of landscape engineering—drainage canals and farm ponds—is unique to the MMR. We argue that it was a highly innovative agricultural strategy that enabled the Casarabe culture to substantially increase the cultivation period for maize, as well as providing easy access to fish, birds and game. Through the sophisticated system of drainage canals, some savannah wetlands were converted into drained fields suitable for intensive maize monoculture in the wet season, whereas the construction of clusters of farm ponds in other savannahs provided a reservoir of water that allowed pot irrigation, which enabled the continuation of maize agriculture throughout the dry season. The combination of these two water management systems would have allowed at least two harvests of maize per year. The lack of any evidence of cultivation and fire in the nearby forested areas suggests that slash-and-burn agriculture was unlikely to have been practised. Instead, this pre-Columbian Casarabe culture probably preserved the spatially limited, and hence highly valuable, forest resource for other key ecosystem services, such as firewood, building materials, medicinal plants and probably polyculture agroforestry.

Our results overturn the assumption that the seasonally flooded savannah of southwestern Amazonia is suitable only for cattle ranching and intensive Asian rice agriculture, and unsuitable for nutrient-demanding crops such as maize. These findings have implications for our understanding of pre-Columbian subsistence economies across Amazonia and beyond. They indicate that, during the late Holocene, alongside intensive polyculture (mixed-cropping) agroforestry on Amazonian Dark Earths, other agricultural systems such as drained fields and farm ponds in the Llanos de Moxos were primarily focused on the cultivation of maize. These practices bear similarities to agricultural strategies observed in later Andean states and chiefdoms. Collectively, as long argued, intensive cultivation of maize has had a major role in supporting the economy of some of the most complex societies in the Americas. The Casarabe people demonstrated the ability to establish a highly intensive monoculture farming system on the savannahs based on maize, maintaining the surrounding forest cover and supporting one of the most complex pre-Columbian societies in lowland South America. The Casarabe culture of the MMR provides a clear example of when the rise of social complexity is linked to intensive food production and, more specifically, to maize monoculture. It also confirms the role of grain agriculture as the main driver for increasing social complexity and, probably, inequality.

Key Geologic Concepts:

Drainage networks; sedimentation; sediment core analysis; wetland.

Supplemental Materials:

Youtube: [Fire and Water: Pre-Columbian landscape management in the Southwestern Amazon](#) by N. Duncan, University of Central Florida.

Smithsonian Magazine: ["Lost Cities of the Amazon Discovered From the Air"](#) by B. Handwerk. May 22, 2022.

University of Reading ["Ancient Amazonians' water wisdom kept families fed all year"](#). 29 January 2025.

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2.2: Classroom Activity

Scaling Analysis of Savanna Farm Drainage Network

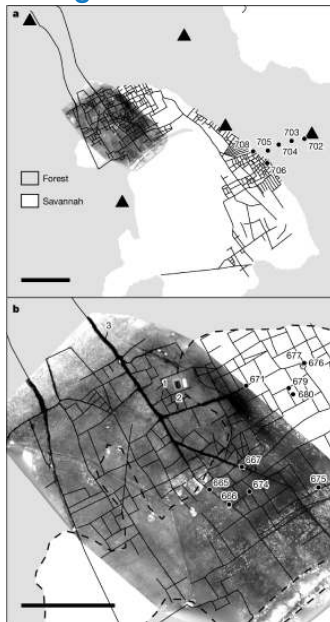


Figure 2.2.1: **a**, The complete drainage network. Numbered dots indicate the location of phytolith profiles. **b**, Detail of the digital elevation model of the northern part of the drainage network. Dashed lines represent the forest-savannah boundary, showing that a great deal of the drainage network is presently covered by forest. Scale bars, 1 km (**a**), 500m (**b**). (From Lombardo et al. 2025.)

The work by Lombardo et al. (2025) states that the drainage canals for seasonal flooding have dimensional differences classified into three orders (or levels) of sizes. This indicates that the canals form a hierarchically ordered network, like the modern water distribution network. In hierarchically ordered networks, the dimensional measures are non-linearly scaled across levels, meaning that the amount of any network property as measured by a particular parameter (such as length) increases disproportionately with network level. Consider the data provided in the paper for the drainage network parameters listed below. Make reference to Fig. 2.2.1.

Table of network parameters versus canal level.

Canal Level	Total Length (m)	Cross-Sectional Area (m ²)	Perimeter Length (m)
1			
2			
3			
3 (>1.5 km from lake)			

- Based on data reported in the paper, what is the total canal length for each of the three levels of the drainage network?
- Based on data reported in the paper, what is the canal cross-sectional area for each of the three levels of the drainage network?
- Based on data reported in the paper, what is the average canal cross-section perimeter length for each of the three levels of the drainage network? (The cross-section perimeter length is the equivalent of the circumference of a circle.)
- Plot the data in the table with canal level on the x axis and length, cross-sectional area, and perimeter length in the y axis.
- Observe the non-linear scaling of the three dimension parameters with canal level.
- Consider the natural stream network patterns described in Figure 2.2.2:
 - Name each of the natural stream network patterns shown in the figure.
 - Describe how the canal network discovered on the Casarabe savanna is different from the natural stream networks. How this difference can be used as a basis for claiming that the Casarabe canals are a manmade infrastructure.

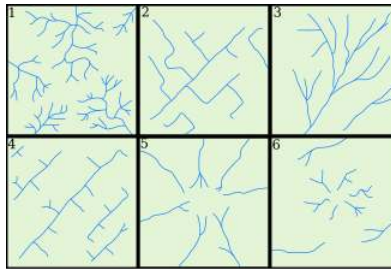


Figure 2.2.2: Common natural drainage network patterns. ([Drainage network](#); CC BY-SA)

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2.3: Assignment

Assignment:

1. What are the two water management infrastructure at the Casarabe culture agriculture savanna? How many harvests of maize per year do the water system support, as suggested by the botanical remains data?
2. What are the three scientific techniques used in this investigation of the landforms at the time of the Casarabe culture?
3. What are the land uses of the forest by the Casarabe culture? What are other ecosystem service and resource uses of the forest by the Casarabe culture as suggested by the botanical remains data?
4. Where else in South America was/were pre-Hispanic low-density urbanism also discovered? Were those landscapes similar or dissimilar to that of the Casarabe culture?
5. How are the monumental mounts and water ponds specially related? What does this spacial association suggest about the political and agricultural production systems of the Casarabe culture?
6. What is the landform characteristics of the "forest-savanna mosaic" landscape?
7. How did the forest cover in the Casarabe settlement area change during the period that the culture cultivated maize monoculture to support its population?
8. What was suggested to be the staple crop for the Casarabe culture in the savanna when the drainage and pond infrastructure were in operation?
9. What evidence does the paper cites to suggest that the farm ponds were anthropogenic rather than naturally formed?
10. What are the two significances of the drainage canals and farm ponds water infrastructure?
11. The article argues that it overturns the notion that seasonally flooded savanna is unsuitable for nutrient rich farming and for supporting a complex society. What is the main implication of this finding on ancient societies and settlements in South America?

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CHAPTER OVERVIEW

3: Watery Rituals on Mississippi Floodplain in Pre-Columbian America, 1,000 BP

[3.1: Reading/Media](#)

[3.2: Classroom Activity](#)

[3.3: Assignment](#)

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3.1: Reading/Media



Cahokia, an indigenous culture around 1050 CE near modern-day Collinsville, Illinois, was the most populous settlement in pre-Columbian North America. Scholars argue that both the vitality and the demise of Cahokia were tied to the culture's relation to water, set by the geologic landscape of the Mississippi floodplain. (Image from [wikimedia.org](https://commons.wikimedia.org/wiki/File:Cahokia_Mounds_National_Monument_2013.jpg).)

Watery Rituals on Mississippi Floodplain in Pre-Columbian America, 1,000 BP

Excerpts from "[Cahokia as urban anomaly](#)" by T. R. Pauketat, S. M. Alt, A. M. Betzenhauser, et al. *Journal of Urban Archaeology* 7, 253 (2023). CC BY-NC 4.0

The watery setting of Cahokia

Excerpt: After decades of debate over societal types and levels of complexity, many researchers have settled on recognizing the great, precolonial-era, Indigenous complex in the middle Mississippi River Valley—Cahokia—as some form of urbanism. On the one hand, this recognition is possible thanks to robust new archeological data on the scale, density, and hybridity of this extensive, tripartite, urban complex. These data point to a historical phenomenon that meets Louis Wirth’s (1938) criteria of ‘urbanism’—places that were large, dense, and heterogeneous. In other ways, Cahokia appears anomalous in North America if not the entire ancient world.

Cahokia’s known anomalous characteristics include its rapid emergence, its distanciated configuration, its unusual location, and its relatively brief florescence. Cahokia’s three quasi-distinct ‘precincts’ were built quickly using wood, thatch, and earth. They were also built astride and amid marshes and bodies of water, including the Mississippi River. Why this was the case may be rooted in the spiritual or affective powers of watery places. That is, Cahokians built their urban complexes atop or in alignment with what was undoubtedly an already animate or spiritually charged landscape. The people referenced fundamental elements, substances, atmospheric phenomena, and celestial bodies, as well as the movements and transubstantiations thereof, in ways that gave Cahokia vitality. Thousands of people flocked to it. Yet precinct locations amidst and astride marshy wetlands and bodies of water might have long-term negative consequences. In fact, two of the precincts, Cahokia and East St Louis, were built in what one famous visitor in 1842 regarded as an ‘ill-favoured’ stretch of muddy, hot, and humid Mississippi River flood-plain historically known in less-than-complimentary terms as the ‘American Bottom’. The Cahokians do not seem to have mitigated these so-called ill-favored attributes, and the entire urban experiment lasted but a century and a half. In the end, Cahokia’s ‘Mississippian’ descendants never attempted to recreate the scale, density, and heterogeneity of their founding.

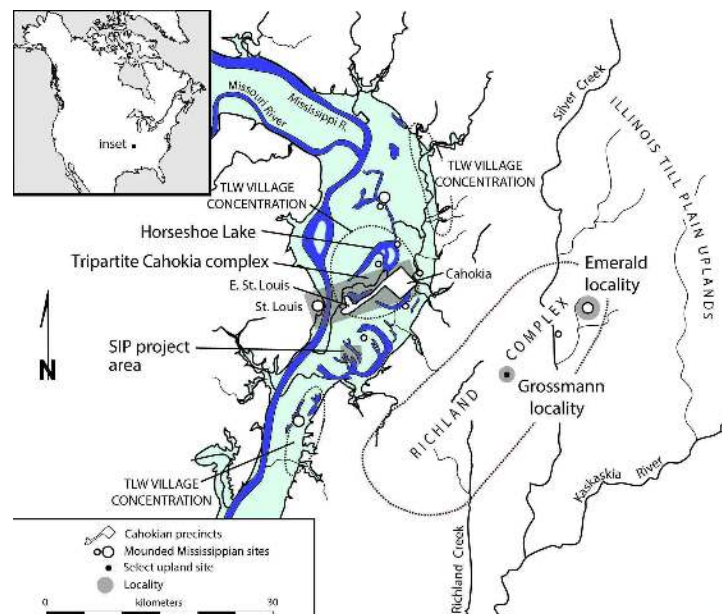


Figure 3.1.1: The Greater Cahokia region, highlighting precincts, sites, and localities mentioned in the text. (From Pauketat et al. 2023.)

Precinct characteristics

Unfortunately, understanding Cahokia's scale, density, and heterogeneity is hampered by the fact that two of its central-complex precincts—East St Louis and St Louis—have been badly damaged or destroyed by the urban-industrial expansion of the modern cities of East St Louis and St Louis, respectively. The entire St Louis precinct was erased through extensive modifications to the western river bluffs following the Civil War. It had been comprised of twenty-six rectangular and circular platform mounds around a three-plus hectare plaza. The entire precinct may have covered c. 100 ha. At its north end over the entrance to a cavern sat the largest of the St Louis mounds, a rectanguloidal 'ridge top' form. At least one other natural sinkhole, adjacent to an apparent circular platform mound, afforded access into the watery, karstic underworld below the site.

The East St Louis precinct was not entirely erased, but it was decapitated, its more than forty-five mounds levelled to the ground. Fortunately, the rest of the precinct remains largely intact below the ruined post-industrial landscape of modern-day East St Louis. In the late 2000s, archaeologists from the Illinois State Archaeological Survey salvaged a palimpsest of some 1,500 pole-and-thatch buildings within an 11 ha excavation area (i.e., less than 5 per cent of the site) at this second-largest precinct of Cahokia. The precinct itself is conservatively estimated to encompass 290 ha (or 2.9 km²) of the Mississippi floodplain fronting the river, not counting the mounded strip of habitation area that continues to the north-east toward Cahokia proper. There are hints in domestic architecture (dating to AD 1050) and in the presence of foreign-style (but locally made) pottery vessels dating to the eleventh through twelfth centuries that residents included both locals and foreigners, the latter from modern-day Missouri, southern Indiana, and Arkansas if not beyond.

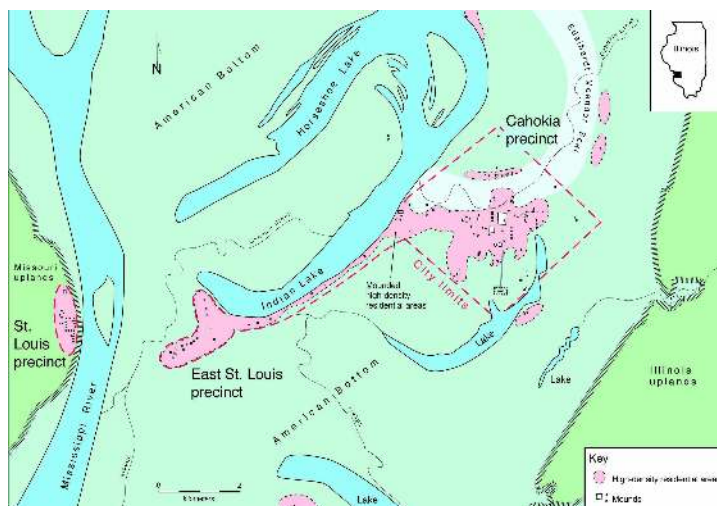


Figure 3.1.2: The three precincts—Cahokia, East St. Louis, and St. Louis—of the Greater Cahokia (pink), the Mississippi floodplain (light blue), the Mississippi River and other water bodies (dark blue), and the Illinois and Missouri uplands (green). The white rectangle at the center of the Cahokia city marks Monks Mound; note that the North Plaza, the area immediately north of the Monks Mounds, is situated in a meander scar, a depressed land elevation likely a former oxbow lake at the time of Cahokia. (From Pauketat et al. 2023.)

Five kilometres to the east-north-east of East St. Louis was the western edge of the Cahokia precinct, marked by several ridge-top mounds and seamlessly connected to East St. Louis by the previously noted row of mounds and occupation debris along Indian Lake. Three more kilometres to the east was the great pyramid of the Cahokia precinct, Monks Mound, and the 24 ha ‘Grand Plaza’ that it faced (Fig. 3.1.3). The Cahokia precinct is estimated to have covered some 1,300 ha (or 13 km²), about 180 ha (or 14 per cent) of which consisted of ‘high-density’ habitation areas. In these high-density areas during the urban Lohmann and Stirling phases stood four to nineteen pole-and-thatch buildings per ha (400–1,900 per km²) at any one time, assuming building longevity estimates of 10–15 years. Gardens and infields may have been scattered across some portions of this area.

The rest of Cahokia’s 1,300 ha area consisted of low-density habitation areas (<4 houses/ha), special pole-and-thatch buildings, mounds (of which there were more than 120), plazas (of which there were several), scattered gardens, borrow-pit reservoirs (depressions left over after construction fills were removed), and marshy backswamp zones. The borrow pits were probably intentionally sited and dug to depths sufficient to hold water and fish for the entire year. Likewise, the large, rectangular ‘North Plaza’, situated in an ancient oxbow channel immediately north of Monks Mound, may have been built expressly to hold water during the wet late winter to early summer months. An even larger naturally marshy lowland at the southern end of the precinct was transected by a kilometre-long earthen causeway, the standing water teeming with amphibians and waterfowl during the late winter, spring, and early summer. Apparently, these natural and built features were not empty meaningless spaces but integral parts of the city. Long causeways ran from the central civic-ceremonial portions of the precinct into the southern wetland, and short causeways ran around borrow pits and between square and circular platform mounds, the latter associated with both water and the water vapour produced inside circular steam baths.

The circular steam bath is one of several kinds of non-domestic architecture that comprise a Cahokian architectonic ‘module’. Besides the circular buildings (large and small), there were oversized square temples or council houses, upright free-standing posts, ‘shrine houses’ or small temples, and T-shaped, L-shaped, and cruciform ‘medicine lodges’. As a set, these buildings defined Cahokia’s precincts, neighbourhoods, and outlying ritual-residential sites down to the level of the ‘nodal farmstead’ — single-family rural domestic habitations that nevertheless featured one or more non-domestic, ostensibly Cahokian structures. Three to five per cent of all structures in the excavated 1,500-structure East St. Louis sample, and up to 20 per cent of buildings in Cahokia’s core zone, were comprised of such non-domestic buildings.

From what can be ascertained from many excavated contexts, all such extra-domestic buildings and upright posts might have been occupied, so to speak, by non-human beings. Spirits, for instance, enlivened the ‘medicine bundles’ that would have been kept within some buildings, while ancestral spirits might have animated the wooden posts standing vertically outside such buildings from time to time. That is, these were not merely passive things or places of worship. Rather, they manifested the gods themselves in the social spaces of people. They were portals to other worlds. Accordingly, Alleen Betzenhauser and Timothy Pauketat (2019)

likened their presence to the infusion of non-human or ancestral spiritual powers into residential zones. Such an infusion was likely a top-down process, as evidence in a series of oversized rectangular temples built in a grid pattern at East St Louis. In a sense, the non-human beings within human residential sectors made Cahokian urbanity even more heterogeneous than it was based only on the diverse cultural backgrounds of people.



Figure 3.1.3: Monks Mound, the centerpiece of Cahokia's urban monuments, as seen today. Scholars suggest that the North Plaza immediately north of the mound "may have been built expressly to hold water during the wet late winter to early summer months" (Pauketat et al. 2023) and "was an inundated feature on the landscape throughout Cahokia's occupation" (Rankin, 2022). (Image from [NARA](#))

Vitality, anomaly, and fragility

Beginning at AD 1050, the rate of Cahokian development and the scale of Cahokian construction, resettlement, and ceremonial events was unprecedented, and indicate the willing participation of tens of thousands of locals, immigrants, and pilgrims. People wanted to be a part of Cahokia, and they labored to make it so. Arguably, this energy was a function of Cahokia's location—in the middle of a special, animate regional landscape characterized by easy access to different kinds of water (subterranean groundwater, river water, backwater, rain water)—and its mode of incorporating other-than-human powers into its urban spaces, including those related to water. That same landscape, carved up by numerous oxbow lakes and marshes and studded by karst sinkholes and caverns to the north, south, and west, might be the reason for the odd distanced configuration of the central complex. That is, the distribution of the powerfully animate landscape features meant that the seat of regional authority, whatever it was, had to spread out to occupy or assemble those features under one umbrella—Cahokia. Perhaps, given Cahokia's incorporation of multiple other-than-human forces into the daily domestic spaces of individual precincts via its modular architecture, we may be seeing evidence of a central core insufficiently strong to be materialized as a single nucleated city, despite the obvious magnitude of Monks Mound in the middle of the Cahokia precinct.

Cahokian modular architecture in the countryside as well as the city may attest to the same thing. Indeed, the same episodes of change—transformation, expansion, and contraction—dating to AD 1050, the early 1100s, and c. 1200 characterize the four rural localities reviewed here. Possibly, this is evidence of a high degree of articulation between rural farmers and Cahokians, perhaps through events like those that produced the layers of sub-Mound 51 ceremonial-feasting debris. True, each rural locality reviewed herein seems to reveal a slightly different aspect of this regional articulation, probably a result of rural people exerting their own agency or living their own history to some extent. Also evident, however, is the agency of a Cahokian elite. We see it most clearly in the overbuilt and underused habitation areas at East St Louis (in the so-called Southside and Northside excavations) and at Grossmann. Their physical remains are found in the theatrical mortuaries of the region's ridge-top mounds.

Presumably, these were the Cahokians who had a hand in directing the urban development of Cahokia. And we might presume that foremost in their minds would have been the production of sufficient foodstuffs, fish, and wild game to supply the necessary support for the farm families who cleared the fields, levelled the precinct and shrine-complex landforms, provisioned the ceremonies and festivals, built the two hundred earthen pyramids, and filled the storehouses of the elites. In addition to their support and encouragement for farmers, it remains possible under the circumstances that elite management of the region's resources may have been necessary to maintain the Cahokian dynamo. Someone probably had to oversee the rapid construction of housing at and after ad 1050. Someone would have to manage the collection of hundreds to thousands of untold quantities of tree saplings, wattle, and thatch for the roof of these same houses; this would have meant setting aside, and then cutting and hauling,

great quantities of poles, wattle, and thatch. Ample supplies of wood would have been available from across the floodplain and uplands. Thatch would have been readily available from the Richland-Complex prairies to the east of the city.

The procurement of game animals, which were clearly taken in large numbers for central events (such as the feasts in Cahokia's Grand Plaza), may have presented the people of Greater Cahokia with a managerial challenge. Deer, for instance, are easily overhunted and subject to population crashes. Yet unambiguous archaeological signatures exist of higher-quality cuts of deer meat disproportionately consumed at Cahokia. To ensure that adequate deer were always available, game reserves (nearly invisible archaeologically) may have been necessary. Horseshoe Lake would have been ideal. To produce such quantities of meat for the precincts' events and elites, hunters may have lined up across the southern end of the Horseshoe Lake peninsula to drive the quadrupeds north before them. Or they may have culled the deer populations of the adjacent Ozark Mountains to the south and west of the American Bottom. Somebody likely specialized in the process of borrowing the earth used to build the city's causeways and platforms. Of course, there was no shortage of earth in and around Cahokia but digging and transporting it must have been organized by people with knowledge of soil properties and the rights to do so. Fills were procured from sources that included black waterlogged muds or sands adjacent to the planned monument and from more distant blufftop sources around the American Bottom. Working with the various kinds of earth would have entailed a basic understanding of their properties when applied as they were in various dry-mixed and wet-plastic states in layers one atop the other.

Finally, someone or some corporate entity was probably responsible for organizing the cutting and hauling of wood. This is especially true of great cypress logs that were probably cut from stands along the Mississippi River in southern Illinois. Such logs were dressed by woodworkers using chert-bladed adzes during central Cahokian festivals, as indicated by thousands of wood chips and bark from sub-Mound 51 deposits. They were then emplaced in large post pits at each Cahokian precinct, sometimes as parts of larger galleries or rows. These galleries, along with the extensive earthmoving operations, the monumental pole-and-thatch building constructions, and the creation of earthen platforms, causeways, and plazas, seem to have been used to create grand theatrical spaces that aligned people and spirits with cosmic cycles via the precinct and shrine-complex grids. Hundreds to thousands of people took part in processions, ceremonies, feasts, and constructions. Cahokians even carried their vision if not their bundles far afield. Foreign dignitaries likely arrived to learn the secrets of Cahokia's powerful medicine. The fervour spread.

The impressive scale and vitality of Greater Cahokia aside, there are reasons to suspect that urbanism in an 'ill-favoured' patch of floodplain, focused so exclusively on the performative, religious aspects of human experience, would have been uniquely fragile. In fact, recent hydroclimatic investigations have called the long-term sustainability of Cahokia into question, given paleoenvironmental indicators of droughts and one-off floods in the later 1100s and 1200s. That sustainability seems especially at issue given the general absence at and around Cahokia of the kind of urban infrastructure evident in other precontact American contexts.

That is, Cahokia lacked systems or facilities that provisioned food and water or that supplied the transportation, communication, and waste management needs to a public while they reduced the costs of such provisioning or facilitation. Where, for instance, are the water-control and drainage features built for non-religious, non-ceremonial, civic purposes? Possibly, the North Plaza was engineered to retain water that moved through the Cahokia Creek bottom (and the ancient, abandoned Mississippi River channel in which it sits). Likewise, the sandy and topographic properties of the Grand Plaza seem to have enhanced the drainage of surface water; a narrow ditch probably drained surface water from a residential area at Cahokia proper; and borrow-pit reservoirs may have been intended to supply the drinking water needs for the people of the precincts. But all of these are low-level if not incidental systems at best.

Besides these features, no higher-level water-management infrastructure has yet been identified at and around Cahokia. For example, irrigation features are unknown. Perhaps they were deemed unnecessary given the floodplain's ordinarily high productivity levels. Similarly, there are no identified precolonial-era earthen dams or retention basins in the critical base-of-the-bluff zone east of Cahokia. Yet flash floods that sweep across the American Bottom, originating in the upland Cahokia and Canteen Creek watersheds to the east, were probably as common in the past as they are today.

Perhaps water-control features may yet be discovered buried beneath modern landscape alterations. Or perhaps the absence of such water-control features might be related to the same ontological reverence afforded water by Cahokians as that which lent this early urban experiment its vitality. Elsewhere, Susan Alt (2019) has detailed the multiple watery domains of the Greater Cahokia region, including the floodplain's many oxbow lakes, the subterranean caverns below the St Louis precinct, the karst landscape north and south of the city, the 'weeping hill' atop which the Emerald Acropolis was built, and more. Perhaps the Cahokians lived with water

in ways that discouraged developing high-level water-management infrastructure. If so, this might also help explain the lack of wastewater and septic infrastructure in the city precincts. Presumably, abandoned subterranean food-storage pits, designated borrow pits, and nearby infields were used as toilet facilities. The results of the latter washed off into nearby water bodies.

Key Geologic Concepts:

Alluvial channel; stream flow characteristics; erosional and depositional landforms; floodplain.

Supplemental Materials:

Article: [Floodplain](#)(opens in new window). In National Geographic.

Article: "[Cahokia: A Pre-Columbian American City](#)" by Timothy R. Pauketat. *History Now* 28 (Summer 2011).

Article: "[Building Monks Mound, Cahokia, Illinois, A.D. 800–1400](#)" by T. Schilling. *Journal of Field Archaeology* 37, 302 (2012).

Article: "[The exceptional environmental setting of the North Plaza, Cahokia Mounds, Illinois, USA](#)" by C.G. Rankin. *World Archaeology* 54, 84 (2022).

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3.2: Classroom Activity

Landform Identification on Mississippi River Floodplain Using Google Earth

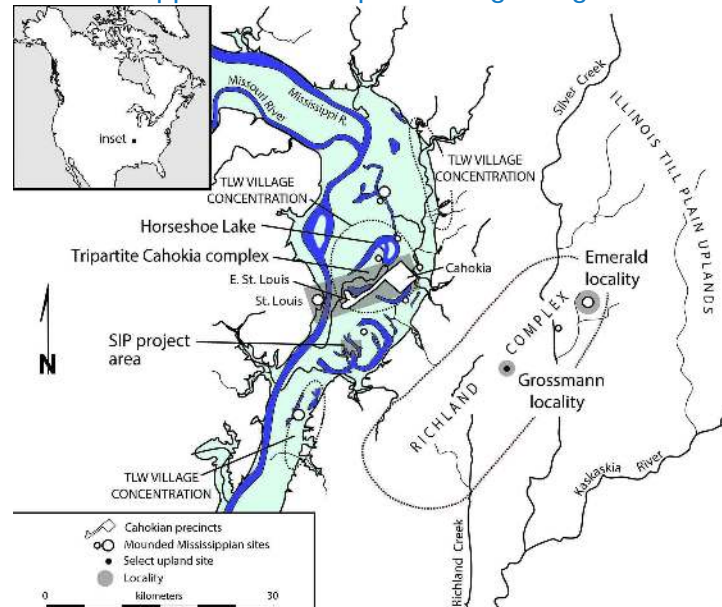


Figure 3.2.1: Mississippi River and its floodplain in the region including Cahokia at the time of its settlement around 1050 CE. (From Pauketat et al. 2023.)

Open [Google Earth](#) Online.

1. Focus on the same region as the 1050 CE (Fig. 3.2.1) map above. Make geomorphological comparison on identifiable landforms. What are the identifiable landforms within and around the floodplain in the 1050 CE map? Are these landforms identifiable on the Google Earth map of the present time? How have their morphologies changed? Make a list of these landforms and their geomorphological changes.
2. How have the boundaries of the floodplain changed between 1050 CE and the present time? Make qualitative observation and quantitative floodplain width measurement/estimation at several representative locations.
3. How has the path of the Mississippi River channel changed between 1050 CE and the present time? Make qualitative observation and quantitative channel width measurement/estimation at several representative locations.

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3.3: Assignment

Assignment:

1. Describe the main characteristics of the floodplain of an alluvial channel:
 1. What is the typical width of a floodplain of a large river like the Mississippi River?
 2. When is the floodplain inundated with water?
 3. What created the sediments, i.e., the alluvium, on the floodplain?
 4. How have humans utilized the floodplain?
2. Describe the major erosional landforms on the floodplain:
 1. Cut bank,
 2. Meander,
 3. Oxbow lake.
3. Describe the major depositional landforms on the floodplain:
 1. Natural levee,
 2. Point bar.
4. The article by Pauketat et al. states that "single-family rural domestic habitations...featured one or more non-domestic, ostensibly Cahokian structures."
 1. What percentage of Cahokia's buildings were "non-domestic" structures?
 2. What were some of the "non-domestic" structures?
 3. Who lived in the "non-domestic" structures?
 4. What significance do the "non-domestic" structures bring to the notion that the Cahokian urbanism is anomalous?
5. The North Plaza, the area immediately north of Monks Mound, was the topic of investigation in the paper by Rankin (2022).
 1. What was the environmental condition of North Plaza at Cahokia's time?
 2. What does this condition imply about the Cahokian urbanism?
6. The authors of the article states that Cahokia's known anomalous characteristics include its "distanciated configuration" among the precincts.
 1. Consider the "distanciated configuration" in relation to proximity to water bodies as shown in the maps shown in the Reading.
 2. Discuss whether this configuration was intended to border the bodies of waters.

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CHAPTER OVERVIEW

4: Self-Healing Concrete for Aqueduct in Imperial Rome, 2,000 BP

[4.1: Reading/Media](#)

[4.2: Classroom Activity](#)

[4.3: Assignment](#)

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4.1: Reading/Media



The Roman aqueduct at Pont du Gard, France, built with ancient Roman concrete in the first century CE. The longevity of the Roman aqueduct is in part due to the self-healing property of the Roman concrete, a long-standing mystery resolved in the second/third decades of the 21st century. (Photo by [Benh Lieu Song](#), Wikimedia.)

Self-Healing Concrete for Aqueduct in Imperial Rome, 2,000 BP

Excerpts from "[Hot mixing: Mechanistic insights into the durability of ancient Roman concrete](#)" by L. M. Seymour et al. *Science Advances* 9, eadd1602 (2023). CC BY

Introduction

Excerpt: For many centuries, and throughout the entire ancient Roman Empire, architectural elements, such as walls and foundations, and infrastructure systems, including aqueducts, roads, and bridges, were created from unreinforced concrete. This concrete was typically composed of volcanic tuff and other coarse aggregates (caementa), and bound by a mortar based on lime and pozzolanic materials such as volcanic ash (pulvis), the detailed formulations of which were tailored to their specific intended applications. Whereas aerial lime mortars relied on the uptake of CO_2 from the air to harden, hydraulic mortars combined lime and water with reactive silicates and aluminosilicates (pozzolanic materials) to form cementitious hydrates [e.g., calcium aluminosilicate hydrates (C-A-S-H)].

By developing these hydraulic mortars, the Romans were able to create a stronger, more durable material that allowed them to build larger, more complex-shaped architectural structures for purposes that were not previously possible (Fig. 4.1.1), including constructions in the sea. The production process for Roman mortar began with the calcining of lime from a source such as limestone, marble, or travertine (all predominantly calcite, CaCO_3) to form quicklime [calcium oxide (CaO)]. This lime-based material, which can be hydrated using water (a process known as slaking) or added directly (a process known as hot mixing), was then mixed with volcanic ash, ceramic fragments (cocciopesto), or other pozzolana, sand, and water to form the hydraulic mortar.



Figure 4.1.1: "The Baths at Caracalla", painting by Lawrence Alma-Tadema, 1899. Bathhouses were among the urban infrastructure built with Roman concrete. (Public domain image.)

Studies focusing on the durability of Roman concrete constructed in marine environments, for example, evidenced the dissolution of lime and vitric tuff clasts at high pH, followed by the precipitation of C-A-S-H-containing reaction rims and, subsequently, the post-setting crystallization of Al-tobermorite and phillipsite in the matrix. In both Augustan and Imperial era architectural concretes, a similar C-A-S-H precipitation and subsequent crystallization and growth of platy strätlingite crystals in the perimeters of scoriae and the cementing matrix were observed. More recently, both Al-tobermorite and strätlingite crystals were found in the mortars of the Augustan period (ca. 30 BCE) tomb of Caecilia Metella. The prolonged reactivity of volcanic aggregates and their potential role in the long-term durability of these materials has thus been an ongoing focus of recent studies on Roman concretes.

In addition to the features described above, aggregate-scale relict lime clasts (Fig. 4.1.2), also referred to as remnant lime or lime lumps, are a ubiquitous and conspicuous feature of both architectural and maritime Roman concretes. The presence of these distinctive bright white features has been previously attributed to several scenarios including incomplete or over-burning during the calcining of lime, carbonation before concrete preparation, incomplete dissolution during setting, or insufficient mixing of the mortar.

In maritime structures, these lime clasts can be heterogeneous in composition; may contain calcite, vaterite, brucite, ettringite, hydrocalumite, C-A-S-H, tobermorite, and Al-tobermorite; and can be categorized into one of the following three groups: (i) geologic, (ii) partially dissolved, and (iii) fully dissolved (transformed). Geologic inclusions are calcite-bearing aggregates that did not fully calcine during the production of quicklime. The other two, partially and fully dissolved clasts, have provided insight into the chemical evolution of maritime concretes. For example, partially dissolved clasts show a C-A-S-H-containing reaction rim, gradating toward a calcite-rich core. Fully dissolved clasts, in contrast, exhibit C-A-S-H throughout and, in some cases, the formation of Al-tobermorite. In both partially and fully dissolved clasts, the clast exteriors contain hydrocalumite and ettringite, attributed to hydration with seawater. Although these clasts are well characterized in maritime Roman concretes, less is known regarding the microstructure and chemical composition of relict lime clasts in open-air Roman constructions (structures on land) and the role that they might play in processes associated with the durability of these structures.

To address these yet unresolved questions, we report on the chemical characterization of relict lime clasts found in 2000-year-old Roman concrete samples obtained from the archaeological site of Privernum, Italy. The investigated samples are compositionally consistent with other architectural mortars encountered throughout the Roman Empire, and were sourced from the masonry mortar of the city wall, an open-air structure. We characterized the composition of the lime clasts and their surrounding matrix using large-area scanning electron microscopy and energy dispersive x-ray spectroscopy (SEM-EDS), powder x-ray diffraction (XRD), and confocal Raman imaging. The results of these analyses provide compelling evidence for hot mixing of Roman mortar using quicklime instead of, or in addition to, slaked lime. From these findings, we propose that persistent, aggregate-scale, high surface

area lime clasts that result from this process could serve as a source of reactive calcium for long-term pore and crack filling and therefore provide a chemically dominated intrinsic self-healing mechanism.

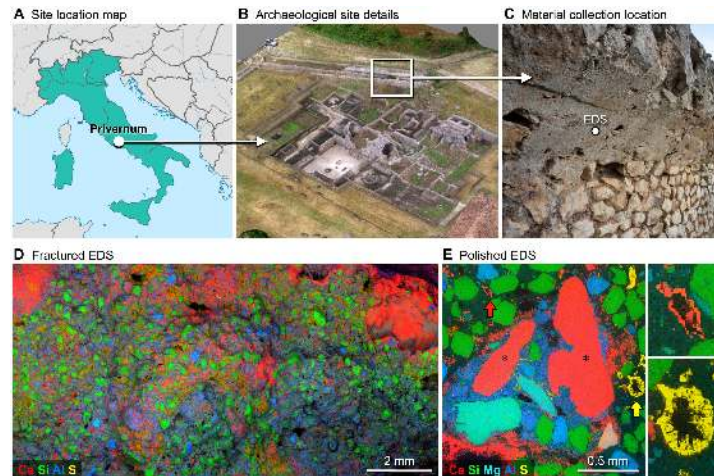


Figure 4.1.2: The test samples came from the archaeological site of Priverum, near Rome, Italy (A), and shown as a photogrammetry-based three-dimensional reconstruction (B). The architectural mortar samples were collected from the bordering concrete city wall (C). Large-area EDS mapping of a fracture surface (D) reveals the calcium-rich (red), aluminum-rich (blue), silicon-rich (green), and sulfur-rich (yellow) regions of the mortar. Further imaging of polished cross-sections (E) shows aggregate-scale relict lime clasts within the mortar (the large red features denoted by asterisks). The colored arrows in (E) denote the pore-bordering rings visible in the EDS data that are rich in calcium (red) or sulfur (yellow), which are enlarged at right to show additional detail. Photo credits (B and C): Roberto Scalesse and Gianfranco Quaranta, Associazione AREA3, Italy. (From Seymour et al. 2023).

Self-healing mechanism in Roman concrete

Excepts: Previous evidence suggests that in ancient Roman cementitious structures, the relict lime clasts can react over time with other mortar components, forming both amorphous (C-A-S-H) and crystalline (e.g., Al-tobermorite and strätlingite) phases. These maturation pathways, however, are not the only ones observed in Roman cementitious materials and, as shown here, can also follow different trajectories depending on the local environmental conditions. While the polished cross-sections of the ancient Roman concrete samples described in the present study do show clear inclusion of silicon and aluminum in the lime clast, suggesting that some conversion to C-A-S-H and/or its crystalline homologues occurred, calcium carbonate, predominantly as calcite, remains within their cores.

Whereas previous evidence supports the formation of Al-tobermorite minerals in lime clasts of maritime structures due to the heat of the pozzolanic reaction, the results presented here suggest that, by contrast, when quicklime is introduced via hot mixing in terrestrial structures, the reaction is limited to the outer rim of the lime clast, encapsulating calcium-rich core structures within mortar matrix. This particular configuration can be observed in the comparison of Roman and modern samples (Fig. 4.1.2), both showing the same type of lime clast inclusions, hydration-driven cracking, and distinctive reaction rims. The initially matrix-incorporated clasts would then undergo a slow transformation into calcium-rich, highly porous phases of various polymorphs of calcium carbonate.

Inspired by these discoveries, it is thus likely that the high abundance of aggregate-scale lime clasts in ancient Roman mortars could thus serve as a source of calcium for post-pozzolanic processes in a pore- and crack-filling “self-healing” mechanism that combats the progressive degradation of these cementitious materials. Over time, as cracks and pores form, the intrusion of water causes the dissolution of calcium-based phases in the relict lime clasts carrying them into the pore network. As the calcium-rich fluids leach into the cracks or the connected pore network, many pathways exist for potential post-pozzolanic reactions. For example, excess pozzolanic material, such as volcanic ash that did not react during the initial setting and curing, or aggregates of volcanic origin, can now dissolve and react with Ca-rich fluids originating from the lime clasts to form C-A-S-H phases, thus reinforcing the interfacial zones between volcanic aggregates/ash and the binding matrix. This strengthening is associated with the consolidation of the interfacial zones and increased mechanical performance of the C-A-S-H compared to its precursors. Another possible pathway is the recrystallization of CaCO_3 phases within the pore/crack space. This pathway, in which secondary calcium

carbonate is precipitated through a mechanism similar to the one occurring in the formation of calthemites, relies on the wetting and drying cycles experienced through normal weathering conditions. These processes have been observed previously in both modern and ancient carbonate-based mortars. In contrast to these previous studies, however, we suggest here that the hot mixing-transformed lime clasts act as a calcium source for these processes and, furthermore, the precipitation of calcium carbonate as a crack-filling mechanism is already a known pathway for autogenous healing in other ancient lime-containing mortars. In the present study, we demonstrate the calcium enrichment of matrix phases adjacent to the lime clasts, supporting the hypothesis that the lime clasts are a source of calcium for leaching and recrystallization within the pore space of the mortars (Fig. 4.1.2) . Microcrack filling by calcite has been recently observed in ancient Roman mortars from the tomb of Caecilia Metella, and the self-healing tests carried out on our modern samples described in the present study further support this hypothesis.

Key Geologic Concepts:

Carbonate; calcite; mineral growth in water; volcanic ash.

Supplemental Materials:

Article: "[Phillipsite and Al-tobermorite mineral cements produced through low-temperature water-rock reactions in Roman marine concrete](#)" by Marie D. Jackson, et al. *American Mineralogist* 102, 1435 (2017). CC BY

Podcast: "[The significance of the ancient Roman concrete for a decarbonizing world](#)", University of Utah.

Article: "[Scientists may have found magic ingredient behind ancient Rome's self-healing concrete](#)", Science.

Article: "[Reinventing Concrete, the Ancient Roman Way](#)", New York Times, October 19, 2024.

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4.2: Classroom Activity

Mineral Identification of Calcite and Quartz Using X-Ray Diffraction Data

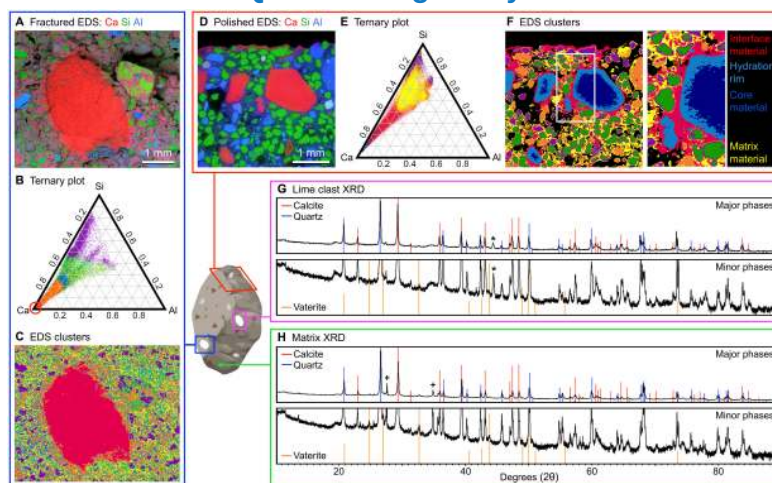


Figure 4.2.1: Multimodal compositional analysis of ancient Roman concrete. EDS maps of a freshly fractured surface (A) and polished cross-section (D) are quantified, and each pixel is replotted as a relative ratio of calcium, silicon, and aluminum on a ternary diagram (B and E), with the most Ca-rich phases shown in red and denoted by the red circle near the Ca vertex in (B). Pixels in the ternary diagrams (B and E) and phase maps (C and F) were colored on the basis of the cluster of EDS data to which they belong. Surrounding each of the lime clasts is a clear rim of a compositionally unique phase (the hydration rim), which is denoted by the light blue zones in (F) and is shown at higher magnification at right with color-coded text for additional clarity. Powder XRD of a relict lime clast (G) and its surrounding matrix (H) confirms the presence of calcite and quartz and suggests the presence of vaterite among other phases [e.g., halite (*) and volcanic minerals (diopside, leucite, etc.) (+)] in the mortar. (From Seymour et al. 2023.)

In this activity, we will use XRD data to identify calcite and quartz minerals. In subplot G of Fig. 4.2.1 above, the XRD spectra for calcite and quartz are shown. In XRD, X-ray photons are incident on the sample crystals and are scattered by the atoms in the crystal; the angles of the scattered X-rays are related to the orientation of the sets of atomic planes in the crystal. Bragg's law relates the lattice spacing d of a set of atomic planes and the diffraction angle θ :

$$2d \sin \theta = n\lambda \quad (4.2.1)$$

where $\lambda = 0.154 \text{ nm}$ is the wavelength of the X-rays from copper emission used in the experiments. By identify the several sets of atomic planes, one can finger print the identify of the mineral. For example, the strongest diffraction peak in the calcite spectrum (red) occurs at the angle of $2\theta = 29.2^\circ$. From Bragg's law, one can determine the lattice spacing to be $d = 0.305 \text{ nm}$; this distance matches the spacing of the (104) atomic planes of calcite.

1. Locate the four strongest diffraction peaks for calcite (red) in subplot G. From the angle of diffraction of these peaks, use Bragg's law to identify the corresponding atomic plane lattice spacing d . Verify that all four lattice spacings belong to the crystal calcite.
2. Locate the four strongest diffraction peaks for quartz (blue) in subplot G. From the angle of diffraction of these peaks, use Bragg's law to identify the corresponding atomic plane lattice spacing d . Verify that all four lattice spacings belong to the crystal quartz.

Supplemental Materials:

Libretexts: [X-ray diffraction identification of minerals.](#)

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4.3: Assignment

Assignment:

1. The puzzle of the Roman concrete was significantly resolved through the work by Jackson et al. (2017) and Seymour et al. (2023). Both point to sealing at the mineral-water interface as the cause of material durability, but through different mechanisms and involving different minerals.
 1. What is the mineral that seals off cracks in Roman on-land concrete according to Seymour et al.? What type of mineral is it? Where does it come from geologically?
 2. What is the mineral that seals off cracks in Roman marine concrete according to Jackson et al.? What type of mineral is it? Where does it come from geologically?
2. Two millennia have passed since the Roman concrete was developed in the first century BCE. But is this mechanism totally new? Or does it have similarities in known rock processes?
 1. Consider the cementation mechanism in clastic sedimentary rock formation. What are the similarities between this mechanism and the self-healing mechanism of the Roman concrete?
 2. Consider the recrystallization mechanism in metamorphic rock formation in chemically reactive fluids. What are the similarities between this mechanism and the self-healing mechanism of the Roman concrete?
3. Note that in the work by Jackson et al, the mineral Al-tobermorite is an aluminosilicate, like the mineral zeolite. Compare the similarities between Al-tobermorite and zeolite in source of generation and crystal framework.
4. Both the work by Jackson et al. and by Seymour et al. link their respective findings on ancient Roman concrete to the current issue of sustainability and CO₂ emissions.
 1. In the work by Seymour et al., what is the rationale that ancient Roman concrete can help reduce anthropogenic CO₂ emissions in the present society?
 2. In the work by Jackson et al., what is the rationale that the mechanism of mineral cementation learnt from the Roman concrete can be used to help remove CO₂ from the atmosphere and store it as solid minerals in volcanic solids?

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CHAPTER OVERVIEW

5: Water Filtration with Microporous Minerals in Preclassic Maya, 2,100 BP

[5.1: Reading/Media](#)

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5.1: Reading/Media



The central plaza at Tikal, Guatemala. In the remnant of the Corriental reservoir 1.5 km from the plaza, new finding of a sedimentary stratum comprising zeolite and quartz minerals suggests the ancient Maya people had developed water filtration systems. (Photo by [Siyuan Chen](#).)

Water Filtration with Microporous Minerals in Preclassic Maya, 2,100 BP

Excerpt from "Zeolite water purification at Tikal, an ancient Maya city in Guatemala" by K.B. Tankersley, N.P. Dunning, C. Carr, et al. *Scientific Reports* 10, 18021 (2020). CC BY

Excerpt: Archaeologists have long believed that the indigenous people of the Western Hemisphere lacked any formal water filtration systems. In North America, ancient indigenous cultures obtained clean water from naturally filtered springs, used boiling, and earthenware pottery in which contaminants, silt, and clay were pulled to the sides of the vessel. In Mesoamerica, the Aztec relied on abundant artesian spring water brought into their cities (e.g., Tenochtitlan) through aqueducts, which did not require purification techniques. Aqueducts were also built by the Inca, which brought mountain spring water to cities in the Andean region of South America. The Maya were the only ancient New World civilization that needed water filtration because many of their cities were located on a karst landscape in a tropical and monsoon climate. While sand, gravel, plant, and cloth filtration systems have been documented in Egypt, Greece, and South Asia as early as the fifteenth century BCE, comparable data are lacking for the Maya region. There is no comparative case for Maya water purification systems, that is, there are no comparative data available. To date, excavations have been conducted in only a few dozen of the many thousands of ancient Maya reservoirs, and many of these excavations have been limited to a single test pit. Here we report our findings from Tikal, Guatemala, where zeolite was found in the one of the largest storage facilities of Maya drinking water in use during the Late Preclassic to Late Classic cultural periods (~2200–1100 yr. B.P.). The apparent zeolite filtration system at Tikal's Corriental reservoir is the oldest known example of water purification in the Western Hemisphere and the oldest known use of zeolite for decontaminating drinking water in the world.

Tikal, known as Yax Mutal to the ancient Maya, was a city of more than 3000 structures situated in the karst topography and tropical forest ecosystem of the southern Maya Lowlands. Throughout the late Holocene, this area was affected by highly variable seasonal precipitation and subsurface drainage. In this environmental setting, the Maya constructed reservoirs to provide a reliable and sustainable source of drinking water during both seasonal and cyclical droughts.

The first systematic archaeological investigation of Tikal began in 1881 and accelerated through the twentieth century, resulting in detailed maps, photographs, and stratigraphic records of the site. While subsequent investigations documented the architecture and planning of Tikal's water management system, including precise dimensions of the catchment areas, human-modified watersheds, reservoirs, and their carrying capacity, the issue of water purification remained unresolved. Given the area is subject to extreme seasonal droughts, a large population, and long-term occupation, the drinking water of Tikal was prone to contamination from a plethora of microbial sources (e.g., cyanobacteria) and leachates from toxic minerals such as cinnabar. Uncertainty remains about how these contaminants might have been removed from the drinking water. We reexamined three of the largest reservoirs at Tikal and a sinkhole as a control to evaluate the mineralogical composition and chronological contexts of the sediments in order to assess potential water purification methods and their time of implementation.

Our mineralogical and chronological analyses focused on three reservoirs (Corriental, Perdido, and Temple) and a control sinkhole known as inscriptions, that are separated by large independent catchment areas. The reservoirs were constructed and maintained from the early colonization of Tikal during the Late Preclassic period, ~2500 yr. B.P., until the abandonment of the city ~1100 yr. B.P. With the exception of the Corriental reservoir, all excavated reservoirs have stratigraphic discontinuities from dredging during ancient Maya times.



Figure 5.1.1: Maya cylinder vase (c. 700-800 CE), Guatemala. A ritual drinking vase depicting a king wearing a headdress adorned with water lilies. Water lilies symbolized sources of clean water in Maya culture. (Museum of Fine Arts, Boston.)

The mineralogy of the reservoir and sinkhole sediments was determined using X-ray diffraction (XRD) analysis. Sediment samples collected at 10 cm intervals from solid-sediment percussion cores, analyzed using XRD, and relative mineral percentages were calculated for each of the samples. XRD analysis demonstrates that all of the sediment samples contain similar quantities of the minerals calcite, smectite, and quartz. Calcite originates from the local Cretaceous-Tertiary limestone bedrock, which forms the karst landscape of Tikal and the South Petén basin. Smectite and quartz, however, are volcanogenic in origin. Smectite is a clay mineral derived from the terrestrial alteration of airborne acidic volcanic ash (i.e., glass). Similarly, microcrystalline quartz (~50 μm) in the reservoir sediments originated as airborne volcanogenic bipyramidal crystals known as “first quartz”. The ubiquitous co-occurrence of volcanogenic smectite and microcrystalline quartz in the reservoirs and sinkhole sediments suggests that volcanic ash accumulated episodically in the reservoirs throughout the occupation of Tikal. Pristine, sharp-edged, microcrystalline quartz and zircon crystals in the reservoir sediments also demonstrates that smectite arrived in the reservoirs and sinkholes, and across the southern Maya Lowlands from volcanic ash rather than erosion.

The mineral zeolite was found solely in the sediments of the Corriental reservoir where it was omnipresent and co-occurs with macro-crystalline (0.5–2.0 mm) euhedral quartz. There are ~50 distinct species of zeolites including analcime, clinoptilolite, and mordenite. In Guatemala, analcime occurs as an extensively altered form of jadeite and clinoptilolite and mordenite occur in association with the mineral's quartz, calcite, and smectite in wet spring settings where volcanoclastic tuffs have altered to zeolites. While clinoptilolite and mordenite are not locally available at Tikal, they occur in volcanic rock cavities in western Guatemala where there are active, dormant, and extinct volcanoes. Clinoptilolite and mordenite have also been discovered in a coarse crystalline Cretaceous-Tertiary tuff exposed northeast of Tikal where clean potable water discharges. The co-occurrence of macro-

crystalline euhedral quartz, zeolite, and clean drinking water was likely the symbolic connection and empirical basis for the Maya choosing to mine this resource.

Zeolite is a non-toxic, three-dimensionally porous, crystalline, hydrated aluminosilicate. Zeolite has adsorbent properties because its three dimensional microcrystalline pore spaces (3–4 Å) create a natural molecular sieve. Consequently, zeolite has the ability to filter out harmful microbes, nitrogenous compounds, and other dispersed insoluble and soluble inorganic and organic toxins from drinking water.

Corriental is one of the largest reservoirs (~58,000,000 L) at Tikal (Fig. 5.1.2). Earthenware sherds of water jars of varying size were found in all of Corriental's strata. Corriental has only minor evidence of chemical pollutants and no evidence of blue-green algal blooms or other pollutants and it is the only excavated reservoir, which was not heavily dredged. In this regard, Corriental is not only anomalous at Tikal, but throughout the Maya Lowlands. Corriental is also the only reservoir, which has evidence of a zeolite water filtration system.

The Corriental water filtration system was composed of clinoptilolite, mordenite, and coarse to very coarse sand-sized euhedral quartz crystals. These zeolites and macro-crystalline quartz are likely derived from a coarsely crystalline Upper Cretaceous tuff stratum exposed along lower margins of deep scarps defining the Bajo de Azúcar located ~30 km northeast of Tikal, where it forms an aquifer known locally for its clean water. The filtration system was likely held behind dry-laid stone walls with the zeolites and macro-crystalline sand-sized quartz crystals further constrained with woven petate (woven reed or palm fiber matting) or other perishable porous material positioned just upstream of, or within the reservoir ingresses, which were periodically ejected into the reservoir during flash floods caused by tropical cyclones. Evidence for these events can be found in the sequential crystalline quartz lenses in the reservoir sediments (Figs. 5.1.3). Because zeolite crystals are much smaller in size (0.1 to < 10 µm), they were more easily water transported and deposited in the reservoir sediments during the functioning of the Corriental reservoir.

While a stand-alone coarse sand-size crystalline quartz filtration system would have been capable of water clarification, it would have had no effect on the removal of harmful microbes or deleterious insoluble or soluble toxins. Zeolite was a crucial component of the Corriental water purification system. At Tikal, zeolite occurs in the laminated organic clays of the Corriental reservoir sediments (Fig. 5.1.3). These strata are indicative of a low energy depositional environment. The clays are interstratified with coarse sand-sized crystalline quartz deposited during periods of high-volume, fast-moving, storm flow. The stratigraphic reoccurrence of embedded macro-crystalline quartz strata suggests that the filtration systems likely had to be replaced following flash-floods.

The uppermost stratum in the Corriental reservoir containing zeolite and sand-sized macro-crystalline quartz dates to the Late Classic. This stratum represents the final destruction of the filtration system. In other words, the filtration system was not restored after this event. The subsequent occurrence of anthropogenic mercury (Hg) in the Corriental reservoir likely originated from the weathering of artificial cinnabar (HgS) in the numerous residential areas and burials within the watershed. Anthropogenically Hg contaminated soil within the Corriental catchment would have in-washed from these areas causing an uptick in Hg. While it is impossible to know why the water filtration system was not rebuilt, it is possible that the Maya no longer had access to the necessary raw materials.

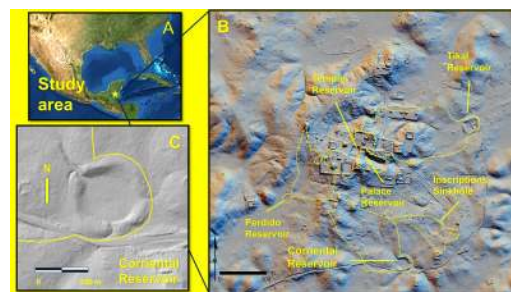


Figure 5.1.2: (A) Location of Tikal in the southern Maya lowland. (B) The location of the Corriental, Palace, Perdido, Temple, and Tikal reservoirs, and the Inscription sinkhole and their catchment areas. (C) A lidar-derived hillshade image of the Corriental reservoir. (From Tankersley et al. 2020.)

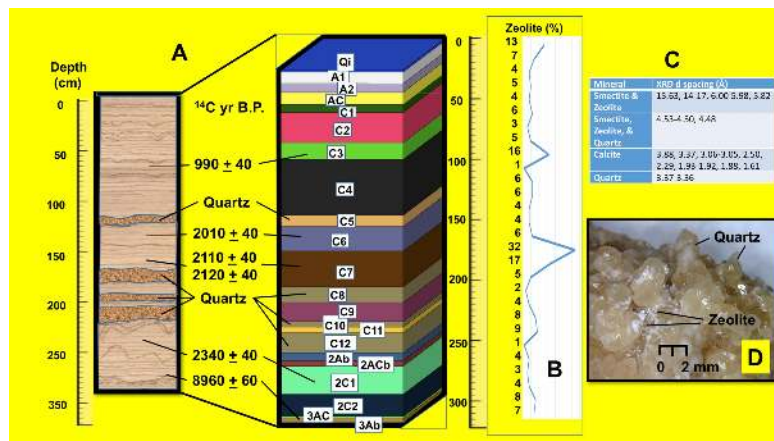


Figure 5.1.3: (A) Soil horizons and sediments of the Corriental reservoir showing the location of anthropogenic quartz and radiocarbon ages yr B.P. (B) Relative percent of zeolite by depth. (C) Distinctive mineral XRD peaks. (D) Photomicrograph of anthropogenic euhedral quartz crystals and zeolite. (From Tankersley et al. 2020.)

Key Geologic Concepts:

Silicate minerals; SiO₄ tetrahedral network; ionic exchange; sun angle; seasons.

Supplemental Materials:

Article "[Zeolite Clinoptilolite: Therapeutic Virtues of an Ancient Mineral](#)" by A. Mastinu et al. *Molecules* 1517 (2019). CC BY

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5.2: Classroom Activity

Sun Angle Analysis for Tikal Using NOAA Solar Calculator

1. Use [Google Earth](#) to explore the land area near the city center of Tikal, Guatemala. Locate the Corriental reservoir. Record the latitude and longitude of Tikal.
2. Open [NOAA Solar Calculator](#). Use NOAA Solar Calculator to determine Tikal's sun angle for the following dates:

Table of seasonal sun angles.

Season	Date	Sun angle	Intensity of solar energy delivered
Spring equinox	March 21		
Summer solstice	June 21		
Autumn equinox	September 21		
Winter solstice	December 21		

1. Note that Tikal's latitude is between the Equator and the Tropic of Cancer.
 1. For how many times in a year does Tikal have direct sunlight (i.e., 90 degree sun angle)?
 2. What are the date(s) when Tikal has direct sunlight? (Use the NOAA Solar Calculator to determine this.)
 3. Consider the seasons around the times of direct sunlight at Tikal and the seasonal shifting of the location of subtropical low pressure belt, explain why Tikal's rainfalls are concentrated in spring and summer.
2. How does the seasonal variation of solar energy delivered explain the seasonal variation of rainfalls at Tikal?
3. Variation in sun angle also affect the wet/dry conditions at other latitudes in the Americas.
 1. For how many times in a year does Chicago have direct sunlight?
 2. Why does variation in sun angle affect much less the resource of water in North and South America compared to Central America?
 1. Discuss this question by considering the size of the continent and drainage basins, and how rivers and groundwater are dependent on continental sizes.
 2. Use Chicago as an example, explain why seasons do not affect water availability in North America.

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5.3: Assignment

Assignment:

1. When describing the minerals in reservoirs and sinkholes at Tikal, the article says that "calcite originates from the local Cretaceous-Tertiary limestone bedrock." Based on the geological time scales for the Cretaceous and Tertiary periods, what are the ages of the calcite minerals? What was the environment of Tikal at that time (on land, in coastal sea, in deep ocean)?
2. The archaeological study of the Tikal site followed a logical pattern. According to the authors, what aspects of the investigation have been completed in previous studies? What aspects of the investigation are the goals of the current study? What are the techniques to be used to achieve these goals?
3. The article stated that the zeolite sedimentary stratum were only found in the Corriental reservoir and that there were discontinuities in the sedimentary strata besides the Corriental reservoir. By considering the complete sedimentary strata shown in the paper, describe a relative approach to determine whether the absence of the zeolite stratum is due to erosion or loss.
4. The article views the simultaneous presence of macro-crystalline quartz and zeolite in the stratum in the Corriental reservoir as an indication of systematic water filtration. What is the function of the macro-crystalline quartz? What is the function of zeolite?
5. In a perspective article published in the journal *Proceeding of the National Academy of Science of the U.S.A.*, a geologist specialized in ancient Maya water systems but not associated with the zeolite study commented: "That said, zeolite is found in volcanic deposits (e.g., highland Guatemala) and would not have been readily available in most areas of the southern lowlands. Further, the Corriental Reservoir has the only known zeolite filtration system in the Maya area (though only 50 Maya reservoirs have been excavated or cored)." ([Lucero, 2023](#)) Consider the balance of opinions in relation to evidence, should the reported finding of zeolite filtration taken with general faith, or should there be further evidence?

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CHAPTER OVERVIEW

6: Irrigation Canals for Agriculture in Euphrates-Era Mesopotamia, 3,000 BP

[6.1: Reading/Media](#)

[6.2: Classroom Activity](#)

[6.3: Assignment](#)

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6.1: Reading/Media



Artist's representation of the Port of Eridu on the ancient Euphrates river in southern Mesopotamia. The change of course of the river at 3,000 BP left the region in a desert. ([World History Encyclopedia](#).)

Irrigation Canals for Agriculture in Euphrates-Era Mesopotamia, 3,000 BP

Excerpts from "[Identifying the preserved network of irrigation canals in the Eridu region, southern Mesopotamia](#)" by J. Jotheri, M. Rokan, A. Al-Ghanim et al. *Antiquity* 99, 405 (2025). CC BY 4.0

Excerpt: Rivers in the Mesopotamian floodplain (Figure 6.1.1) are the primary water source for irrigation, and farmers in the past needed to have basic skills in diverting water from rivers to their farms. These skills developed from simpler methods, such as digging a few metres of canal over a crevasse splay (Figure 6.1.2) and developed over time with knowledge and experience passed from one generation to another, eventually resulting in canals 100km long. Two natural geomorphological characteristics made the rivers of the Mesopotamian floodplain manageable for early farmers. First, the rivers' highly elevated levees enable water to flow by gravity to irrigate the surrounding agricultural land. Second, the formation of crevasse splays (Figure 6.1.2), natural or artificial breaks in the river levee, releases water directly onto the floodplain through a fissure channel. However, most of our knowledge about irrigation and farming in southern Mesopotamia still comes from indirect evidence, such as cuneiform tablet texts.

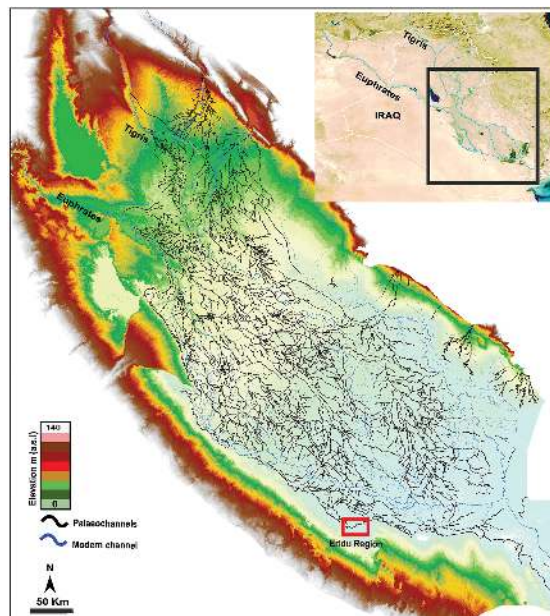


Figure 6.1.1: Topographic map of the Mesopotamian floodplain, drawn using Shuttle Radar Topography Mission data, showing the location of the Eridu Region and the networks of modern and ancient rivers and canals in the floodplain. (From Jotheri et al. 2025.)

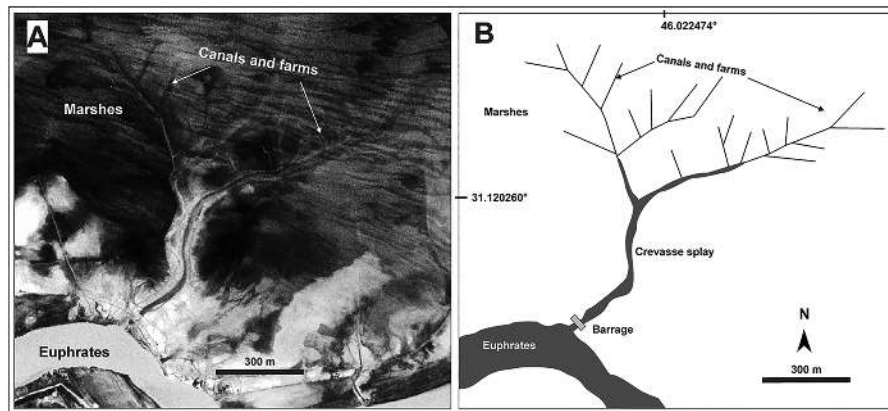


Figure 6.1.2: An example of a contemporary crevasse splay on the modern Euphrates 30km north-east of the Eridu Region: A) Corona satellite image taken in 1968; B) the reconstructed crevasse splay, illustrating how farmers can modify a crevasse splay, dig irrigation canals, build a barrage to control the flooded water and claim land for farming in southern Mesopotamia. (From Jotheri et al. 2025.)

Most of the ancient irrigation canal networks now visible on the ground in modern Iraq belong to the Parthian and Sasanian periods (from the late first millennium BC) onward. The older irrigation networks were covered by the younger networks or the sedimentation of rivers. Consequently, little is known about earlier irrigation canals and associated farms—evidence as to size, shape, location and extent has largely been erased. By contrast, the Eridu region of southern Mesopotamia (Figure 6.1.1) was occupied from the Early Ubaid until the Neo Babylonian periods (late sixth to early first millennium BC). A shift in the ancient course of the Euphrates River left this region dry and consequently unoccupied after the early first millennium BC until now. This has allowed the archaeological landscape of this region to remain intact and thus we were able to identify and map a vast, intensive and well-developed network of irrigation canals that pre-date the early first millennium BC.

The present study implemented a combination of geological, geomorphological, remote sensing, historical and archaeological approaches. Geological and geomorphological maps of the region were reviewed. Satellite images of different resolutions and times, including historic CORONA imagery, were consulted. Fieldwork was carried out, including the ground-checking of remote-sensing work and the collection of drone images and camera photography. Differentiation between natural and artificial canals includes consideration of canal patterns, topographic cross-sections, crevasse splays, marshes, meanders, cut-offs and oxbow lakes, and stream directions.

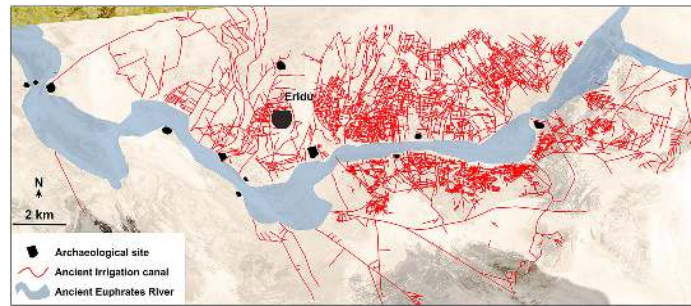


Figure 6.1.3: The reconstructed irrigation canal network in context with the ancient Euphrates riverbed and the archaeological sites of the Eridu region. (From Jotheri et al. 2025.)

A vast and well-developed network of artificial irrigation canals, including more than 200 primary and large canals, was identified and mapped (Figure 6.1.3). The main canals are directly connected to the ancient course of the Euphrates and are between 1 and 9 km long, and between 2 and 5 m wide. Moreover, more than 4,000 minor and branch canals connected to the main canals are identified. The length of these branch canals is between 10 and 200 m while the width is between 1 and 2 m. More than 700 farms are identified, and minor or branch canals are typically found around the perimeter of each farm. The area of each farm is between 500 and 20,000m². It seems that the ancient course of the Euphrates stayed in its riverbed for most of the time the farms were occupied, only moving laterally within the riverbed. There were no avulsions or significant shifts of the river in the region during the period of occupation, allowing the primary canals to connect with the river continuously. Both sides of the river were canalised and farmed, although farmers exploited the northern side more heavily than the southern side.

This reconstructed network of irrigation canals represents the combined agricultural activities for all the periods of occupation in the region and it is unlikely that all of the canals were running simultaneously during the entire occupation period (i.e. from the sixth until the early first millennium BC). Canals require immense labour and experience in water management to operate successfully. Therefore, it is essential to conduct additional research on the chronology of the canals to better understand changes in the irrigation systems and agricultural landscape over time. Reconstruction of the ancient marshes in this region would also indicate any reclamation and exploitation activities. Finally, comparing the character and dimensions of the canals and farms with contemporaneous descriptions in the texts of the cuneiform tablets could provide additional, valuable insights into agricultural practices and management in the Euphrates floodplain and in Mesopotamia more broadly.

Key Geologic Concepts:

Floodplain; natural levee; crevasse splays.

Supplemental Materials:

Website: [Eridu](#), [World History Encyclopedia](#).

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6.2: Classroom Activity

Geometry Analysis of Eridu Irrigation Canal Networks

1. The geometric structure of a network provides information about its complexity and levels of hierarchy. The geometric structure can be described by the quantification of network elements. The most basic network elements are: nodes (junctions), edges (connections), and the degree (the number of edges at a node). An analysis of this kind can be performed for chosen constant areas covering the overall network region. An analysis performed for the irrigation canal network shown in Figure 6.2.1 discovered at the Eridu region of southern Mesopotamia dated before 3,000 BP may provide useful data for meaningful comparison between ancient and modern agricultural irrigation networks.

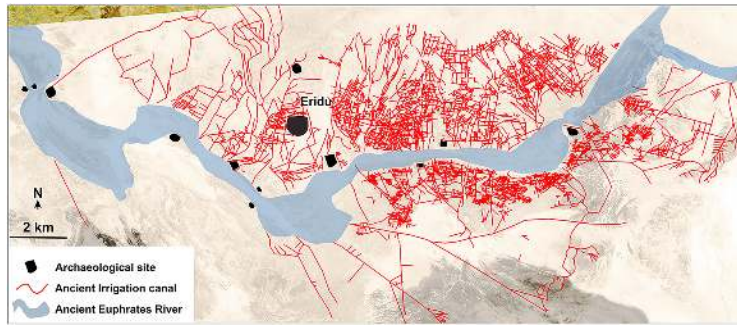


Figure 6.2.1: Irrigation canal networks at the Eridu region in southern Mesopotamia. (From Jotheri et al, 2025.)

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6.3: Assignment

Assignment:

1. What were the two natural geomorphological formations that made the rivers of the Mesopotamian floodplain manageable for early farmers?
 2. How did the skills of early farmers in diverting water from rivers to their farms develop over time? What type of evidence has provided most of our knowledge about irrigation and farming in southern Mesopotamia?
 3. What is the main reason why little is known about earlier irrigation canals and associated farms in southern Mesopotamia? Why was the archaeological landscape of the Eridu region in southern Mesopotamia able to remain intact?
 4. What was discovered in the Eridu region of southern Mesopotamia that provided insight into ancient irrigation systems?
 5. What was the approximate size range of the areas of the farms identified near the ancient course of the Euphrates? How did the ancient course of the Euphrates affect the primary canals during the period of occupation?
 6. Why is it essential to conduct additional research on the chronology of the canals in the region? What could comparing the character and dimensions of the canals and farms with cuneiform tablets provide?
-

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CHAPTER OVERVIEW

7: Cuneiform Writing on River Clays in Old Babylonia, 3,800 BP

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7.1: Reading/Media



Temple ruins in Uruk, an ancient city in southern Mesopotamia. Written language is believed to have been born in Uruk as cuneiform inscription on river clays. A collection of cuneiform artefacts from Uruk and other Mesopotamian locations are examined here for their making processes and mineralogical origins. (Image by [tobeytravels](#), Wikimedia.)

Cuneiform Writing on River Clays in Old Babylonia, 3,800 BP

Excerpts from "[A synchrotron X-ray powder diffraction study of cuneiform clay artefacts](#)" by R. Cameli Manzo, Z.J. Földi, S. Jáka-Sövegjártó, et al. *npj Heritage Science* 13, 605 (2025). CC

River-deposited clay as a writing medium

Excerpt: In ancient Mesopotamia, the clay provided by the Tigris and Euphrates alluvial plains (Fig. 7.1.1) was used for many purposes, such as for construction and for manufacturing votive objects, and as a writing medium. Inscribed with cuneiform signs, clay artefacts record a variety of information, including administrative records, letters, medical text, and literature. A significant number of written documents date back to the so-called Ur III period (21st c. BC) because of a massive reorganization of state administration at that time. With respect to the manufacturing of tablets, authors have suggested that these artefacts were mostly sun-dried, while only a small number were intentionally fired in antiquity. Clay cones and clay bricks, inscribed with accounts of the ruler's building activities, were supposedly baked and then placed in the foundations and walls of monumental buildings. Nonetheless, determining which artefacts were treated intentionally is difficult, given that firing was a common practice developed by museums for conservation purposes, especially from the 1950s to the early 1990s, until this treatment was deemed unnecessary in 1987 and 1993. Furthermore, historical events such as the sacking of royal archives following the siege of Nineveh in 612 BC complicate the correct determination of intentional firing as a pottery practice.



Figure 7.1.1: Map showing the site provenance of the 36 written artefacts considered in this study. (From Cameli Manzo et al. 2025.)

To better understand the raw material used for manufacturing these artefacts, an important method for determining the mineral composition is X-ray powder diffraction (XRPD). This technique has been implemented both invasively and non-invasively. In the cases where the analysis was destructive, a portion of the clay tablets was scratched or removed, whereas in one instance, a micro X-ray diffractometer was used to identify the main minerals in reflection geometry. Non-invasive analyses are important owing to the conservation of the artefacts and for the possibility to reproduce the experiments.

Archeological background: a case study

Clay cone 1913.131 from the MK&G collection bears a building inscription attributed to Sîn-kāšid, an Amorite ruler of Uruk in the Old Babylonian period (20–17th c. BCE) (Fig. 7.1.2). The same inscription has been observed on over a hundred written artefacts, including clay cones and tablets, some discovered through scientific excavations of the remains of Sîn-kāšid's palace at Uruk and others acquired from the antiquities market. The inscription is edited in Frayne, D. R. as no. 4.4.1.3. For a detailed list of corresponding artefacts see Frayne, D. R. 444–447. The transliteration and translation presented here follow the edition in this volume. Italics indicate Semitic elements in the Sumerian text, including the ruler's name and the name of an Amorite tribe. The present artefact belongs to the latter category and lacks a documented excavation context. Nevertheless, given that Sîn-kāšid is known only from Uruk, the provenance of the artefact can be reliably assigned to this site. The chronological placement of Sîn-kāšid's reign in the 19th c. BCE provides an approximate date for the object. The inscription comprises nine lines written in the ductus of Old Babylonian monumental inscriptions. The transliteration and translation of the Sumerian text inscribed on the cone are as follows:

1. ^dsuen-ka₃-ši-id / Sîn-kāšid
2. nita kalag-ga / mighty man
3. lugal unug^{ki}-ga / king of Uruk
4. lugal am-na-nu-um / king of the Amnānum (tribe)
5. u₂-a / provider
6. e₂-an-na / of the Eanna (temple)
7. e₂-gal / built
8. nam-lugal-la-ka-ni / his royal
9. mu-du₃ / palace



Figure 7.1.2: Image (right) and hand copy of the inscription (left) of clay cone 1913.131. The translation of the inscription is given above. (From Cameli Manzo et al. 2025.)

Clay cones, along with other artefacts bearing short royal inscriptions, were commissioned by rulers in connection with construction and restoration projects. These objects, which include tablets, cones, figurines, and architectural elements such as door sockets, were produced en masse in workshops and placed within buildings as part of foundation or dedicatory assemblages. Clay cones were specifically designed as decorative elements inserted into the walls. In some cases, more than a thousand cones bearing the same inscription have been preserved, underscoring the scale of their production. Once embedded in the walls, the text on their shaft remained hidden from human sight, as their inscriptions were intended for a divine audience to affirm the ruler's piety and immortalize his achievements in the presence of the gods. Furthermore, rulers of later times were also meant to discover foundation deposits and honour previous builders and restorers with their own inscriptions. Royal inscriptions, when preserving the name of the ruler, are generally straightforward to date. In the case of Sîn-kāšid, both the dating and provenance are not problematic, as his rule is exclusively associated with Uruk. However, in many other cases, establishing a date and provenance is considerably more challenging, especially when artefacts lack a documented archaeological context or when excavation records are incomplete. Without such information, researchers must rely on internal textual features, palaeographic analysis, and comparative material to approximate the time and place of origin.

Mineralogical composition

The experiments revealed considerable variability in the mineral composition among the artefacts. A mineral identified in all the cases is quartz, given its ubiquitous abundance and high thermal stability. Feldspars were also found in all the objects, represented by the plagioclase endmember albite, whereas other studies report plagioclase or plagioclase+K-feldspar as the main feldspar phases. Clay minerals were represented mainly by illite, both in terms of distribution and abundance, whereas lower concentrations of kaolinite, chlorite and, in some instances, palygorskite were also observed. Small amounts of amphibole hornblende were found in most of the artefacts. Calcite was also highly represented, with only two samples completely missing its characteristic peaks. In these two samples, namely, a clay tablet (2023.1) and a clay cone (1913.132) from Uruk and dated to the 19th c. BC, illite and hornblende were not observed, but the zeolite analcime was present. Other carbonates, such as aragonite and dolomite, were observed in some of the samples. Gypsum, found only in one clay cone, 1913.128 (Lagash, 22nd c. BC), has been identified in a study on tablets from Umma, Dilbat, Larsa, Ur, Babylon, Uruk, Sippar, and Nippur (Ur III and Early Achaemenid periods) using micro X-ray diffraction. This mineral could form on the surface of the artefact as an alteration product. The clinopyroxene diopside was found in some artefacts in conspicuous amounts, and samples 2023.1 and 1913.132 contained up to 70 wt. % diopside according to phase quantification with the Rietveld method. Finally, we determined the occurrence of spinel-phase magnetite in a clay tablet whose envelope was from Girsu, 21st c. BC. The occurrence of magnetite in other samples is not excluded but could not be determined given that the intense peaks overlap with the diopside peaks.

Mineral content in relation to morphology, provenance and dating

The surfaces of some of the artefacts considered in this study, including clay cone 1913.130, were blackened. However, we could not identify any relevant mineral conferring this effect. Since alterations of the surface often consist of only a few atomic layers, surface diffraction methods in reflection geometry (e.g., grazing incidence) might provide greater insight into the nature of this blackening. However, such an investigation was beyond the scope of our study. Considering the individual documents according to morphology, the leg-shaped artefact displays the paragenesis of quartz, calcite, albite, aragonite, amphibole and illite (1983.286), shared with most of the other clay tablets, including their envelopes. This composition is independent of the inferred provenance

for tablets belonging to the Ur III period and for the leg-shaped artefact, which dates approximately 1000 years later. The objects from the 22nd c. BC and the 19th c. BC, consisting of two tablets (2023.1 and 2023.2) and all the investigated clay cones, contain various amounts of diopside. Nonetheless, according to existing research on clay tablets from the Old Babylonian (ca. 1800 BC), Neo-Babylonian (ca. 550 BC), and Early Achaemenid (ca. 500 BC) periods and from the inferred Neo-Babylonian, pyroxene was not observed. In our study, the presence of diopside is independent of provenance and period. All the clay cones contain various amounts of diopside. This suggests a differentiation of manufacture according to the purpose of the clay cones, which confirms the description in Chiera (1938). Sufficient statistics of measurements would clarify this finding.

Clay processing

The raw starting material used for manufacturing the measured objects resulted in illitic clay or silt with various contents of chlorite, kaolinite, and palygorskite. A comprehensive study in which XRPD, FTIR, and SEM-EDX methods were performed on small samples from cuneiform tablets also revealed palygorskite-based silt with inclusions of calcite, quartz, and amphibole³. In our case, palygorskite is not the main representative clay mineral in all the objects. Instead, the main clay fraction resulted in an illitic phase. The mineral composition of some of the tablets is comparable to that of deposits along the Euphrates from Hilla (Babylon) to Basrah, Iraq, with illite, chlorite, kaolinite, and palygorskite being the major representative minerals of the clay fraction. The clay mineral contents in the sediments studied were, on average, 20%. However, in the samples considered here showing comparable mineralogy, the average clay mineral content increased to 40 wt. % after Rietveld quantification. This difference could be attributed to the variability in the mineralogy of sediments from the Mesopotamian Plain according to the area distribution and depth. Among the heavy fraction, sediments near Nasiriyah, Iraq, also contain hornblende. Compared with sediments from the Basrah area, which is closer to the Persian Gulf, there is a substantial difference, namely, the lack of gypsum—except for the small amount in one sample, possibly due to percolation and precipitation during burial—or halite in our samples derived from estuarine fluctuations.

With respect to the determination of thermal treatments, firing tests conducted on materials used in the manufacturing of ceramics in the Algarve Basin in southern Portugal attributed the occurrence of diopside to the thermal decomposition of dolomite. The findings were observed from temperatures ranging from 700–900 °C depending on the starting composition of the minerals. This pyroxene forms from either the vitreous phase derived from the decomposition of clay minerals and silicates or at the interfaces between minerals. Additionally, thermal decomposition of chlorite can lead to the formation of clinopyroxene and a spinel phase (magnetite). Our results indicate that dolomite can occur in some of the tablets in modest amounts, whereas the main carbonate comprised calcite in all the cases. To explain the high contents of diopside in artefacts 1913.132 and 2023.1, the high content of MgO available during a probable firing must be considered. In addition to dolomite, illite and chlorite are included. An important contribution to the reaction of MgO might also be derived from the thermal decomposition of palygorskite, a clay mineral containing high contents of MgO, which we observed in some cases and is found in raw materials from the Mesopotamian Plain, along the Tigris and the Euphrates. The occurrence of magnetite, together with diopside, could be determined in only one sample, and owing to its low content and peaks in the diffractogram overlapping those of the more represented diopside, whether other samples might also contain small amount following high-temperature treatment is unclear. Iraqi sediments contain small amounts of magnetite; however, magnetite is also a product of firing pottery. For this reason, it is unclear whether magnetite is derived from the sediment or a firing process.

Key Geologic Concepts:

Chemical weathering of silicates; river erosion and deposition of rock materials; clays.

Supplemental Materials:

Youtube: National Geographic: [Ancient Mesopotamia 101](#)

Youtube: [The Samaritans: Fall of the first cities.](#)

Institute for the Study of Ancient Cultures, University of Chicago: [Cuneiform tablets collection.](#)

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7.2: Classroom Activity

Mineral Identification of Cuneiform Clays Using X-ray Diffraction Data

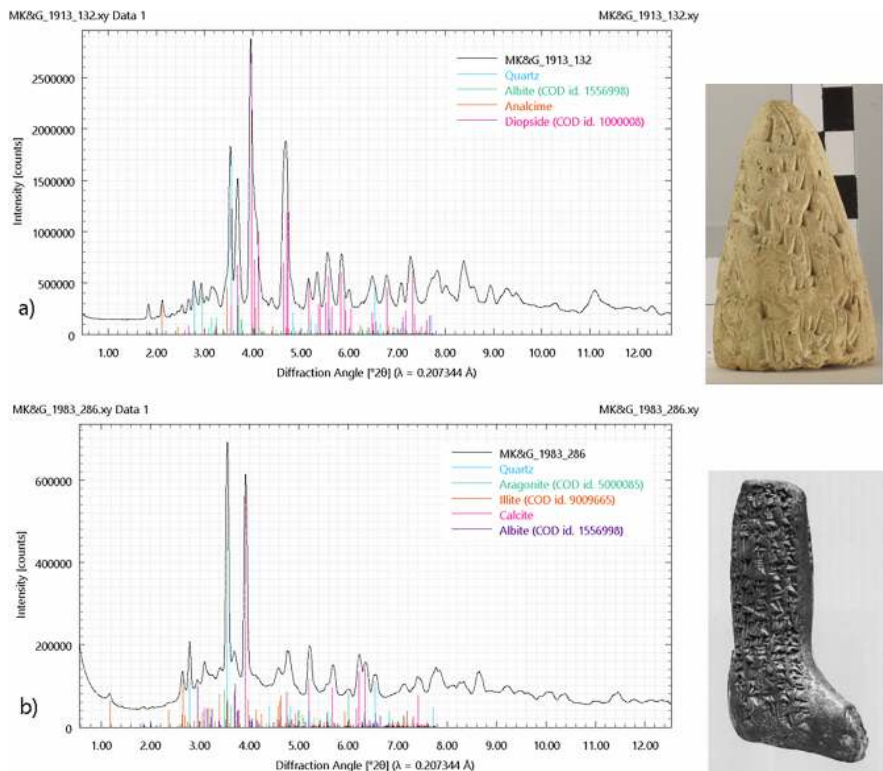


Figure 7.2.1: Synchrotron X-ray diffraction data for (a) clay cone 1913.132 and (b) the leg-shaped clay artefact 1983.286. (From Cameli Manzo et al. 2025.)

Table of X-ray diffraction data of minerals in clay.

Mineral identified	Clay cone 1913.132	Leg-shaped clay artefact 1983.286	Diffraction angle, $2\theta(^{\circ})$	Lattice spacing, $d(\text{\AA})$	Atomic plane, (hkl)
albite (example)	No	Yes	2.97	3.99	(101)
analcime					
aragonite					
calcite					
illite					
diopside					
quartz					

In this activity, we will use XRD data from Fig. 7.2.1 of the paper to identify the major minerals comprising the clay cone and leg-shaped artefacts. In XRD, a ray of X-rays is incident on the sample crystal and are scattered by the atoms in the crystal; the angles of the scattered X-rays are related to the orientation of the sets of atomic planes in the crystal. Bragg's law relates the lattice spacing d of a set of atomic planes and the diffraction angle θ :

$$2d \sin \theta = \lambda \quad (7.2.1)$$

where $\lambda = 0.207 \text{\AA}$ is the wavelength of the X-rays from the synchrotron; note that $1 \text{\AA} = 0.1 \text{nm} = 10^{-10} \text{m}$. By determining several sets of atomic planes d from several diffraction peaks, one can identify of the mineral. Here, we will only determine one strong diffraction peak for each mineral. For example, for the mineral albite, one strong diffraction peak is observed in the X-ray diffraction data for the leg-shaped clay (purple line) at the diffraction angle of $2\theta = 2.97^{\circ}$. From Bragg's law, $2 \times d \sin(2.97/2)$

$= 0.207$, which can be solved to give the lattice spacing of $d = 3.99\text{\AA}$; this d-spacing matches the spacing of the (101) atomic planes of albite.

1. Locate one strong, distinct (not mixed) diffraction peak for each of the listed minerals in the table above. From the angle of diffraction of these peaks, use Bragg's law to identify the corresponding atomic plane lattice spacing. Verify that all four lattice spacings belong to the crystal calcite.
2. Based on the X-ray diffraction intensity counts relative to the standards (the colored lines), identify the presence or absence of the minerals for the clay cone and the leg-shaped clay artefact.
3. Which mineral found among these two sample artefacts are most common and found in all clay artefacts examined in this study?
4. Which mineral found among these two sample artefacts are likely to represent the result of decomposition due to thermal treatment (i.e., baking)?
5. Which minerals are silicates?
6. Which minerals are clays, the weathering products of silicates?
7. Which minerals are carbonates?

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7.3: Assignment

Assignment:

1. According to the article excerpt, what types of information were recorded in cuneiform inscription on clay tablets in ancient Mesopotamia?
2. According to the article excerpt, what were the manufacturing methods by which the written clays were dried and preserved in ancient Mesopotamia?
3. The culture of Mesopotamia were critically dependent on the Tigris and the Euphrates rivers. What were the relation between these two rivers? That is, were they two branches of a same river with the same headwater? Were the two rivers with two separate headwaters but share the same floodplain? Were they two separate rivers with two separate headwaters and two separate floodplains?
4. In the text "They Wrote in Clay", the author Edward Chiera describes the evolution of writing language from pictograph to ideograph and states that "the practice of efficiency" in inscribing the clay with the stylus play the dominant role in the evolution of the written language. Over time, how did the written language change in terms of shape and resemblance to objects?
5. The article states that "[a]ll the clay cones contain various amounts of diopside. This suggests a differentiation of manufacture according to the purpose of the clay cones, which confirms the description in Chiera (1938)." From the text of Chiera (Chapter 2), identify the statements that verify this accordance of differentiation of manufacture.
6. According to the article excerpt, "the identification of high contents of diopside is suggested to indicate thermal treatment rather than the use of a materials from a source other than Tigris and Euphrates sediments." Explain why high contents of diopside suggest thermal treatment of the clay artefact.

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CHAPTER OVERVIEW

8: Pyramid Building Along Nile Branch in Kingdoms-Era Egypt, 4,500 BP

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8.1: Reading/Media



The pyramids of Giza. It was widely believed that a river must have been involved for transporting the massive building materials. But it wasn't until 2024 that a sand-buried river branch connecting most of the pyramids was discovered---the ancient Ahramat branch of the Nile river. (Photo by [kennyOMG](#), Wikimedia)

Pyramid Building Along Nile Branch in Kingdoms-Era Egypt, 4,500 BP

Excerpts from "[The Egyptian pyramid chain was built along the now abandoned Ahramat Nile branch](#)" by Eman Ghoneim, Timothy J. Ralph, Suzanne Onstine, et al. *Communications Earth & Environment* 5, 233 (2024). CC BY-NC-ND

Excerpts from "[Nile waterscapes facilitated the construction of the Giza pyramids during the 3rd millennium BCE](#)" by H. Sheisha, D. Kaniewski, N. Marriner, et al. *Proc. Natl. Acad. Sci. U.S.A.* 119 (37) e2202530119 (2022). CC BY-NC-ND

Ancient climate and environmental conditions in the Nile valley

Excerpt (Ghoneim et al.): The landscape of the northern Nile Valley in Egypt, between Lisht in the south and the Giza Plateau in the north, was subject to a number of environmental and hydrological changes during the past few millennia. In the Early Holocene (~12,000 years before present), the Sahara of North Africa transformed from a hyper-arid desert to a savannah-like environment, with large river systems and lake basins due to an increase in global sea level at the end of the Last Glacial Maximum (LGM). The wet conditions of the Sahara provided a suitable habitat for people and wildlife, unlike in the Nile Valley, which was virtually inhospitable to humans because of the constantly higher river levels and swampy environment. At this time, Nile River discharge was high, which is evident from the extensive deposition of organic-rich fluvial sediment in the Eastern Mediterranean basin. Based on the interpretation of archeological material and pollen records, this period, known as the African Humid Period (AHP) (ca. 14,500–5,000 years ago), was the most significant and persistent wet period from the early to mid- Holocene in the eastern Sahara region, with an annual rainfall rate of 300–920 mm yr⁻¹. During this time the Nile would have had several secondary channels branching across the floodplain, similar to those described by early historians.

Excerpt (Ghoneim et al.): During the mid-Holocene (~10,000–6,000 years ago), freshwater marshes were common within the Nile floodplain, causing habitation to be more nucleated along the desert margins of the Nile Valley. The desert margins provided a haven from the high Nile water. With the ending of the AHP and the beginning of the Late Holocene (~5,500 years ago to present), rainfall greatly declined, and the region's humid phase gradually came to an end with punctuated short wet episodes. Due to increased aridity in the Sahara, more people moved out of the desert towards the Nile Valley and settled along the edge of the Nile floodplain. With the reduced precipitation, sedimentation increased in and around the Nile River channels causing the proximal floodplain to rise in height and adjacent marshland to decrease in the area estimated the Nile flood levels to have ranged from 1 to 4m above the baseline (~5,000 BP). Inhabitants moved downhill to the Nile Valley and settled in the elevated areas on the floodplain, including the raised natural levees of the river and jeziras (islands). This was the beginning of the Old Kingdom Period

(ca. 2,686 BCE) and the time when early pyramid complexes, including the Step Pyramid of Djoser, were constructed at the margins of the floodplain. During this time the Nile discharge was still considerably higher than its present level. The high flow of the river, particularly during the short-wet intervals, enabled the Nile to maintain multiple branches, which meandered through its floodplain. Although the landscape of the Nile floodplain has greatly transformed due to river regulation associated with the construction of the Aswan High Dam in the 1960s, this region still retains some clear hydro-geomorphological traces of the abandoned river channels.

Since the beginning of the Pharaonic era, the Nile River has played a fundamental role in the rapid growth and expansion of the Egyptian civilization. Serving as their lifeline in a largely arid landscape, the Nile provided sustenance and functioned as the main water corridor that allowed for the transportation of goods and building materials. For this reason, most of the key cities and monuments were in close proximity to the banks of the Nile and its peripheral branches. Over time, however, the main course of the Nile River laterally migrated, and its peripheral branches silted up, leaving behind many ancient Egyptian sites distant from the present-day river course. Yet, it is still unclear as to where exactly the ancient Nile courses were situated, and whether different reaches of the Nile had single or multiple branches that were simultaneously active in the past. Given the lack of consensus amongst scholars regarding this subject, it is imperative to develop a comprehensive understanding of the Nile during the time of the ancient Egyptian civilization. Such a poor understanding of Nile River morphodynamics, particularly in the region that hosts the largest pyramid fields of Egypt, from Lisht to Giza, limits our understanding of how changes in the landscape influenced human activities and settlement patterns in this region, and significantly restricts our ability to understand the daily lives and stories of the ancient Egyptians.

Position of the Khufu branch in relation to the Giza pyramids

Excerpt (Sheisha et al.): The pyramids of Khufu, Khafre, and Menkaure, located on the Giza Plateau, overlook the west bank of the Nile River. Built during the Fourth Dynasty (Old Kingdom 2,686–2,160 BCE), they are one of the world's most iconic cultural landscapes and constitute ancient engineering feats that have fascinated humanity for millennia. To edify the plateau's pyramids, tombs, and temples, it now seems that ancient Egyptian engineers took advantage of the Nile and its annual floods, using an ingenious system of canals and basins that formed a port complex at the foot of the Giza plateau. The harbor complex currently lies >7 km west of the present-day Nile, but it is widely accepted that Fourth Dynasty engineers exploited a now defunct branch of the Nile, which flowed along the western edge of the Nile floodplain during the Egyptian Old Kingdom and that we refer to as the Khufu branch. These canals and basins had to be deep enough to accommodate shallow-draft vessels all year round. Larger cargo ships could probably only navigate during the flood season (August–October), when water levels in the Nile channel rose by ~7 m.

The fluvial-port-complex hypothesis postulates that pyramid builders cut through the western levee of the Khufu branch of the Nile and dredged basins down to river depth in order to harness the annual 7-m rise of the flood like a hydraulic lift, bringing the higher water levels to the base of the Giza plateau. In this way, it was possible to transport supplies and building materials directly to the pyramid complex. These canals and ports would also have been key for the longer-distance transport of materials via the Nile, facilitating transport logistics and for the continuous supply of the plateau's diverse building projects and linking Giza with nearby cities in the Memphite region and on the delta. Nonetheless, the interactions between ancient Egyptian societies and environmental changes along the Khufu branch are complex and poorly understood. We evaluate its water levels during the last 8,000 y, with a particular focus on the Dynastic Period and the Old Kingdom, using sediment cores and long-term ecosystem dynamics. Our data shed light on previous reconstructions because environmental and historical data are more closely coupled; such resolution has never been achieved in this region. Furthermore, our sequence can be extrapolated to upstream and downstream areas of the Egyptian Nile, allowing comparison with other archaeological sites.

To estimate variations in the water level of the Khufu branch, five cores were drilled on the present Giza floodplain, east of the pyramid complex (Fig. 8.1.1). Bioindicators (pollen grains) were extracted from cores G1 and G4 situated in what has been geographically defined as the Khufu branch of the Nile. We identified 61 taxa grouped into seven pollen-derived vegetation patterns (PdVs) based on their ecological affinities. Among the defined PdVs, the Cyperaceae (papyrus, sedge; located on the banks of the Nile), tropical Nilotic taxa (pollen carried downstream by the Nile from tropical areas of the watershed), and helophytes reveal the presence of a permanent waterbody on the Giza floodplain... The highest water levels are attested by high abundances of Cyperaceae and helophytes, with a higher input of tropical pollen from the Nile River, while the low levels are framed by an increase in terrestrial taxa. Nile flow variations, as deduced from the PCA-Axis 1, are correlated with changes in the lithofacies.

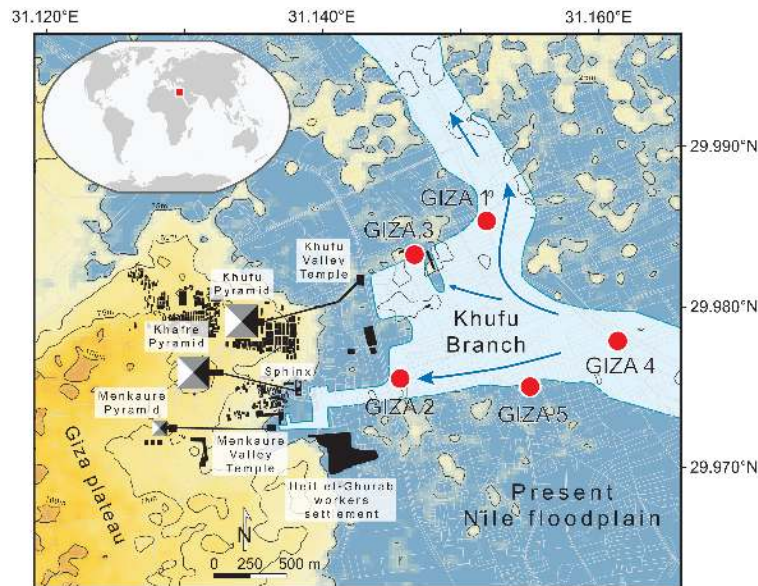


Figure 8.1.1: Location of the cores on the Giza floodplain. The two cores used to reconstruct Holocene variations in Khufu-branch levels (cores G1 and G4) are located where the Khufu basin was connected to the Nile. The Giza Pyramid Complex currently lies >7 km from the present-day Nile branch. Harbor remains were previously found at the site of G3;. (From Sheisha et al. 2022.)

Our score-based reconstruction shows that the water level of the Khufu branch (termed K-1) was higher during the African Humid Period, with a local termination estimated at 3550 ± 80 BCE ($5,500 \pm 80$ BP) and a later peak recorded at $2,950 \pm 80$ BCE after a significant drop at $3,450\text{--}3,250 \pm 80$ BCE. During this period, it has been shown that conglomerations of predynastic and early dynastic settlements ($3,550\text{--}3,250$ BCE) existed along the east bank of the Khufu branch and on the floodplain between the paleo-channel and the pyramid plateau. We suggest that the environmental attractivity of Giza during the fourth millennium resulted from a decrease in fluvial levels following the end of the African Humid Period. The reconstructed higher level of Khufu branch is also supported by Nile Delta sedimentation rates, is attributed to increased rainfall over Lake Tana, the source of the Blue Nile and Lake Victoria, the source of the White Nile. Nile flow is mediated by monsoon activity in tropical Africa. The Holocene intensity of the East African Monsoon, as reconstructed at Lake Abiyata and Lake Rutundu in Ethiopia, is modulated by the north–south movement of the Intertropical Convergence Zone (ITCZ), with higher rainfall levels during the early Holocene consistent with a more northward migration of the monsoon rain belt driven by higher insolation. We found that the Khufu branch has recorded the same trend, with a high-stand level that correlates with greater summer insolation and a northward migration of the ITCZ, which reinforced the intensity of the East African Monsoon over the Nile Valley and created higher flow regimes in the Khufu branch. The peak in the Khufu-branch level at 2950 ± 80 BCE, while not documented in Lake Abiyata (Fig. 8.1.2), is recorded at Lake Rutundu, Lake Tana, and Lake Victoria, and on the Nile Delta (Fig. 8.1.2). Higher Khufu-branch levels at Giza are also in phase with higher levels in North African lakes (high and intermediate lakes; Fig. 8.1.2). The most significant negative fluctuations in Khufu-branch levels during this period ($\sim 8,000\text{--}5,500$ y ago) are correlated with volcanic forcing (leading to diminished Nile summer flooding). Moreover, a drought episode recorded in Lake Tana at 5,550 BCE, due to a southward shift in the monsoon front, is also documented by a drop in the Khufu-branch level at Giza $5,550 \pm 80$ BCE.

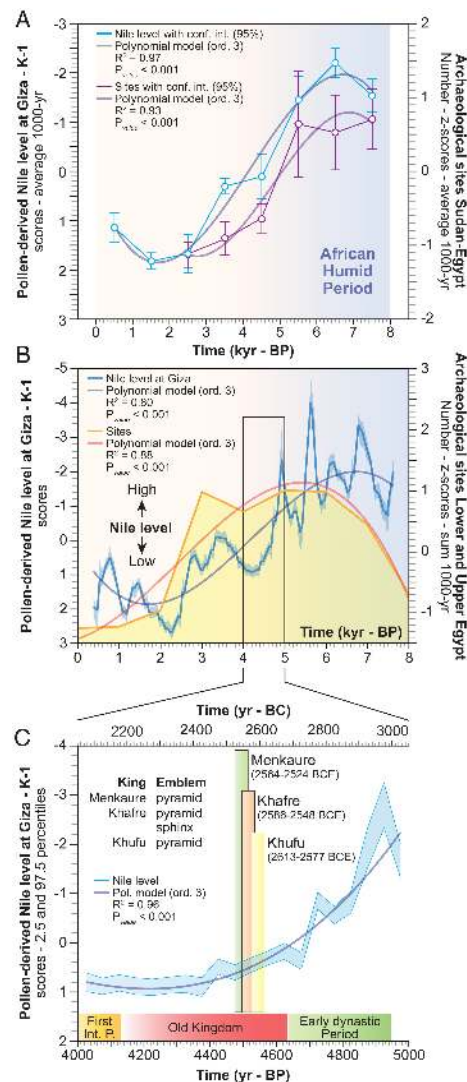


Figure 8.1.2: (A) Level of the Khufu branch (K-1, blue line) compared to the number of archaeological sites in Sudan and Egypt (light purple line). Archaeological site numbers were transformed into z-scores. The two datasets are shown as 1,000-y averages (with a 95% confidence interval). Long-term trends are represented by polynomial models (order 3, $P_{value} < 0.001$). (B) Level of the Khufu branch (blue line; Loess smoothing scores with 2.5 and 97.5 percentiles) compared to archaeological sites in Lower and Upper Egypt (orange line). The number of archaeological sites is shown as a 1,000-y sum, transformed into z-scores. Long-term trends are illustrated by polynomial models (order 3). (C) Khufu-branch levels (2.5 and 97.5 percentiles) during the construction of the pyramids of kings Khufu, Khafre, and Menkaure (blue line). The long-term trend is represented by a polynomial model (order 3). The background colors show the transition from the African Humid Period to the aridification of Egypt (A and B). (From Sheisha et al. 2022.)

Position and morphology of the Ahramat branch

Excerpt (Ghoneim et al.): Synthetic Aperture Radar (SAR) imagery and radar high-resolution elevation data for the Nile floodplain and its desert margins, between south Lisht and the Giza Plateau area, provide evidence for the existence of segments of a major ancient river branch bordering 31 pyramids dating from the Old Kingdom to Second Intermediate Period (2,686–1,649 BCE) and spanning between Dynasties 3–13 (Fig. 8.1.3 a). This extinct branch is referred to hereafter as the Ahramat branch, meaning the “Pyramids branch” in Arabic. Although masked by the cultivated fields of the Nile floodplain, subtle topographic expressions of this former branch, now invisible in optical satellite data, can be traced on the ground surface by TanDEM-X (TDX) radar data and the Topographic Position Index (TPI). Data analysis indicates that this lateral distributary channel lies between 2.5 and 10.25 km west from the modern Nile River. The branch appears to have a surface channel depth between 2 and 8 m, a channel length of about 64 km and a channel width of 200–700 m, which is similar to the width of the contemporary neighboring Nile course. The size and longitudinal continuity of the Ahramat branch and its proximity to all the pyramids in the study area implies a functional waterway of great significance.

A trace of a 3 km river segment of the Ahramat branch, with a width of about 260 m, is observable in the floodplain west of the Abu Sir pyramids field (Fig. 8.1.3 b–d). Another major segment of the Ahramat branch, approximately 20 km long and 0.5 km wide can be traced in the floodplain along the Western Desert Plateau south of the town of Jirza (Fig. 8.1.3 e). The visible segments of the Ahramat branch in TDX are now partially occupied by the modern Bahr el-Libeini canal. Such partial overlap between the courses of this canal, traced in the 1911 historical maps (Egyptian Survey Department scale 1:50,000), and the Ahramat branch is clear in areas where the Nile floodplain is narrower (Fig. 8.1.3 b–d), while in areas where the floodplain gets wider, the two water courses are about 2 km apart. In light of that, Bahr el-Libeini canal is possibly the last remnant of the Ahramat branch before it migrated eastward, silted up, and vanished. In the course of the eastward migration over the Nile floodplain, the meandering Ahramat branch would have left behind traces of abandoned channels (narrow oxbow lakes) which formed as a result of the river erosion through the neck of its meanders. A number of these abandoned channels can be traced in the 1911 historical maps near the foothill of the Western Desert plateau proving the eastward shifting of the branch at this locality (Fig. 8.1.3 b–d). The Dahshur Lake, southwest of the city of Dahshur, is most likely the last existing trace of the course of the Ahramat branch.

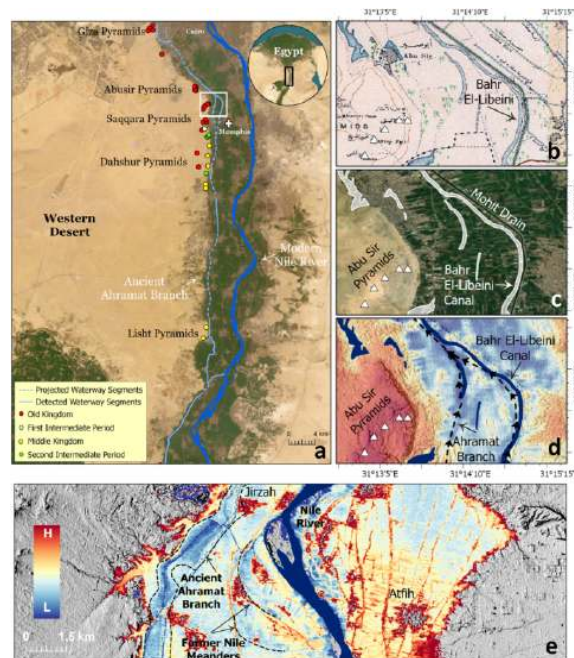


Figure 8.1.3: The water course of the ancient Ahramat branch. **a** Shows the Ahramat branch borders a large number of pyramids dating from the Old Kingdom to the 2nd Intermediate Period and spanning between Dynasties 3 and 13. **b** Shows Bahr el-Libeini canal and remnant of abandoned channel visible in the 1911 historical map (Egyptian Survey Department scale 1:50,000). **c** Bahr el-Libeini canal and the abandoned channel are overlain on satellite basemap. Bahr el-Libeini is possibly the last remnant of the Ahramat branch before it migrated eastward. **d** A visible segment of the Ahramat branch in TDX is now partially occupied by the modern Bahr el-Libeini canal. **e** A major segment of the Ahramat branch, approximately 20 km long and 0.5 km wide, can be traced in the floodplain along the Western Desert Plateau south of the town of Jirza. Location of **e** is marked in white a box in **a**. (From Ghoneim et al. 2024.)

Alignment of old- and middle-kingdom pyramids to the Ahramat branch

Excerpt (Ghoneim et al.): The royal pyramids in ancient Egypt are not isolated monuments, but rather joined with several other structures to form complexes. Besides the pyramid itself, the pyramid complex includes the mortuary temple next to the pyramid, a valley temple farther away from the pyramid on the edge of a waterbody, and a long sloping causeway that connects the two temples. A causeway is a ceremonial raised walkway, which provides access to the pyramid site and was part of the religious aspects of the pyramid itself. In the study area, it was found that many of the causeways of the pyramids run perpendicular to the course of the Ahramat branch and terminate directly on its riverbank.

In Egyptian pyramid complexes, the valley temples at the end of causeways acted as river harbors. These harbors served as an entry point for the river borne visitors and ceremonial roads to the pyramid. Countless valley temples in Egypt have not yet been found and, therefore, might still be buried beneath the agricultural fields and desert sands along the riverbank of the Ahramat branch. Five

of these valley temples, however, partially survived and still exist in the study area. These temples include the valley temples of the Bent Pyramid, the Pyramid of Khafre, and the Pyramid of Menkaure from Dynasty 4; the valley temple of the Pyramid of Sahure from Dynasty 5, and the valley temple of the Pyramid of Pepi II from Dynasty 6. All the aforementioned temples are dated to the Old Kingdom. These five surviving temples were found to be positioned adjacent to the riverbank of the Ahramat branch, which strongly implies that this river branch was contemporaneously functioning during the Old Kingdom, at the time of pyramid construction.

Analysis of the ground elevation of the 31 pyramids and their proximity to the floodplain, within the study area, helped explain the position and relative water level of the Ahramat branch during the time between the Old Kingdom and Second Intermediate Period (ca. 2,649–1,540 BCE). Based on Fig. 8.1.5, the Ahramat branch had a high-water level during the first part of the Old Kingdom, especially during Dynasty 4. This is evident from the high ground elevation and long distance from the floodplain of the pyramids dated to that period. For instance, the remote position of the Bent and Red Pyramids in the desert, very far from the Nile floodplain, is a testament to the branch's high-water level. On the contrary, during the Old Kingdom, our data demonstrated that the Ahramat branch would have reached its lowest level during Dynasty 5. This is evident from the low altitudes and close proximity to the floodplain of most Dynasty 5 pyramids. The orientation of the Sahure Pyramid's causeway (Dynasty 5) and the location of its valley temple in the low-lying floodplain provide compelling evidence for the relatively low water level proposition of the Ahramat branch during this stage. The water level of the Ahramat branch would have been slightly raised by the end of Dynasty 5 (the last 15–30 years), during the reign of King Unas and continued to rise during Dynasty 6. The position of Pepi II and Merenre Pyramids (Dynasty 6) deep in the desert, west of the Djedkare Isesi Pyramid (Dynasty 5), supports this notion.

In addition, our analysis shows that the Qakare Ibi Pyramid of Dynasty 8 was constructed very close to the floodplain on very low elevation, which implies that the Nile water levels were very low at this time of the First Intermediate Period (2,181–2,055 BCE). This finding is in agreement with previous work conducted by Kitchen, which implies that the sudden collapse of the Old Kingdom in Egypt (after 4,160 BCE) was largely caused by catastrophic failure of the annual flood of the Nile River for a period of 30–40 years. Data from soil cores near Memphis indicated that the Old Kingdom settlement is covered by about 3m of sand. Accordingly, the Ahramat branch was initially positioned further west during the Old Kingdom and then shifted east during the Middle Kingdom due to the drought-induced sand encroachments of the First Intermediate Period, “a period of decentralization and weak pharaonic rule” in ancient Egypt, spanning about 125 years (2,181–2,055 BCE) post Old Kingdom era. Soil cores from the drilling program at Memphis show dominant dry conditions during the First Intermediate Period with massive eolian sand sheets extended over a distance of at least 0.5 km from the edge of the western desert escarpment. The Ahramat branch continued to move east during the Second Intermediate Period until it had gradually lost most of its water supply by the New Kingdom.

Key Geologic Concepts:

Sedimentation; floodplain; river migration; Pleistocene-Holocene climate change.

Supplemental Materials:

Archeology News: "[New study reveals Egyptian pyramids were built along a now-abandoned Nile branch](#)", May 17, 2024.

New York Times: "[A Long-Lost Branch of the Nile Helped in Building Egypt's Pyramids](#)", August 30, 2022.

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8.2: Classroom Activity

Sediment Core Analysis of the Ahramat Branch

Excerpt (Ghoneim et al.): The geophysical profile interpretation for the Ahramat Branch at this locality was validated using two sediment cores of depths 20 m (Core A) and 13 m (Core B) (Fig. 8.2.1). In Core A between the center and left bank of the former branch we found brown sandy mud at the floodplain surface and down to ~2.7 m with some limestone and chert fragments, a reddish sandy mud layer with gravel and handmade material inclusions at ~2.8 m, a gray sandy mud layer from ~3–5.8 m, another reddish sandy mud layer with gravel and freshwater mussel shells at ~6 m, black sandy mud from ~6–8 m, and sandy silt grading into clean, well-sorted medium sand dominated the profile from ~8 to >13 m. In Core B on the right bank of the former branch we found recently deposited brown sandy mud at the floodplain surface and down to ~1.5 m, alternating brown and gray layers of silty and sandy mud down to ~4 m (some reddish layers with gravel and handmade material inclusions), a black sandy mud layer from ~4–4.9 m, and another reddish sandy mud layer with gravel and freshwater mussel shells at ~5 m, before clean, well-sorted medium sand dominated the profile from 5 to >20 m.

Sediments from the Ahramat Branch riverbed, which were collected from the two deep soil cores (cores A and B), show an abrupt shift from well-sorted medium sands at depth to overlying finer materials with layers including gravel, shell, and handmade materials. This indicates a step-change from a relatively consistent higher-energy depositional regime to a generally lower-energy depositional regime with periodic flash floods at these sites. So, the Ahramat Branch in this region carried and deposited well-sorted medium sand during its last active phase, and over time became inactive, infilling with sand and mud until an abrupt change led the (by then) shallow depression fill with finer distal floodplain sediment (possibly in a wetland) that was utilized by people and experienced periodic flash flooding. Validation of the paleo-channel position and sediment type using these cores shows that the Ahramat Branch has similar morphological features and an upward-fining depositional sequence as that reported near Giza, where two cores were previously used to reconstruct late Holocene Nile floodplain paleo-environments (Sheisha et al., 2022).

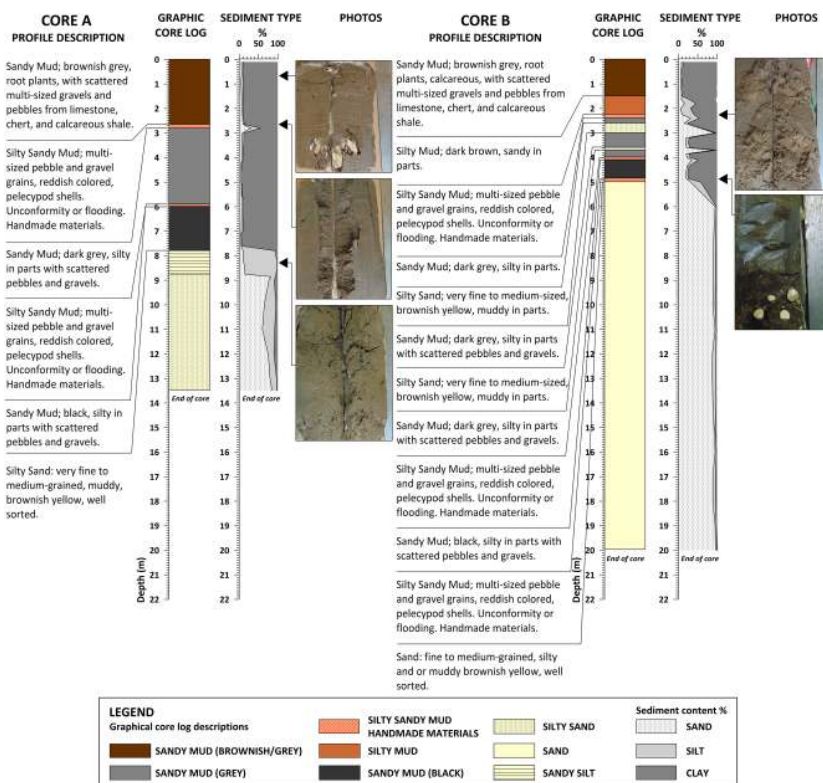


Figure 8.2.1: Deep sediment cores from

the southern segment of the Ahramat branch. (From Ghoneim et al 2024.)

1. What are the lengths of Core A and Core B? What was the depth of the Ahramat branch as the paper by Ghoneim et al. has determined? Do these sediment core data tell us about the depth of the Ahramat branch at the time when the pyramids were built?

2. The excerpt says that the sediment cores show an abrupt shift from "well-sorted medium sands" at depth to overlying "finer materials". Where do this shift occur in Core A and Core B?
3. What do the core sediments containing "limestone, chert, and calcareous shale" tell us about the origins of the sediments? Terrestrial or aquatic?
4. What do the core sediments containing "unconformity and flooding" tell us about the nature of the sedimentation? High energy or low energy?
5. Assuming a deeper core sediment extractions than Core A and Core B were performed. At what depth would you see the bottom of the Ahramat branch based on the finding from other method in this paper? What types of sediment would likely be populated at that depth? Make a sketch of these hypothetical results.

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8.3: Assignment

Assignment:

1. In the first paragraph of the reading, the word "basin" was used twice; once in "lake basins", and once in "Eastern Mediterranean basin". Explain the different meanings of the word in the two different geologic contexts.
2. In the reading, the article states that the Nile discharge was very high during the early Holocene as "is evident from the extensive deposition of organic-rich fluvial sediment in the Eastern Mediterranean basin."
 1. What is fluvial sediment in an ocean basin?
 2. What are the main origin of the organics in the fluvial sediment?
 3. Why is the organic-rich fluvial sediment taken as evidence of high discharge of the Nile River?
 4. Which of the following two scenarios was likely the case for the organic-rich fluvial sediment in question: (a) the thickness of the sediment is greater but the concentration of the organics is about constant; (b) the thickness of the sediment is about constant but the concentration of the organics is greater. Explain why.
3. To argue that the Ahramat Branch was associated with the transport of construction materials and labors for the pyramids, the article cites that
 1. the branch was a "functional waterway of great significance". What are the dimensions (length, depth, width) of the branch as presented in the article?
 2. many causeways leading to the pyramids ran perpendicular to the branch. What was the function of the causeway in an Egyptian pyramid complex? Why is this orientation important for the interpretation of the role of the Ahramat Branch?
 3. the lateral distance between the Nile River and the Ahramat Branch changes with the width of the floodplain. How does this matter in the interpretation of the branch?
 4. the correlation between the distances of the pyramids from the floodplain and the water level of the Ahramat Branch at the time the pyramids were built. What does the article finds in the correlation between the distances and the water levels? Strong or weak? Positive correlation or negative correlation?
4. Ghoneim et al. used three methods to profile the sediments over the now-buried Ahramat branch, as listed below. What information does each of the methods provide about the morphology and sedimentation history of the Ahramat branch?
 1. Sediment core extraction;
 2. Ground penetrating radar;
 3. Electromagnetic tomography.

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CHAPTER OVERVIEW

9: Rice Farming on Yangtze Delta in Predynastic China, 5,100 BP

[9.1: Reading/Media](#)

[9.2: Classroom Activity](#)

[9.3: Assignment](#)

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9.1: Reading/Media



Rice paddy fields in southern China. Wet rice cultivation on the Yangtze delta helped transform human society from hunter-gatherers to farmers at 7,700 BP and then to urban settlers at 5,100 BP. (Photo by [Gao Jialiang](#).)

Rice Farming on Yangtze Delta in Predynastic China, 5,100 BP

Abstract of "Fire and flood management of coastal swamp enabled first rice paddy cultivation in east China" by Y. Zong, Z. Chen, J. Innes, et al. *Nature* 449, 459-462 (2007).

Excerpts from "**Earliest hydraulic enterprise in China, 5,100 years ago**" by B. Liu, N. Wang, M. Chen, et al. *Proc. Natl. Acad. Sci. U.S.A.* 114 (52) 13637-13642 (2017). CC BY

Rice cultivation and the transition from hunter-gatherers to farmers

Abstract (Yong et al): The adoption of cereal cultivation was one of the most important cultural processes in history, marking the transition from hunting and gathering by Mesolithic foragers to the food-producing economy of Neolithic farmers. In the Lower Yangtze region of China, a centre of rice domestication, the timing and system of initial rice cultivation remain unclear. Here we report detailed evidence from Kuahuqiao that reveals the precise cultural and environmental context of rice cultivation at this earliest known Neolithic site in eastern China, 7,700 calibrated years before present (cal. yr BP). Pollen, algal, fungal spore and micro-charcoal data from sediments demonstrate that these Neolithic communities selected lowland swamps for their rice cultivation and settlement, using fire to clear alder-dominated wetland scrub and prepare the site for occupation, then to maintain wet grassland vegetation of paddy type. Regular flooding by slightly brackish water was probably controlled by 'bundling' to maintain crop yields. The site's exploitation ceased when it was overwhelmed by marine inundation 7,550 cal. yr BP. Our results establish that rice cultivation began in coastal wetlands of eastern China, an ecosystem vulnerable to coastal change but of high

fertility and productivity, attractions maximized for about two centuries by sustained high levels of cultural management of the environment.

Hydraulic-driven farming on Yangtze delta

Excerpt (Liu et al.): 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 BP (Figure 9.1.1). The Liangzhu culture represented a peak of early cultural and social development predating 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 can now 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 (Figure 9.1.2). 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.

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 4,300–4,200 BP. 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.

Crucial for understanding the role of water management in Liangzhu at 5,300–4,300 y BP, the site was situated in a naturally watery setting of low-elevation marshlands bordering the Yangtze Delta. A steady rise in postglacial sea level reached its peak around 6,500 cal BP. As it is known today, the Yangtze Delta thereafter formed with a steady supply of marine deposits coupled with river-transported sedimentation. 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. In the sedimentary layers beneath and predating the Liangzhu settlement, deep marine deposits of grayish clay suggest that the area was estuarine marshes before the Liangzhu period. 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, prompting unprecedented social and economic change.

The requisite labor force (for building hydraulic dams) 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. 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. Furthermore, the paddy fields at Maoshan increased in size dramatically from less than 30–40 m² in the early phase (4,900–4,600 cal BP) to 0.1 ha or up to 0.2 ha in the later phase (4,600–4,300 cal BP). The later phase saw the application of manuring, burning, and frequent draining actions, as the region's hydrology was becoming wetter.

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 1,498 and 5,072.4 million cubic meters, respectively, 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.

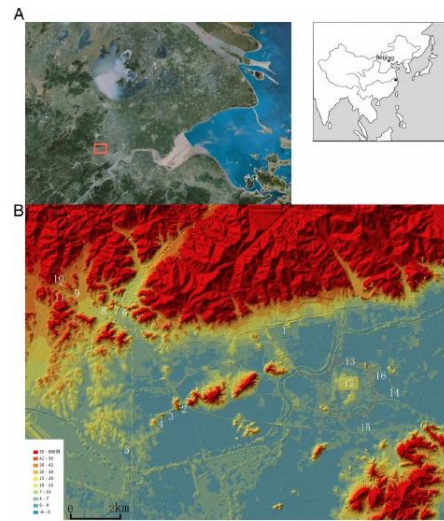


Figure 9.1.1: Location of the Liangzhu culture of predynastic China at the Yangtze River delta near modern-day Shanghai. (From Liu et al. 2017.)

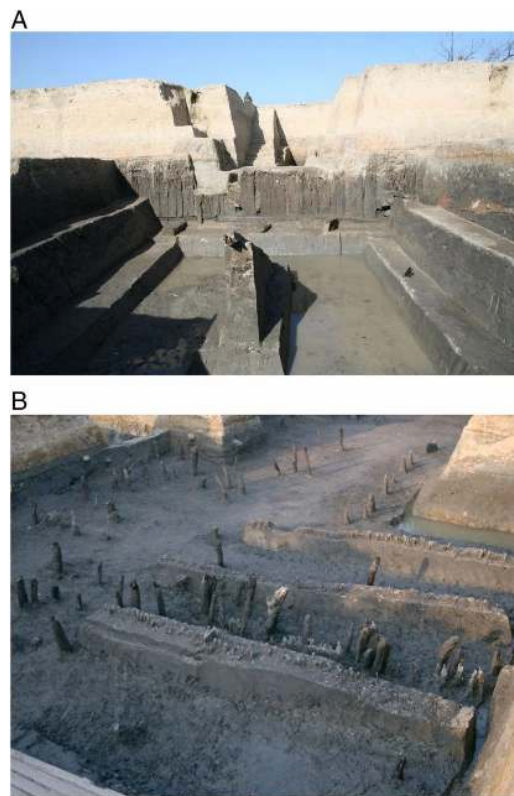


Figure 9.1.2: Excavated hydraulic infrastructure of the Liangzhu culture. (A) structure of bank at Meirendi with standing wooden planks. (B) The pier at Bianjiashen with wooden stakes. (From Liu et al. 2017.)

Key Geologic Concepts:

River delta; wetlands; Pleistocene-Holocene climate change.

Supplemental Materials:

Newsweek: "[Ancient China: Colossal Waterway System Built by 5,000-Year-Old Liangzhu Civilization Discovered by Scientists](#)". December 4, 2017.

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9.2: Classroom Activity

Analysis of Yangtze River Delta at Mid-Holocene

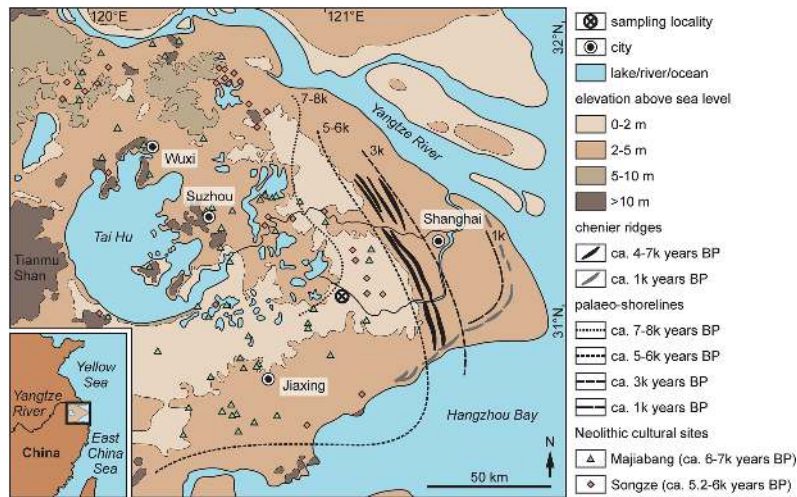


Figure 9.2.1: The palaeo-shorelines, chenier ridges, and Neolithic cultural sites illustrate the delta progradation during the Holocene. (From [Alberti et al. 2024](#), CC)

1. The ancient shorelines for the last 8,000 years are marked on the map (Figure 9.2.1). By how much had the sea level changed during this period of time?
2. Explain why the Yangtze delta's size of land area had increased during the period of time of sea-level rise at the Holocene?
3. What was the typical land elevation above the sea level in areas occupied human populations on the Yangtze delta?
4. The neolithic (New Stone Age) cultures of Majiabang and Songze were predynastic Chinese cultures immediately preceding the Liangzhu culture. What were the approximate sizes of land area on the Yangtze delta and the dates of these two cultures?
5. Locate the sites of the Liangzhu culture on this map.

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9.3: Assignment

Assignment:

1. List in chronological order the major predynastic Chinese cultures mentioned in the two papers cited in the Reading/Media page.
2. What other early cultures with a subsistence agriculture does the paper by Liu et al. mention? What were the climate conditions at these other cultures that contrast with the climate conditions at the Liangzhu culture.
3. Describe the development of the Liangzhu culture in relation to the timing of the Pleistocene-Holocene climate change.
4. In addition to economic development, what other aspects of the complex society evolved with the development of the rice farming in Liangzhu?
5. Describe the erosion and sedimentation of rock materials in the context of an alluvial river.
 1. Describe how the Pleistocene-Holocene climate change affected the erosion and sedimentation of rock materials.
 2. Apply this rationalization to the case of Yangtze River delta.
 3. Use this concept to explain the change in land area in the Yangtze delta as shown in the map.

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