The earliest adobe monumental architecture in the Americas

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Edited by Howard Tsai, University of Michigan Program in International and Comparative Studies, Ann Arbor, MI, and accepted by the Editorial Board September 27, 2021 (received for review February 12, 2021)

Adobe bricks, or mud bricks, are construction elements which have defined major architectural traditions in the Andes over thousands of years. From Moche pyramids and the ancient city of Chan Chan in pre-Hispanic times, to Spanish casonas of the colonial period and rural houses in contemporary South America, adobe has been a central component in Andean architecture. Discovery of the remains of an early monumental building constructed primarily of adobes at Los Morteros (lower Chao Valley, north coast of Peru) places the invention of adobe architecture before 5,100 calendar years B.P. The unique composition, internal structure, and chronology of the adobes from Los Morteros show the beginnings of this architectural technique, which is associated with El Niño rainfall and the construction of the earliest adobe monumental building in the Americas. We propose that adobe architecture became a major Andean tradition after a long period of technical evolution and experimentation with both shape and composition.

geoarchaeology | El Niño | adobe | preceramic | early monumentality

Adobe bricks are central elements of the Andean earthen architectural tradition, as in many other areas around the world (1–3). Adobes or mud bricks are traditionally known as the main components of pre-Hispanic, colonial, and even contemporary earthen buildings. Approximately 30% of the world's population, and 50% of population in developing countries, live in earthen constructions (4). The Spanish word "adobe" comes from the Arabic "*attob*" related to the Egyptian "*thobe*" meaning sun-dried mud brick (5–7). However, the word adobe can have several meanings. Depending on the region, the term adobe can refer to bricks, mortar, rammed earth blocks, or even sediments (5, 6, 8). Here, we use the word adobe to mean an adobe brick or mud brick. Adobe bricks are sun-dried bricks, mainly composed of clay-rich sediments, temper materials, and water, and are used in construction (1, 2, 5, 6, 9, 10). Andean pre-Hispanic adobes vary from conical to rectangular in shape and can be made by hand or with molds. Size and weight vary from one building to another. Although several investigations have dealt with composition and other technical properties of adobes, these studies have focused on late pre-Hispanic and contemporary examples and are mainly concerned with conservation (11–18). None of the available studies look at the origin of adobes or the technological evolution of their structure and composition. For this reason, adobes have been seen as an immutable technology often used in the basic fabrication processes and composition of late pre-Hispanic constructions. In this paper, we show that adobe architecture originated in the Americas in the Preceramic Period, most likely with the use of readily available, naturally formed clay deposits. We propose that adobe architecture became a major Andean tradition after a long period of technical evolution and experimentation with both shape and composition.

Anthropogenic use of unfired clay in Peru has a deep history in multiple modalities. Prior to the Initial Period (ca. 3,600 calendar years [cal y] B.P.) introduction of pottery making from Ecuador, portable, unfired clay figurines were being made during the Late Preceramic Period between ∼4,500 and 3,600 cal y B.P. at places such as Aspero and Caral in the Supe Valley (refs. 19 and 20; reference *SI Appendix*, Fig. S1 for location of sites mentioned in the text). Clay was also used for architectural ornamentation in the Late Preceramic Period at sites such as Aspero (19) and continued in the Initial Period with the large modeled figures at Moxeke, the painted and incised mud friezes at Moxeke, and the complementary site of Pampa de las Llamas, in Casma (21, 22). Incised and often painted mud friezes and other unfired mud ornamentation continued to be common at coastal sites throughout pre-Hispanic times.

Unfired clay as a constructional element is very rare in the Andean archaeological record prior to the Los Morteros adobes reported here and dated between 5,500 and 5,100 cal y B.P. One earlier mention is of "[a]t least two hand-formed dried-mud bricks" at the Las Pircas Phase (∼9,800 to 7,800 cal y B.P.) site CA-09-27 in the Nanchoc area of the upper Zaña

Significance

This study documents the previously unrecognized technological evolution of pre-Hispanic Andean adobe bricks, the central component of this region's millennia-long earthen architectural tradition. Multidisciplinary geoarchaeological research in northern Peru shows that the earliest known standing adobe brick architecture in the Andes dates before 5,100 calendar years B.P., using adobes cut from natural clay deposits created by El Niño flooding. Other than the deliberate shaping of the material, they were unmodified but were used like later adobe bricks. Later pre-Hispanic adobe bricks were made more durable by mixing clay with temper and water. The beginning of adobe architecture in the Andes is associated with the construction of early monumental structures for communal ceremonies and the rise of social complexity.

Author contributions: A.C.M., A.R.K., and D.H.S. designed research; A.C.M., R.G., A.R.H., A.R.K., F.R., D.H.S., and W.V. performed research; A.C.M., R.G., A.R.H., F.R., and W.V. analyzed data; and A.C.M., R.G., A.R.H., A.R.K., F.R., D.H.S., and W.V. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission. H.T. is a guest editor invited by the Editorial Board.

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This article contains supporting information online at http://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2102941118/-/DCSupplemental.

Published November 15, 2021.

Valley (23, p. 101). An accompanying figure (ref. 23, fig. 5.6, p. 103) shows three scattered, approximately square mud blocks measuring ∼25 cm^2, described as part of a hut foundation, with no further description about their composition. Chronologically, the adobes at Los Morteros follow these bricks and were the first to be placed into large walls and joined by mud mortar prior to 5,000 cal yrs. B.P. Handmade adobes were reported as connecting circular plazas with a stone platform in different phases of a preceramic building at Sechín Bajo in the Casma Valley. Although a date of 5,500 y B.P. was proposed for construction, the published radiocarbon chronology of this preceramic building does not provide a secure date for these adobes (24, 25). In Aspero, handmade rectangular adobes varying in size and with a high sand content (26) are reported in a profile of the Huaca Alta. Feldman interpreted these adobes as a minor architectural technique in Aspero, as they were interspersed with rocks in three-course high walls with little mortar (ref. 26, p. 45). Shady and her team reported the use of some adobes, probably reused from a previous construction, as part of the floor of the sunken plaza of Huaca Alta (ref. 27, p. 12). However, there are no published radiocarbon dates for Huaca Alta. Published dates from other mounds at Aspero (with the exception of one anomalously old date out of stratigraphic order) tend to be younger than the dates from the Los Morteros adobe structure, with only the oldest Aspero dates (ref. 26, pp. 246 to 251) overlapping with those from the Morteros adobe room.

Adobes appear more frequently later in the Peruvian Late Preceramic Period. At the monumental site of Ventarrón in the Lambayeque Valley, Alva found extensive use of clay blocks joined with mud mortar beginning in Phase 2 (ref. 28, p. 119). A single published radiocarbon for this phase dates to 4,000 B.P. (29, p. 103), while the preceding phase dates to about 4,300 cal y B.P. (ref. 28, p. 77). It is not clear if these clay blocks were cut from natural sediment or made by manipulation of clay, temper, and water [a photograph shows irregular blocks that might be natural (ref. 28, fig. 135, p. 118)]. At the approximately contemporary site of Alto Salaverry, just south of the Moche Valley, Pozorski and Pozorski (ref. 30, p. 31) found five structures with "large, handmade adobes with fine sand and clay, whose size varies between 53 × 25 × 18 cm. and 37 × 21 × 18 cm. Some have finger impressions." These adobes were intermingled with stones and other materials but never more than a single course high. In one case, a dark, midden mortar was used.

Alva (ref. 28, p. 119) suggests that the clay blocks at Ventarrón are antecedent to cylindrical and conical adobes found at the nearby Initial Period sites of Collud and Zarpán, dating after about 3,600 cal y B.P. Conical adobes are common in Initial Period sites on the north coast of Peru, for instance at Sechín Alto in the Casma Valley, Cerro Blanco and Punkurí in the Nepeña Valley, and Huaca Herederos Chica of the Caballo Muerto Complex in the Moche Valley (22, 31, 32). As with all later adobes, Initial Period conical adobes were manufactured by mixing clay, temper, and water; molds were not used and finger marks are visible (see also ref. 33).

In the subsequent Early Horizon (ca. 2,900 to 2,100 cal y B.P.), Helmer and Chicoine (ref. 34, p. 637) report the use of adobes that are "irregular in form and size from 20 to 50 cm in width, some rectangular and others trapezoidal" at the site of Samanco in the Nepeña Valley. Chicoine (33) also found rectangular adobes at the site of Huambacho in the same valley. By the subsequent Early Intermediate Period, rectangular adobes and mud mortar are the primary building materials for the massive mounds such as the Huaca del Sol and the Huaca de la Luna at the Huacas de Moche site in the Moche Valley (e.g., ref. 35). Through the following periods up to the Spanish Conquest, adobes continued to be the primary construction material on the north and central coast, although sizes and shapes varied through time (e.g., ref. 36 for Chan Chan, a Late Intermediate Period site in the Moche Valley). In contrast to the north coast of Peru, on the south coast, tapia or rammed earth replaced adobes in monumental construction during the late periods (e.g., ref. 37).

The use of yapana or llapana as construction material is also reported in Peruvian archaeology. Although there is no single definition of this local term, in the literature, yapana is usually described as fine-grained, frequently laminated, flood sediments.* An early use of yapana sediments is reported at the Late Preceramic site of Huaricanga in the Fortaleza Valley (4,460 to 4,310 cal y B.P.), where "chunks of naturally occurring clay" were found in a profile as part of an architectural fill (ref. 41, p. 43). However, yapana is more frequently reported in later, Middle Horizon and Late Intermediate Period archaeological sites, used as the foundation for structures or for wall construction (42–46).

This brief review of pre-Hispanic adobe use on the Peruvian coast places Los Morteros as the earliest known site with shaped adobes emplaced in structures with mud mortar as the primary construction material. In contrast to using natural sediments cut into adobes, as at Los Morteros, manufacture of adobes by mixing sediment, temper, and water does not appear until late in the Late Preceramic Period. Widespread use of adobes is not recorded until the Initial Period, almost two millennia after Los Morteros, and adobes do not become the primary building material on the coast until the Early Intermediate Period.

The Adobes of Los Morteros

Recent archaeological excavations at the site of Los Morteros have uncovered preceramic monumental structures dating older than 5,100 cal y B.P. that hold clues to understanding the origins and evolution of adobes in the Andes. Los Morteros is a large, mound-shaped archaeological site (150 × 200 × 15 m) in the lower Chao Valley of the northern Peruvian coast (Fig. 1 *A* and *B*). The site is located in a stark desert, standing on a pronounced wave-cut terrace/paleoshoreline 3 m above a paleoembayment, ∼7 km from Chao River—the nearest source of perennial surface water. In 1976, a team of Peruvian archaeologists discovered the site, dug several shallow test pits, and interpreted it as a stabilized dune whose top was used by preceramic people as a funerary area (47). In 2006 and 2010, an interdisciplinary team of archaeologists and geologists from the University of Maine carried out ground-penetrating radar exploration of the mound, finding evidence of architecture under thick layers of eolian sand (48). In 2012, we performed intensive archaeological excavations at Los Morteros and proved that it is not a natural feature. Rather, it is a built mound formed by complex episodes of occupation that we group into two components (49, 50).

Component I consisted of the deepest and earliest cultural deposits recognized at Los Morteros. Material from this stratum is as yet undated but is stratigraphically underneath the oldest dated phase (Component II, Phase II-1). We have not assigned phases of occupation to Component I, but it has at least 3 m of cultural layers with no major, identified architectural remains (*SI Appendix*, Fig. S4). Component II has three dated phases. The earliest dated occupation, Phase II-1, is a superposition of several archaeological and stratigraphic units having a high density of organic remains, clay surfaces, post holes, and stone hearths, dating to 5,700 to 5,400 cal y B.P.

*Definitions of yapana or llapana include alluvium (huayco) and mudflow. Yapana might refer to alluvial or fluvial sediments, however, there are no published data about its composition. Spanish definitions for yapana or llapana include "flujo de lodo," "agua lodosa," "huayco o lloclla," "sedimento arcilloso aluviónico," and "sedimentos fértiles" (38–40).

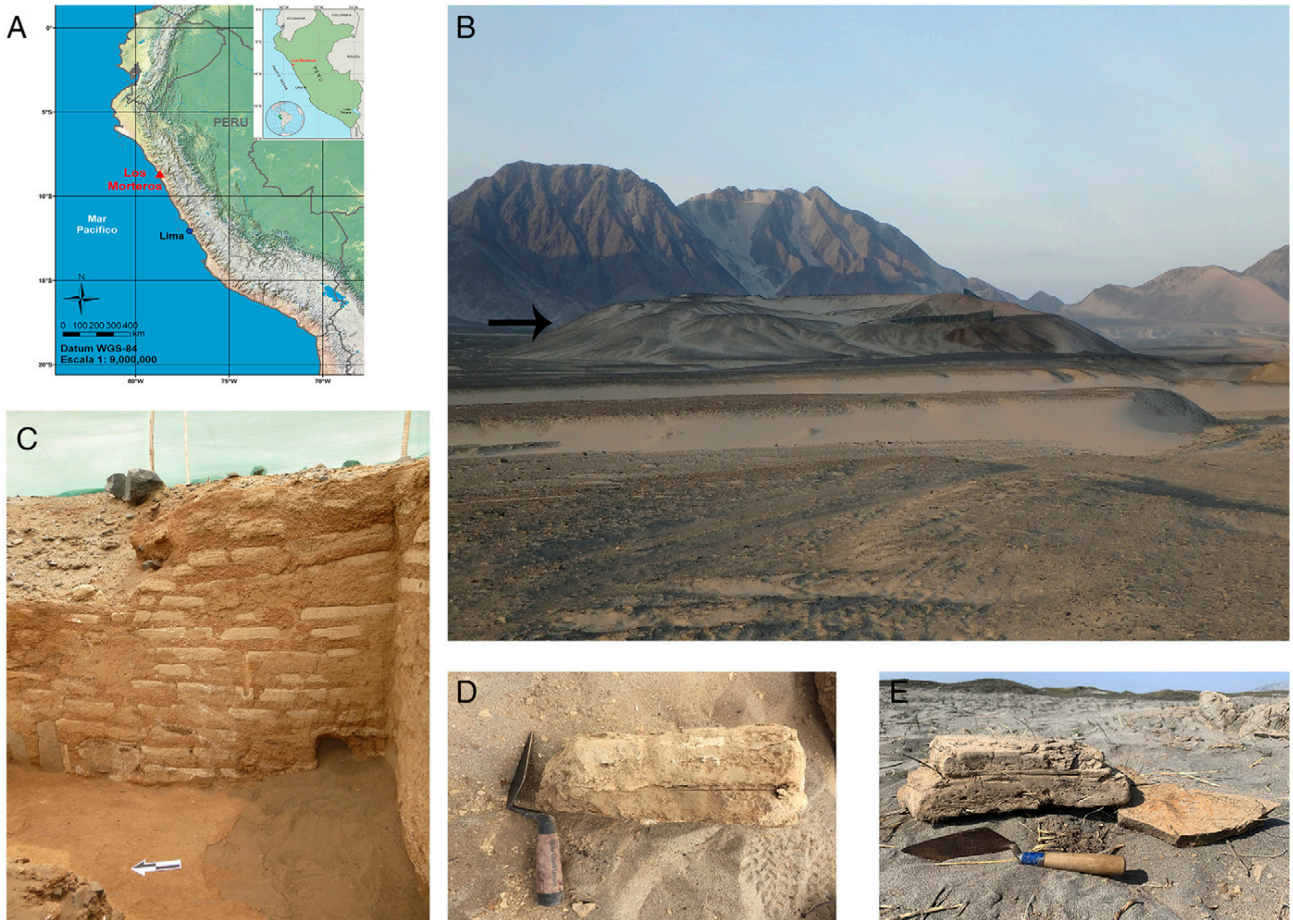

Fig. 1. (*A*) Location of Los Morteros in Peru; (*B*) the mound of Los Morteros (black arrow), view from north; (*C*) internal face of an adobe wall with remains of clay plaster, note rocks at base (arrow points north); (*D*) lateral view of an adobe from Los Morteros; (*E*) a piece of clay from the layer deposited on the alluvial plain on the north bank of the Chao River mouth (Playa de Chao).

(Table 1). The second, overlying Phase II-2 corresponds to architecture composed of at least two rooms with adobe brick walls built on a foundation of rock and mortar. The best-preserved room is rectangular in shape, ~10 m long and 7 m wide. The south corners of this room are up to 2 m of preserved height. The interior of this room has thick clay floors (approximately 5 cm) and walls covered with clay plaster. A 20-cm-high stone-and-clay wall divides the southern section of the room, where the floor is slightly lower, from the rest of the room. A 30-cm-high, square, podium–like block of stone and clay is immediately north of this low wall toward the southeast corner (Fig. 1*C* and *SI Appendix*, Fig. S3*A*). No organic materials have been found to date this architecture directly. However, we dated three child burials that were part of a large votive offering intentionally placed on the floor of the adobe architecture and interpreted as part of a symbolic closing ceremony (*SI Appendix*, Fig. S5). Eight calibrated dates on the burials have a median of ~5,100 cal y B.P. (Table 1). This offering places the use of the room between 5,500 and 5,100 cal y B.P. and underscores the importance of this structure to the people of Los Morteros. This ritual activity, as well as the large size and distinctive construction, identifies this adobe structure as monumental in design and use. Phase II-3 is stratigraphically above Phase II-2 and corresponds to stone architecture built immediately over the adobe–Phase II-2 structures on the north end of the mound and on the top of the mound to the south. This newer architectural phase has rectangular rooms ~8 m long and 6 m wide, with distinctive rounded corners, stone platforms, and large standing stones (locally called huancas) placed in the center of some of the rooms. Phase II-3 has yielded one date of 5,470 to 4,990 cal y B.P. (Table 1).

The Phase II-2 adobe architecture of Los Morteros has unique characteristics with no known corresponding examples reported from Preceramic sites in the Andes. Here, unlike other locations, adobes were the main constriction material. Additionally, the Los Morteros adobe structure predates all other Late Preceramic sites with adobe components (all of which postdate 5,000 cal y B.P.). At Los Morteros, the bricks are the primary building material, while in other locations adobes were used only as a minor component in buildings made mostly with rocks and mud (e.g., adobes were interspersed with rocks in walls and as steps in small staircases, 23 to 27). The better-preserved adobe structure of Los Morteros has foundations of medium-sized (30 × 20 cm) rocks mortared with clay. Topping this stone foundation are walls were made of rows of rectangular mud bricks cemented with reddish clay mortar. All adobes were roughly rectangular in shape and ~30 to 40 cm long × 10 cm wide × 7 cm in height (Fig. 1 *C* and *D* and *SI Appendix*, Fig. S2*D*). Their internal structure and composition make them very unusual when compared to adobes from later periods. Through direct observation, these adobes appeared to be composed of very fine-grained, clay-sized sediments, without obvious addition of larger clasts. The texture of these adobes is very uniform and crumbles to the touch. Clay laminations are

https://doi.org/10.1073/pnas.2102941118

Table 1. Radiocarbon chronology of Los Morteros archaeological site

Radiocarbon dates of Los Morteros								
Component	Phase	Laboratory code	Excavation code	Material	RC yrs. B.P.	2 σ cal yrs. B.P.	Median probability	Architectural characteristics
II	Phase II-3	AA104438	A1-S1-C1-OG17	Burnt seed	4,629 ± 63	5,470–4,990	5,299	Stone and clay architecture
	End of Phase II-2	D-AMS 033197	A2-S3-C5-T201-OG04	Reed mat	4,583 ± 54	5,446–4,977	5,177	Child burials in adobe and clay architecture
		D-AMS 033204	A2-S3-T201-OH01	Tooth (enamel)	4,935 ± 45	5,746–5,482	5,637	
		D-AMS 033205	A2-S3-T202-OH01	Tooth (enamel)	4,445 ± 43	5,280–4,857	5,001	
		D-AMS 033199	A2-S3-C5-T202-TX04	Charred textile	4,592 ± 33	5,439–5,048	5,176	
		D-AMS 033198	A2-S3-C5-T202-TX02	Charred textile	4,539 ± 33	5,309–4,982	5,159	
		D-AMS 033201	A2-S3-C7-T203-OG01	Gourd	4,409 ± 32	5,213–4,846	4,937	
		D-AMS 033200	A2-S3-C7-T203-OG001	Reed mat	4,808 ± 45	5,594–5,327	5,511	
		D-AMS 033206	A2-S3-T203-OH01	Tooth (enamel)	5,037 ± 33	5,895–5,603	5,728	
	Phase II-2	No radiocarbon date directly associated						Adobe and clay architecture
	Phase II-1	Beta-467140	A6-CT1-C10-MU89	Charcoal	4,880 ± 30	5,654–5,476	5,576	Stone hearths with clay surfaces and organic remains
		AA104440	T2-S4-C6-R4-OG13	Charcoal	4,916 ± 48	5,736–5,477	5,621	
I		Undated						Stone hearths with clay surfaces and organic remains

Calibration was performed using OxCal version 4.4.2 (Bronk Ramsey 2020), SHCal20 curve (76).

visible on the adobes' longitudinal sides. These features suggest that the adobes were cut from a natural, water-laid clay deposit, perhaps when the deposit was still damp. In the sixth millennium cal y B.P. when these adobes were made and used, periodic rainfall associated with infrequent El Niño events was the only source of precipitation to mobilize and deposit clay sediments in the stark coastal desert (51). This observation is supported by the discovery in July 2019 of an extensive, thick clay-and-silt deposit formed by fluvial flooding associated with recent El Niño events, possibly in 1998, on the north bank of the Chao River mouth (~500 m from the river and ~400 m from the ocean) (Fig. 1*E* and *SI Appendix*, Figs. S6 and S7). Analysis of two samples of this deposit shows very similar physical and structural characteristics to the adobes from Los Morteros (compare Fig. 1 *D* and *E*).

Available information shows that adobes made in later periods (starting in the Initial Period around 3,600 cal y B.P. and continuing to present) were normally produced using a combination of clay, water, and other elements (e.g., sand, pebbles, shells, grass, etc.) as temper to strengthen the matrix. The age and distinct characteristics of the Morteros adobes (lack of temper, composition of fine-grained sediments, laminations) place them at an early stage in the evolution of this technology, before people developed the formula for making the more durable adobes seen in later sites.

Results

Structure and Grain Size of Adobe Bricks. To investigate the chemical composition and structure of the Los Morteros adobes and to test our initial hypothesis of the linkage between the adobes and a potential nearby source, we analyzed three samples from three different adobes from the room uncovered in the 2012 Los Morteros excavations (Morteros 1, 2, and 3 samples) (Fig. 1 and *SI Appendix*, Figs. S2 and S3) and two samples from the clay deposit discovered on the floodplain near the mouth of the Chao River (Playa de Chao 1 and 2 samples) (Fig. 1*E* and *SI Appendix*, Figs. S6 and S7). Additionally, we used two other samples for comparison: a Moche culture adobe from Plaza 1 of Huaca de la Luna at the site of Huacas de Moche (ca. 500 to 600 AD) (52) (Moche sample) and a Chimú culture adobe from the Uhle Compound at the site of Chan Chan (ca. 900 to 1100 AD) (53) (Chimú sample).

Digital reflected light microscopy (Fig. 2) shows clear differences among samples: the presence of organic elements (bones, shells, grass, charcoal) and larger grains in the Moche and Chimú samples represents tempering elements (organics and sand) indicating that these later adobes were made by mixing clay and temper. The absence of these elements in adobes from Los Morteros suggests a different origin. Clay laminations, indicative of an unmodified, natural water-laid clay deposit, are only visible in Los Morteros samples. Examination of the Morteros sample using short-wave ultraviolet fluorescence shows a mineral, possibly gypsum, infilling cracks. The presence of this evaporate mineral is consistent with fine-grained sediment deposited naturally in an arid setting and the evaporite would have dissolved in any manufacturing process involving water. The identification of lamination and cracks in the Morteros adobes is further confirmed by the scanning electron microscopy analysis (SEM), while the presence of organics and coarser grains was confirmed by X-ray diffraction (XRD).

Fig. 3 shows representative SEM images in back scattering electron mode at the same magnification (200×) for Morteros 1 (A), Morteros 2 (B), Moche (C), and Chimú (D) adobe samples. Morteros samples differ significantly from the later adobes. Morteros adobes exhibit a more uniform and significantly finer structure when compared with Moche and Chimú adobes. The microstructure of the Morteros samples is composed mainly of fine matrix particles, with equiaxial and elongated shapes (see *Inset* in Fig. 3*A*). The Morteros samples exhibit separation along parallel fractures (indicated with discontinuous yellow lines in Fig. 3*B*). These features may be associated with natural stratification. In contrast, the microstructure of the Moche and Chimú adobes is composed of a matrix with a wider range of particle sizes and coarse inclusions, with no parallel fractures. The Chimú sample shows a greater amount of matrix material than the Moche sample, but in both cases, the matrix material is composed of larger grains than those noted in the Morteros samples. The coarser inclusions in the Moche sample have similar shapes to those in the Chimú sample. The morphology and microstructure of the Moche and Chimú samples are similar to those reported in previously published investigations (13–15)

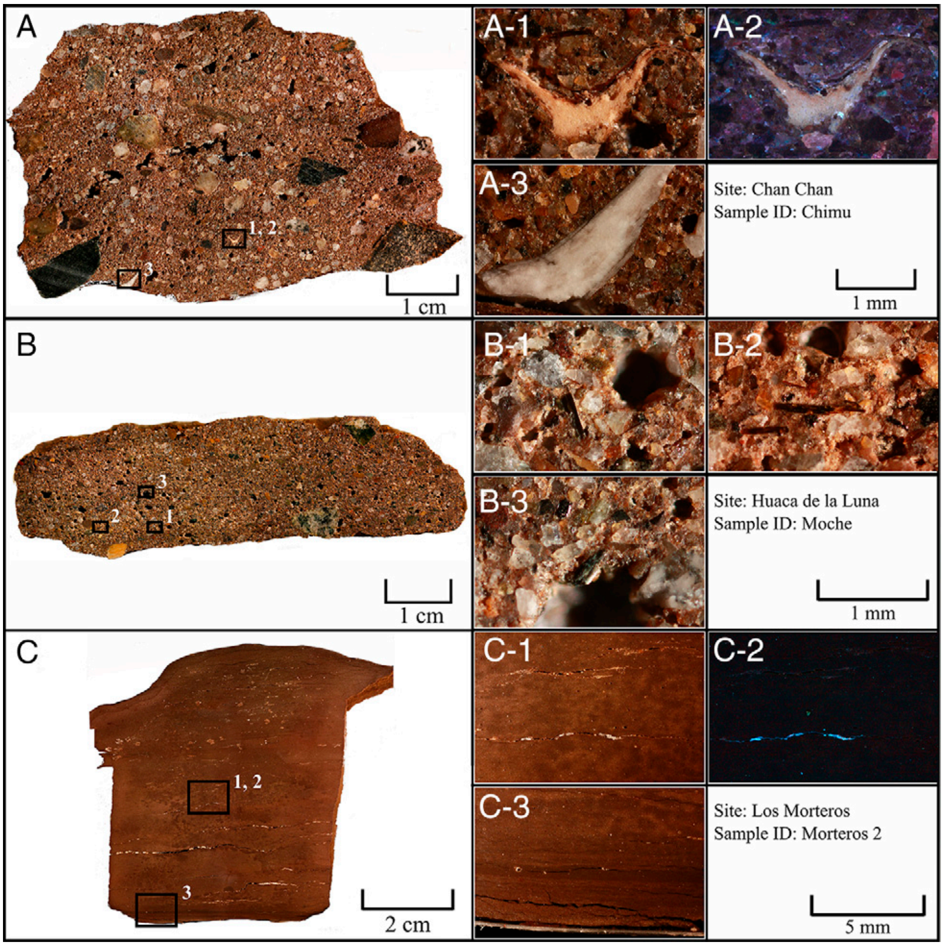

Fig. 2. Digital reflected light microscopy of the Chimú (*A*), Moche (*B*), and Morteros 2 (*C*) samples. Chimú and Moche samples incorporate organic materials including fish bone (*A-1* and *A-2*), marine shell (*A-3*), grass (*B-1* and *B-2*), and charcoal (*B-3*) in a matrix composed of mixed sand and clay/mud. By contrast, the Morteros sample is composed of thin layers of laminated clay with mineral infilling of cracks and voids (*C-1*, *C-2*, and *C-3*) and no incorporated organic material.

of adobes made using a conventional fabrication procedure (mixing clay and temper, forming, and sun drying). In the Los Morteros adobes, the uniform morphology, fine microstructure, lack of coarse reinforcing inclusions, as well as laminations and separation along parallel fractures, are consistent with natural low-energy, water-lain deposits.

To support this statement, a grain size analysis was performed. The grain size analysis (Fig. 4 and *SI Appendix*, Table S1) revealed that in the Playa Chao 2 sample grain sizes >4 mm were absent and grain sizes of 4 to 0.25 mm contributed each at most 0.33% to total sample weight. Grain sizes of 0.125 to 0.038 (fine sands to silts) contributed in total 23.9% to the total weight. In total, 75.57% of the total weight of the Playa Chao 2 sample was made up of clays. The sample is well sorted. This in combination with the sediment grain size distribution shows a sediment typical for a proximal to medial river floodplain environment.

The Morteros 3 sample shows a complete absence of grain sizes >1 mm and a very minor, total contribution of 0.15% of the coarse to fine sands fractions 1 to 0.125 mm to the total sample weight. The 0.125- to 0.38-mm fractions (very fine sands and silts) contribute together only 1.06% of total weight. In total, 98.80% of the sample weight is made up of clays. The sample is very well sorted. The Morteros 3 adobe is similar in composition to the Playa Chao 2 sample but finer-grained and better sorted. The sediments constituting the adobe are interpreted to belong to a distal fluvial floodplain or lake environment.

The Chimú sample shows a wide range of grain sizes ranging from 20 mm (pebbles) to ≤0.038 mm (clays). The grain size classes are more or less evenly distributed, with a higher percentage of fine sands 0.25 to 0.125 mm and clays (≤0.038 mm). This sample is thus very poorly sorted and much coarser than the Playa Chao 2 and Morteros 3 samples. The grain size distribution is not typical for an environment with flowing water (fluvial, lacustrine, or marine) but corresponds more to a human-composed sediment mixture, or perhaps a debris flow, although the latter possibility is thought to be unlikely.

Composition of Adobe Bricks. Energy dispersive spectroscopy (EDS) was employed to analyze the elemental chemical composition of the samples. Fig. 3*E* and Table 2 show representative EDS spectra and the corresponding elemental chemical composition for the Morteros 1, Morteros 2, Moche, and Chimú samples, respectively. The chemical elements in these samples are those commonly presented in the matrix and inclusions of adobe samples (15–17). No remarkable difference is observed at the bulk level for these samples; spectra are very similar with minor variations in intensity for some elements. Elements found are typical of quartz and feldspar minerals (O, Si, Al, K, and Mg), which comprise a large portion of the clay matrix in these adobes. Additionally, other elements are seen in the coarser grains (Si, K, Ca, Na, and Fe) and likely represent common silicate minerals contributed by a range of rock types found in the broader region.

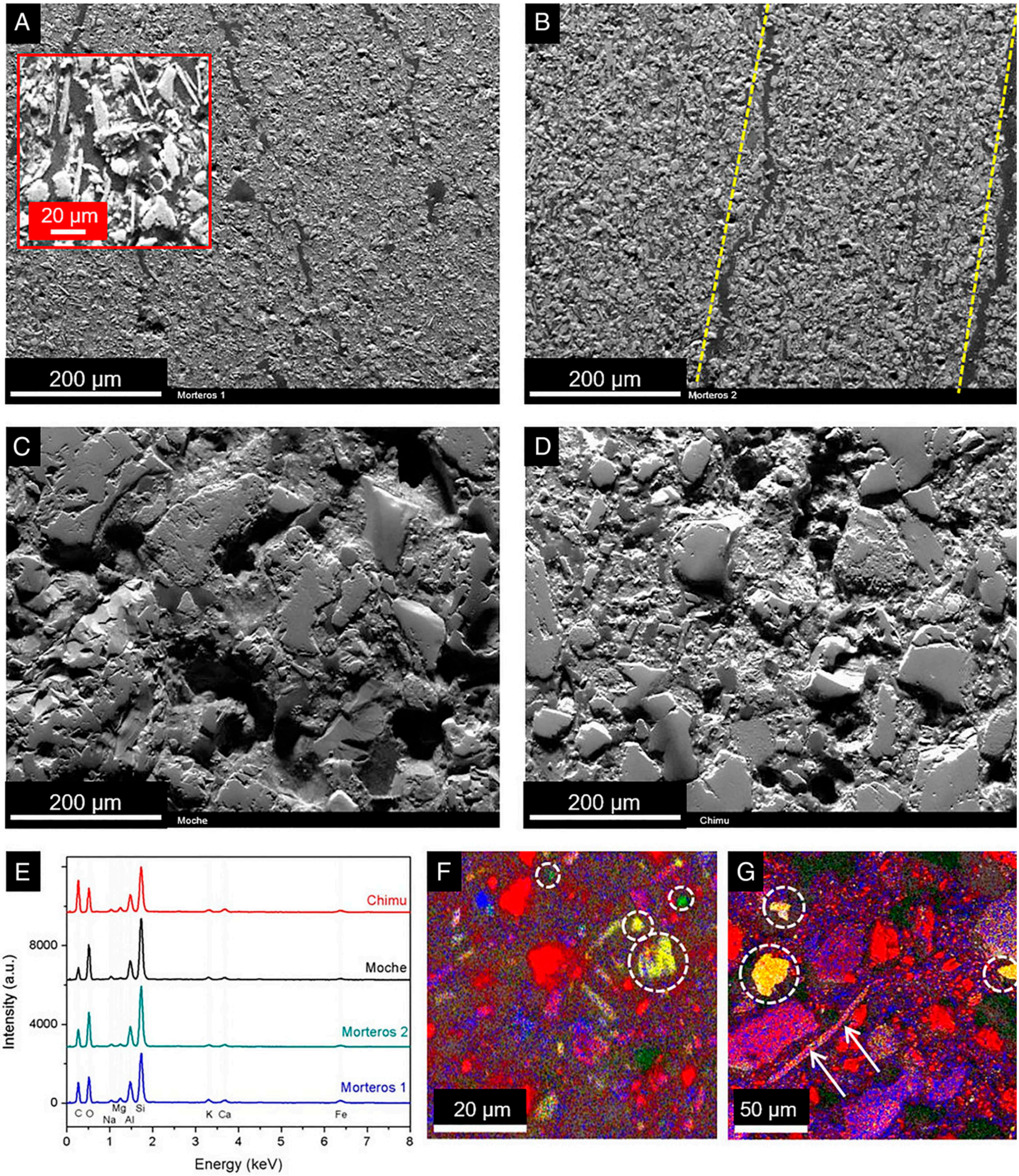

Fig. 3. SEM images (200×) of Morteros 1 (*A*), Morteros 2 (*B*), Moche (*C*), and Chimú (*D*) adobe samples (dashed yellow lines indicate the lamination-like feature). *Inset* in *A* corresponds to a high magnification image of the Morteros 1 sample. Representative EDS spectra for all adobe samples (*E*) indicates a consistent use of similar materials over time. EDS phase mapping images of Morteros 1 (*F*) and Moche (*G*) adobe samples (phase color is associated to its characteristic element: red = Si, blue = Al, light green = Ca, dark green = K, yellow = Fe, purple = Na); white colored discontinuous circles and white arrows indicate Fe-rich and Ca-rich phases and fiber-like constituents, respectively.

Even though the volumetric chemical composition is similar for these four samples, an EDS elemental mapping analysis reveals subtle differences, particularly in those associated with the temper material. Fig. 3 *F* and *G* shows the EDS phase mapping images for the Morteros 1 and Moche adobe samples, respectively. Despite apparent similarity in mapping images,

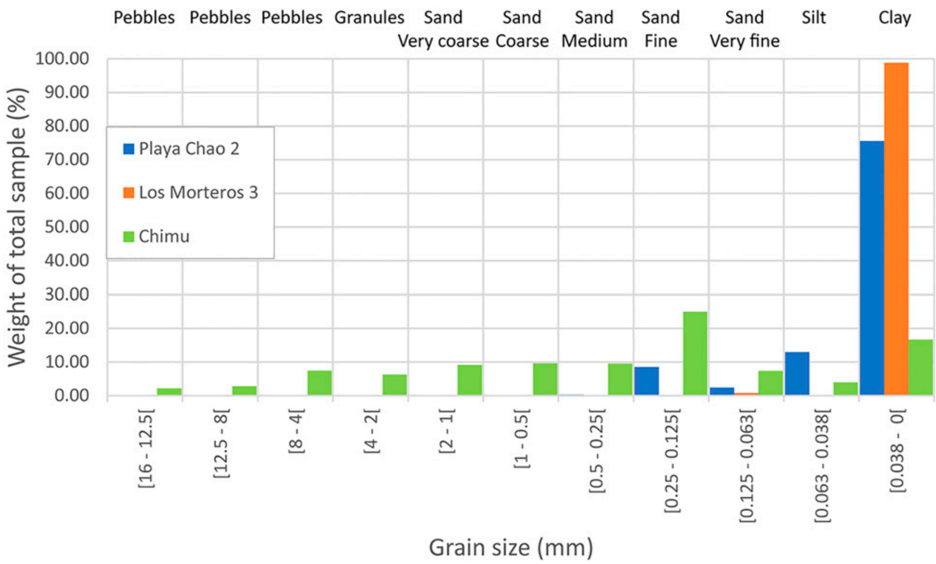

Fig. 4. Grain size distribution histogram of the Playa Chao 2, Morteros 3, and Chimú samples. Note similar distributions of the Playa Chao 2 and Morteros 3 samples and the very different grain size distributions of the Chimú sample. On the *x* axis, opening brackets before the number indicate that number is included in the range and opening brackets after the second number indicate that the second number is not included in the range.

there is a significant difference in the magnification at which each image is presented (Morteros 1: 1,600×; Moche: 500×; magnification was higher in Morteros 1 sample in order to visualize the different mineral grains more clearly). Red, blue, light green, dark green, yellow, and purple correspond to grains where the predominant element is Si, Al, Ca, K, Fe, and Na, respectively. This indicates a rather heterogeneous distribution of the chemical elements. Furthermore, for each grain a specific composition can be assigned giving rise to a better identification of the mineral by XRD later on. The Morteros 1 mapping image shows the distribution of the different minerals that compose the fine-grained adobe material (the clay matrix). Red, blue, light green, dark green, and yellow correspond to grains where the predominant element is Si, Al, Ca, K, and Fe, respectively. The presence of Fe-rich minerals indicated in yellow (see circled areas) is likely associated with magnetite or ilmenite, minerals that occur commonly in the igneous rocks found on the Peruvian north coast. The light green Ca-rich minerals may be detrital pyroxene or amphibole (see circled areas), again commonly associated with igneous rocks of the region. The Moche adobe sample image reveals its wide compositional range and larger grain size. As in the Morteros 1 sample, the red, blue, and yellow color areas in the map correspond to minerals rich in Si, Al, and Fe, respectively, and are seen in both the matrix and the larger temper grains. Fe-rich minerals (magnetite or ilmenite) are also seen in this image.

Table 2. Chemical composition of Morteros 1, Morteros 2, Moche, and Chimú samples

	Weight percent (%)			
Element	Morteros 1	Morteros 2	Moche	Chimú
C	42	49.7	36.1	30.9
O	33.6	29.4	38.6	41.6
Na	0.6	1	1.1	1.2
Mg	0.9	1	0.6	0.4
Al	5.2	4.1	4.9	5.1
Si	12.7	10	14.8	17.5
K	1	1	0.7	0.7
Ca	1	1.3	1	0.9
Fe	3	2.5	2.2	1.7

The Moche sample also exhibits Na-rich minerals (purple color areas) not observed in the Morteros adobe, perhaps an accessory mineral specific to the source area of the Moche adobe. Of particular interest is the fiber-like constituent (indicated with white arrows), which may be part of the adobe temper.

To obtain the crystalline structure of the material, XRD measurements were performed. This allows the identification of the different minerals and thus reveals differences of the samples regarding local material sources as well as the inclusion of noncrystalline (possibly organic) material as well as temper and other nonclay materials. The diffraction patterns of the Morteros 1, Moche, and Chimú bricks are shown in Fig. 5*A*. Two notable areas are highlighted and magnified in the two insets (I and II). Fig. 5*B* compares all the samples from the Morteros site with the two clay samples taken at the Chao River mouth (Playa de Chao). Three samples from the Chao site and two samples from the riverbanks were investigated to reduce the variance of the results. To facilitate interpretation of the XRD patterns, the different minerals are grouped into five different materials: quartz, clay, feldspar, amorphous material, and other minerals not included in the other groups. We found almost no significant differences between the samples of the Chao archaeological site and the riverbank. This strengthens our hypothesis that the Chao River valley was the source of the Morteros adobe material used to produce the mud bricks. Fig. 5*C* summarizes the composition of the investigated samples. The XRD patterns show many similarities. All samples show the presence of quartz and feldspar minerals (Fig. 5 *A*, *Inset* II) that could be summarized as plagioclase and orthoclase. Both minerals are commonly found as clay-sized particles and form the main components of the seven samples (54). The clay laminations in the Los Morteros samples are also seen in the optical analyses (i.e., SEM and camera imaging). Additionally, amorphous material was found in all samples, which might be attributed to the presence of organic material (probable grass inclusions can be seen in the photographs) or amorphous, cryptocrystalline materials in the El Niño flood deposits. The concentration of these amorphous materials is lower in the Moche and Chimú samples. The variation of other components also shows clear differences among the samples. The amounts of other minerals present (e.g., andalusite, pyrope, or albite) vary markedly between Morteros and later-period adobes (Fig. 5*C*). These detrital minerals are found

https://doi.org/10.1073/pnas.2102941118

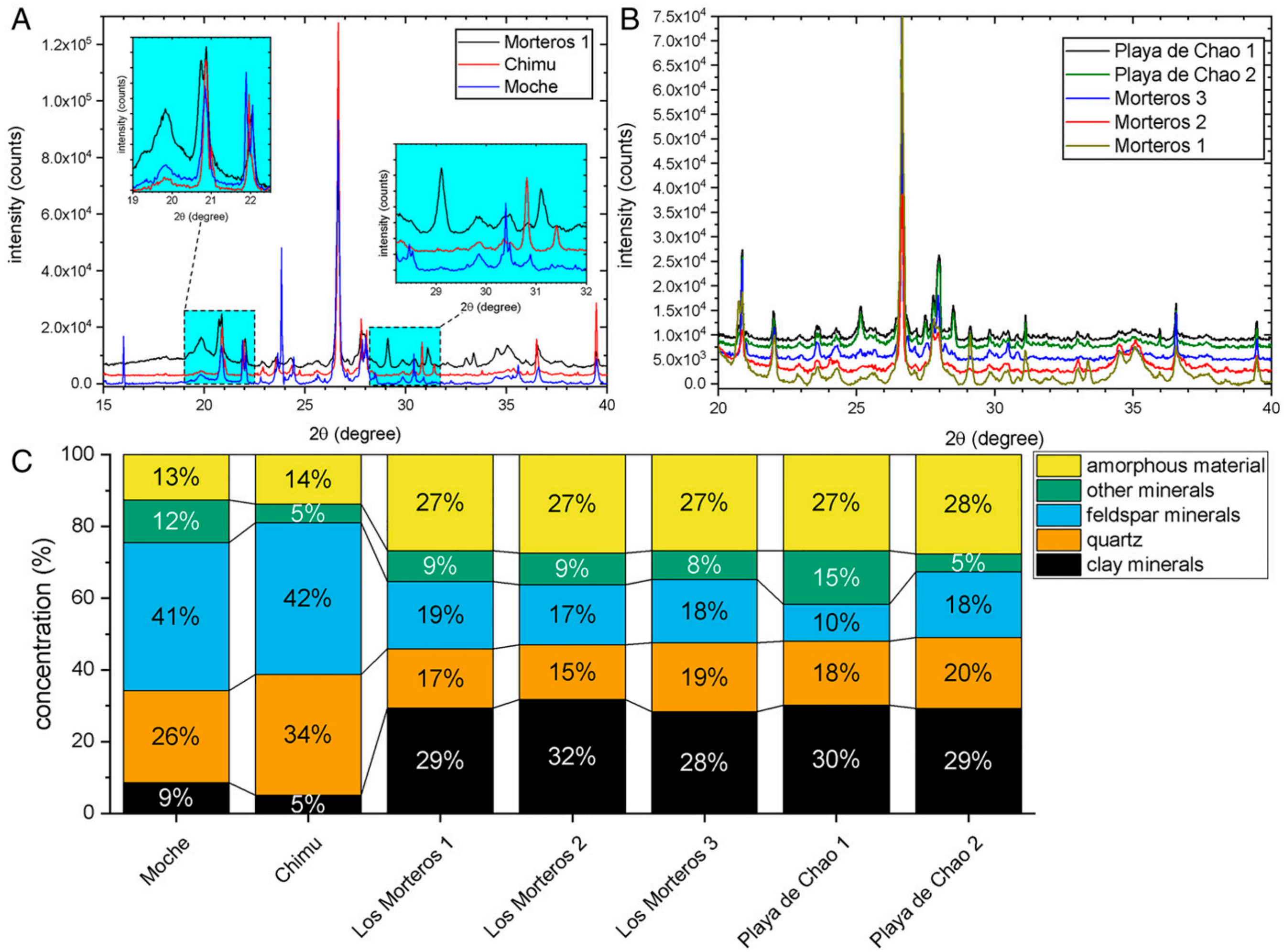

Fig. 5. Diffraction pattern (*A*) comparing Morteros 1 sample to the Moche and Chimú adobe bricks. The *Insets* show features focusing on differences between the samples' diffraction patterns. In *B*, Los Morteros samples are compared with the samples from Chao River. No strong differences can be observed. Additionally, the main mineral composition (*C*) in weight percent of all samples is shown.

in higher concentrations in the Moche and Chimú samples. In the Moche and Chimú samples, albite is present in much higher concentrations. Additionally, sandine is the predominate mineral in the Moche sample. This finding supports the hypothesis that the Moche and Chimú adobe bricks result from a deliberate manufacturing process that included sand and rock fragments as temper and is consistent with well-established adobe-making processes (12, 35, 55). There is a further observable difference in quartz concentrations in the adobes (Fig. 5*C*). Whereas quartz in the Los Morteros samples shows lower concentrations, the concentration of quartz in the Moche and especially in the Chimú adobe is significantly higher. Higher concentrations of quartz may be attributed to the addition of quartz-rich sand during the fabrication process of the Moche and Chimú bricks.

Discussion and Conclusions

Until now, studies of prehistoric adobes in the Andes have focused on characterizing construction patterns and techniques, labor organization, chronology, or structural properties for conservation purposes in later prehistoric contexts (18, 22, 35, 36, 45, 55). However, the origins and technological evolution of Andean adobes have not been addressed. Therefore, our understanding of how adobe technology began and when it became the preferred component for the construction of most pre-Hispanic Andean earthen buildings was incomplete.

The results of the visual, grain size, chemical, and mineralogical analyses of the Los Morteros, Moche, and Chimú adobes, and the Playa de Chao natural samples indicate that the Los Morteros adobes were cut from naturally deposited materials to form rectangular bricks. They were used as they were removed from the ground, without addition of tempering material or other manipulation after cutting. None of the analyses presented here show significant evidence for manipulation of the matrix or addition of material to the Los Morteros adobes. In contrast, our analyses found that the Moche and Chimú samples had larger, poorer-sorted grain sizes and included bone, shell, quartz, feldspar, and minerals—materials not present in natural clay deposits (Figs. 2 and 5*C*). Moreover, digital reflected light microscopy and SEM show laminations indicative of natural water-lain clay deposits in the Morteros adobes (Figs. 2 and 3*B*). This observation is further supported by the significantly finer and better sorted structure of the Los Morteros adobes in comparison with the Moche and Chimú samples. Additionally, the grain size distribution, composition, and texture of the Morteros adobes closely match those of the naturally created, nearby Playa de Chao samples (Fig. 5 *B* and *C*). This suggests that similar materials deposited on the Chao River floodplain are the likely source of the Los Morteros adobes.

The Chao River is a dryland river located on the arid northern coastal desert of Peru. In non–El Niño years, surface flow in the lower portion of the river is intermittent and limited to the months of January to April. During these months, local precipitation in the lower valley is almost absent, but precipitation in the upper portion (above 3,000 mean sea level) of the watershed produces some discharge. In these low flow years, the Chao River has a mean annual flow of 1.43 m^3/s, among the lowest of Peruvian coastal rivers (56, 57), with peak discharge in the larger tributary only reaching 2 m^3/s (*SI Appendix*, Fig. S8). The overbank/deltaic deposit at the Chao River mouth is composed primarily of silt and clay. While annual flooding certainly contributes a small amount of fine-grained deposits to the river mouth, the observed thickness of sediment at this location likely required one or more flood episodes (56, 58, 59). In the lowest flow streams on the coastal desert of northern Peru, such as the Chao, such flooding only occurs as a consequence of heavy rainfall during El Niño events; at 14 m^3/s, peak discharge in the larger tributary of the Chao River during the most recent (2017) El Niño was an order of magnitude larger than during non-Niño years. In these dry environments, overbank flow and floodplain sedimentation have been associated with climate change episodes and can be used to reconstruct climate fluctuations (e.g., changes in precipitation patterns caused by El Niño) (56, 60). The almost-exclusive clay content of the Morteros 2 adobe sample, which is higher than that of the Playa Chao 2 sample, certainly suggests the presence of prolonged water ponding on the floodplain or in a nearby lake, which would be a requirement to deposit that much clay. Such a situation occurs during or shortly after periods of prolonged precipitation such as those induced by El Niño.

Despite our small sample size, many of the differences between the Los Morteros adobes and the later Moche and Chimú examples from this and other studies are differences of kind, not merely number, and are fundamental and important. The later adobes mixed clay- and silt-rich sediments with water and incorporated temper in a process to homogenize the mixture, thus removing any possibility of laminations. In comparison, the Los Morteros adobes lack temper and show laminations from a natural, water-lain origin.

This study shows Los Morteros adobes to be the oldest used for monumental construction. At Los Morteros, the combination of the large, adobe-built rooms and votive closure offerings represents the earliest known monumental adobe architecture in the Americas. These first adobes were cut from natural deposits to create intentionally shaped building materials, rather than used as randomly shaped and sized chunks. The preceramic examples of nearly rectangular adobes reported at Nanchoc, Sechín Bajo, and Aspero may have similar origins as those from Los Morteros. However, they are rare, often isolated, and are of unknown composition. Moreover, wall plaster, clay floors, wall mortars, and figurines indicate that preceramic people were experimenting with these malleable, clay-rich sediments before adobe architecture became widely used in later periods. The adobe architecture of Los Morteros should be seen within a process of experimentation and technological evolution of this material. Only in subsequent periods did people develop the formulae for making and properly drying the more durable (5, 8, 9, 61–63), mass-produced adobes that defined major architectural traditions in prehistoric coastal Peru. At Los Morteros, the adobe architecture of Phase II-2 may well represent a continuation of a process of experimentation with plastic sediments recorded in the clay surfaces associated with stone hearths found in the preceding Phase II-1.

The short life of this architecture can be understood as an opportunistic use of a locally available and already familiar element (clay). Later, monumental architecture in Los Morteros and other neighboring sites had stones walls, mortars, and clay floors, a change that might be related to technical limitation of the more friable and less structurally stable early adobes and to the fact that later buildings were larger and required greater quantities of clay, which was not always available nearby in naturally usable form. The different shapes and dimensions of early adobes seem to be part of this evolutionary process, in which rectangular, manufactured adobes suitable for massive structures represent the final stage.

Records of El Niño on the Peruvian coast stretch back approximately to the Terminal Pleistocene, but this phenomenon is better documented since the Middle Holocene (~8,000 to 4,000 cal y B.P.). Many records of El Niño on the northern Peruvian coast show a hiatus between 9,000 to 5,800 cal y B.P. that corresponds to few or no events. After 5,800 cal y B.P., El Niño became stronger but with a low frequency until 2,900 cal y B.P., when El Niño acquired its current pattern (51, 64, 65). Although this chronology has been challenged, the preponderance of evidence supports the sequence we use for the north coast, which is not inconsistent with the best south coast record of Holocene El Niño (65) (see the review in ref. 51). The transition at 5,800 cal y B.P. is specifically supported at the Salinas de Chao by the molluscan record published by Perrier et al. (66) and reanalyzed by Andrus et al. (ref. 67, especially fig. 3).

The early use of adobes in Los Morteros and later in other Late Preceramic sites is associated with the construction of the first large-scale monumental buildings of the Andes and the timing of regional climatic changes associated with the resumption of El Niño on the north coast just after 6,000 cal y B.P., following a widely reported multimillennial hiatus (51, 65). At Los Morteros, the temporal conjunction of adobe-like, fine-grained sediments deposited by El Niño floods, regional growth in population, and the associated social complexity created conditions for the invention of adobes as a primary building material. The resumption of El Niño around 5,800 cal y B.P. impacted landscapes and may have reconfigured productive environments such as estuaries, coastal lagoons, and fertile alluvial plains along the northern Peruvian coast, creating favored locations for local populations. In the context of the Peruvian coastal desert, manifestations of El Niño would have been associated both with disaster and subsequent fertility, renovation, and abundance, meanings that may have been incorporated into the first communal, ceremonial buildings of the Peruvian coast in the form of earthen bricks.

We propose that this relationship between a natural phenomenon and this social transformation can open a line of investigation for a more comprehensive understanding of the origins of monumental architecture on the Central Andean coast. These first Andean monumental buildings arose as social landmarks in which communities reinforced their social ties and created a social memory through diverse activities, including religious ceremonies such as those involving child burials in the adobe room at Los Morteros. These uses transformed these buildings into sacred places that contributed to cultural landscapes of the region's first complex societies (68, 69). The construction of the adobe architecture of Los Morteros represents a collective endeavor that required some level of coordination, a display of resources to transport the adobes, knowledge to design and build the structures, and communal purposes that guided this effort. This considerable investment of work and resources highlights the complexity of this 5,000-y-old population (70–72). This study's integrated approach suggests a strong connection between climatic events and societal developments and helps us to understand how and perhaps why adobe became a longue durée architectural tradition of the Andes. We now know that the first adobes were technologically very different from later, "classic" adobes, which required a more labor-intensive process and more complicated logistics to bring together water, clay, and temper but which allowed the intensification of adobe-based monumental construction such as the massive mounds of the Moche. Further research is needed to trace this transition from found adobes to those manufactured using human-created mixtures.

https://doi.org/10.1073/pnas.2102941118

Materials and Methods

The Samples. Analyses were completed to characterize the composition and internal structure of the Los Morteros adobes and to test the linkage between the adobes and a potential nearby source. Additionally, we analyzed two adobe bricks from two younger, well-known archaeological sites in an effort to compare composition and internal structure of each one with the older Los Morteros adobes.

The Los Morteros samples were taken from three different adobe bricks uncovered in the 2012 Los Morteros excavation (Morteros 1, 2, and 3 samples) (*SI Appendix*, Figs. S2 and S3) and two samples from the Chao River (Playa de Chao 1 and 2 samples) clay deposit (*SI Appendix*, Figs. S6 and S7). The remaining samples were taken from a Moche culture adobe from Plaza 1 of Huaca de la Luna at the Huacas de Moche site (ca. 500 to 600 AD) (Moche sample) and a Chimú culture adobe from the Uhle compound at the site of Chan Chan (ca. 900 to 1100 AD) (Chimú sample) (*SI Appendix*, Fig. S9). Samples were examined using digital reflected light microscopy, SEM, and XRD measurements.

Sample Preparation. The five analyzed adobes were sampled by bisecting each adobe brick perpendicular to its major axis with an abrasive rod tile saw. Four of the seven samples (Morteros 1, Morteros 2, Moche, and Chimú) were cut and impregnated with low-viscosity polyester resin. Slabs of these four samples (Morteros 1, Morteros 2, Moche, and Chimú) were cut again in the same orientation/direction on a liquid-cooled tile saw and manually polished with a Buehler Ecomet III (*SI Appendix*, Fig. S9). Each of the two Los Morteros slabs were cut again, parallel to and ∼2 cm from the sampling cut to limit the possibility of void packing on the imaged surface. Morteros 3 (adobe brick) and Playa de Chao 1 and 2 (clay deposit) were not impregnated with resin.

Digital Reflected Light Microscopy. The adobe samples were imaged using a 12.2-megapixel Canon XSi dSLR camera prior to impregnation. Notable features, including preserved surfaces and organics, were imaged at higher magnifications (15× to 40×). High-resolution micrograms of the polished, resin-impregnated blocks were collected at low magnification. Image mosaics were then constructed in Adobe Photoshop. Selected internal features were imaged at greater magnification to highlight differences in adobe composition among the selected samples (Fig. 2).

SEM and EDS. Morphology and elemental chemical composition of samples Morteros 1, Morteros 2, Moche, and Chimú were evaluated using SEM and EDS (*SI Appendix*, Fig. S9). Images at varying magnifications were acquired with a Quanta 650 FEI scanning electron microscope, operating at 20 kV in low vacuum mode. EDS was performed with an EDAX Octane Pro EDS detector mounted in the microscope. The overall chemical composition for all samples was obtained with a general scan performed at 20 kV during 200 s in an image at 100×. Several areas per sample were analyzed, with a representative image of each sample selected for comparison purposes. EDS elemental mapping was performed on the Morteros 1 and Moche samples in order to identify localized variations in chemical composition in matrix and inclusion phases. Mapping collection time was 2 h. TEAM EDAX software was used for composition quantification, phase identification, and data analysis. Phase mapping images were obtained and were analyzed in conjunction with elemental distribution maps in order to identify minerals.

Grain Size Analysis. The Morteros 3 and Chimú adobe samples were submerged in water for 10 d to promote disaggregation. These two samples, as well as the Playa Chao 2 sample, were then wet sieved by hand in order to remove the fraction ≤63 μm. This fraction was then wet sieved by hand to separate the 63- to 38-μm (silts) and ≤38-μm (clays) fractions. The water containing the suspended clay fraction and associated water was collected and allowed to rest for 7 d to allow the clays to settle. After this time, most of the water was removed, and the remaining water with the settled clays was passed through a pressure filter with Kraft paper at a constant pressure of 30 psi in order to collect the clays. The recovered silts and clays were oven dried at 65 °C for 48 h and weighed. The fraction >63 μm was oven dried for 24 h and dry sieved by hand in grain sizes according to the Udden–Wentworth scale (73). The dry weight of the sediment fractions was then used to construct a grain size distribution histogram.

XRD. The phase composition of the seven different samples was analyzed using a Bruker D8 Discover XRD. The diffractometer was equipped with copper radiation (wavelength: CuK_α= 0.154184 nm) source and used in a standard Bragg-Brentano Theta-Theta setup. A measuring range of Theta = 10 to 80° (shown: 15 to 40° for better visibility) was chosen. The measuring step size was 0.02° and the time per step 1.5 s. The reference intensity ratio method was used to calculate the concentration of the minerals present (74). The peak positions for the phase identification, as well as the reference values for the calculations of the phase concentrations, were taken from the ICDD PDF 2003 database (75).

Data Availability. All study data are included in the article and/or *SI Appendix*.

ACKNOWLEDGMENTS. Investigations at Los Morteros have been possible thanks to the support of The National Geographic Society, the collaboration of the NSF Project Long-Term Human Ecodynamics in Coastal Peru: A Case Study of Polar-Tropical Teleconnections, led by Dr. Jeffrey Quilter, and the French Institute of Andean Studies. We thank archaeologists Nadia Gamarra Carranza and Carol Rojas Vega from the Chan Chan and Huaca de la Luna archaeological projects who provided the comparative samples. Permits for this research were given by the Ministry of Culture of Peru. The SEM and XRD analyses were performed at the laboratories of the Centro de Caracterización de Materiales of the Pontificia Universidad Católica del Perú.

1. C. Steen, An archaeologist's summary of adobe. *Palacio* **77**, 29–38 (1971).
2. D. Oates, Innovations in mud-brick: Decorative and structural techniques in ancient Mesopotamia. *World Archaeol.* **21**, 388–406 (1990).
3. E. B. Banning. Housing Neolithic farmers. *Near Eastern Archaeology* **66**, 4–21 (2003).
4. World Housing Encyclopedia, Adobe introduction. https://www.world-housing.net/major-construction-types/adobe-introduction. Accessed 30 July 2021.
5. P. W. Brown, J. R. Clifton, I. Adobe, The properties of adobe. *Stud. Conserv.* **23**, 139–146 (1978).
6. H. Houben, H. Guillaud, *Earth Construction: A Comprehensive Guide* (Intermediate Technology Publications, 1994).
7. M. Moquin, "Ancient solutions for future sustainability: Building with adobe, rammed earth, and mud" in *Sustainable Construction: Proceedings of the First International Conference of CIB TG 16*, C. Kibert Ed. (Center for Construction and Environment, M.E. Rinker Sr. School of Building Construction, College of Architecture, University of Florida, 1994), pp. 543–552.
8. J. R. Clifton, *Preservation of Historic Adobe Structures—A Status Report* (Institute for Applied Technology National Bureau of Standards, 1977).
9. C. Costa, Â. Cerqueira, F. Rocha, A. Velosa, The sustainability of adobe construction: Past to future. *Int. J. Archit. Herit.* **13**, 639–647 (2019).
10. D. Rosenberg, S. Love, E. Hubbard, F. Klimscha, 7,200 years old constructions and mudbrick technology: The evidence from Tel Tsaf, Jordan Valley, Israel. *PLoS One* **15**, e0227288 (2020).
11. Proyecto Regional de Patrimonio Cultural y Desarrollo PNUD/UNESCO, *El Adobe: Simposio Internacional y Curso Taller sobre Conservación del Adobe, Informe Final y Ponencias Principales* (ICCROM, 1983).
12. M. Goodman-Elgar, The devolution of mudbrick: Ethnoarchaeology of abandoned earthen dwellings in the Bolivian Andes. *J. Archaeol. Sci.* **35**, 3057–3071 (2008).
13. Y. Millogo, M. Hajjaji, R. Ouedraogo, Microstructure and physical properties of lime-clayey adobe bricks. *Constr. Build. Mater.* **22**, 2386–2392 (2008).
14. J. A. Calabria, W. L. Vasconcelos, A. R. Boccaccini, Microstructure and chemical degradation of adobe and clay bricks. *Ceram. Int.* **35**, 665–671 (2009).
15. E. Adorni, E. Coïsson, D. Ferretti, In situ characterization of archaeological adobe bricks. *Constr. Build. Mater.* **40**, 1–9 (2013).
16. A. Ç. İdil, M. Işikli, A. Gürer, D. Gürer, Restoration project for "Van Ayanis" fort temple area and documentation of adobe (Mud-brick) buildings material for conservation purposes. Gazi. *Univ. J Sci* **28**, 433–444 (2015).
17. J. Zhang *et al.*, The properties of potassium silicate/fly ash slurry used in the conservation of adobe structures. *Stud. Conserv.* **62**, 114–121 (2017).
18. R. Aguilar, M. Montesinos, S. Uceda, Mechanical characterization of the structural components of Pre-Columbian earthen monuments: Analysis of bricks and mortar from Huaca de la Luna in Perú. *Case Stud. Constr. Mater.* **6**, 16–28 (2017).
19. R. A. Feldman, "Preceramic corporate architecture: Evidence for the development of non-egalitarian social systems in Peru" in *Early Ceremonial Architecture in the Andes*, C. B. Donnan, Ed. (Dumbarton Oaks, 1985), pp. 71–92.
20. R. Shady Solís, S. López Trujillo, Ritual de enterramiento de un recinto en el Sector Residencial A en Caral-Supe. *Bol. Arqueol. PUCP* **3**, 187–212 (1999).
21. J. C. Tello, *Arqueología del Valle de Casma, Culturas: Chavín, Santa o Huaylas Yunga y Sub-Chimú* (Universidad Nacional Mayor de San Marcos, 1956), **vol. 1**.
22. S. Pozorski, T. Pozorski, Recent excavations at Pampa de las Llamas-Moxeke, a complex Initial Period site in Peru. *J. Field Archaeol.* **13**, 381–401 (1986).
23. J. Rossen, "Las Pircas Phase (9800-7800 BP)" in *From Foraging to Farming in the Andes: New Perspectives on Food Production and Social Organization*, T. D. Dillehay, Ed. (Cambridge University Press, 2011), pp. 95–115.
24. P. R. Fuchs, R. Patzschke, C. Schmitz, G. Yenque, J. Briceño, Investigaciones arqueológicas en el sitio de Sechín Bajo, Casma. *Bol. Arqueol. PUCP* **10**, 111–135 (2006).
25. P. Fuchs, R. Patzschke, G. Yenque, J. Briceño, Del Arcaico Tardío al Formativo Temprano: Las investigaciones en Sechín Bajo, valle de Casma. *Bol. Arqueol. PUCP* **13**, 55–86 (2009).
26. R. A. Feldman, "Aspero, Peru: Architecture, subsistence economy and other artifacts of a preceramic maritime chiefdom," PhD thesis, Harvard University, Cambridge, MA (1980).
27. R. Shady Solís, D. Cáceda Guillén, *Áspero. Ciudad Pesquera de la Civilización Caral, Zona Arqueológica Caral* (Proyecto Especial Arqueológico Caral-Supe/INC, 2008).

28. I. Alva Meneses, *Ventarrón y Collud: Origen y Auge de la Civilización en la Costa Norte del Perú* (Ministerio de Cultura del Perú, 2012).
29. I. Alva Meneses, Los complejos de Cerro Ventarrón y Collud-Zarpán: Del Precerámico al Formativo en el valle de Lambayeque. *Bol. Arqueol. PUCP* **12**, 97–117 (2008).
30. S. G. Pozorski, T. G. Pozorski, Alto Salaverry: Sitio Precerámico de la costa peruana. *Rev. Mus. Nac. del Perú* **43**, 27–60 (1977).
31. W. C. Bennett, *Archaeology of the North Coast of Peru; An Account of Exploration and Excavation in Viru and Lambayeque Valleys* (Anthropological Papers of the AMNH, American Museum of Natural History, 1939), vol. 37, pt. 1.
32. C. Chauchat, J. Guffroy, T. Pozorski, Excavations at Huaca Herederos Chica, Moche Valley, Peru. *J. Field Archaeol.* **31**, 233–250 (2006).
33. D. Chicoine, Early Horizon architecture at Huambacho, Nepeña Valley, Peru. *J. Field Archaeol.* **31**, 1–22 (2006).
34. M. Helmer, D. Chicoine, Seaside life in Early Horizon Peru: Preliminary insights from Samanco, Nepeña Valley. *J. Field Archaeol.* **40**, 626–643 (2015).
35. C. M. Hastings, M. E. Moseley, The adobes of Huaca del Sol and Huaca de la Luna. *Am. Antiq.* **40**, 196–203 (1975).
36. A. L. Kolata, "Chan Chan: The form of the city in time," PhD thesis, Harvard University, Cambridge, MA (1978).
37. D. T. Wallace, Sitios arqueológicos del Perú (Segunda entrega): Valles de Chincha y Pisco. *Arqueológicas* **13**, 1–131 (1971).
38. ONERN, *Inventario, Evaluación y uso Racional de los Recursos Naturales de la Costa. Cuenca del Río Ica* (Oficina Nacional de Evaluación de Recursos Naturales, 1971).
39. M. T. Oré, *Agua, Bien Común y Usos Privados. Riego, Estado y Conflictos en La Achirana del Inca* (Fondo Editorial de la Pontificia Universidad Católica del Perú, 2005).
40. INGEMMET, *Atlas Catastral, Geológico, Minero y Metalúrgico* (Ministerio de Energía y Minas, 2018).
41. W. Creamer, A. Ruiz, M. F. Perales, J. Haas, The Fortaleza Valley, Peru: Archaeological investigation of Late Archaic sites (3000–1800 BC). *Fieldiana Anthropol.* **44**, 1–108 (2013).
42. F. Engel, *Informe de Avance que Describe el Trabajo del CIZA, Centro de Investigaciones de Zonas Áridas* (Universidad Nacional Agraria de La Molina, 1981).
43. R. Segura, Los contextos funerarios de fines del Horizonte Medio en la Necrópolis de Ancón. Perspectivas de análisis e investigación. *Bol. Arqueol. PUCP* **1**, 241–251 (1997).
44. D. Beresford-Jones, S. Arce, O. Q. Whaley, A. Chepstow-Lusty, The role of Prosopis in ecological and landscape change in the Samaca Basin, lower Ica Valley, South Coast Peru from the Early Horizon to the Late Intermediate Period. *Lat. Am. Antiq.* **20**, 303–332 (2009).
45. J. Canziani, "Origins of monumental architecture in ancient Peru" in *Earth Constructions and Tradition*, H. Feiglstorfer, Ed. (IVA-ICRA Institute for Comparative Research in Architecture, 2016), vol. **1**, pp. 91–107.
46. Y. Huamán Santillán, El Periodo Intermedio Tardío en Cajamarquilla a partir de las evidencias del Sector Tello. *Arqueología y Sociedad* **34**, 367–415 (2021).
47. M. Cárdenas, El periodo Precerámico en el valle de Chao. *Bol. Arqueol. PUCP* **3**, 141–169 (1999).
48. D. H. Sandweiss *et al.*, GRP Identification of an early monument at Los Morteros in the Peruvian coastal desert. *Quat. Res.* **73**, 349–448 (2010).
49. A. C. Mauricio, Los Morteros: Exploraciones geoarqueológicas y paleoambientales de un montículo temprano, valle de Chao. *Bol. Inst. Fr. Estud. Andinos* **43**, 141–169 (2014).
50. A. C. Mauricio, "Los Morteros: Early monumentality and environmental change in the lower Chao Valley, Northern Peruvian Coast," PhD thesis, University of Maine, Orono, ME (2015).
51. D. H. Sandweiss *et al.*, Archaeological climate proxies and the complexities of reconstructing Holocene El Niño in coastal Peru. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 8271–8279 (2020).
52. S. Uceda, R. Morales, E. Mujica, *Huaca de la Luna. Templos y dioses Moche* (Fundación Backus, World Monuments Fund, 2016).
53. C. Campana, *Chan Chan del Chimo. Estudio de la Ciudad de Adobes más Grande de América Antigua* (Editorial Orus, 2006).
54. B. Velde, Ed., *Clays and Clay Minerals in Natural and Synthetic Systems. Developments in Sedimentology, Volume 21* (Elsevier Science, 1977).
55. H. Tsai, Adobe bricks and labor organization on the north coast of Peru. *Andean Past* **10**, 133–169 (2012).
56. G. Huckleberry, "Archaeological sediments in dryland alluvial environments" in *Sediments in Archaeological Context*, J. K. Stein, W. R. Farrand, Eds. (The University of Utah Press, 2001), pp. 67–92.
57. Autoridad Nacional del Agua (ANA), Visor de Estaciones. http://snirh.ana.gob.pe/consultasSnirh/ConsHidrom2.aspx. Accessed 20 November 2020.
58. A. G. Brown, *Alluvial Geoarchaeology. Floodplain Archaeology and Environmental Change* (Cambridge University Press, 2001).
59. G. Nichols, *Sedimentology and Stratigraphy* (Wiley-Blackwell, ed. 2, 2009).
60. K. Hudson-Edwards, "Fluvial environments" in *Environmental Sedimentology*, C. Perry, K. Taylor, Eds. (Blackwell Publishing, 2007), pp. 75–108.
61. G. Chiari, "Caracterización del adobe como material de construcción: Técnicas de preservación" in *El Adobe: Simposio Internacional y Curso Taller sobre Conservación del Adobe, Informe Final y Ponencias Principales*, Proyecto Regional de Patrimonio Cultural y Desarrollo, PNUD/UNESCO Ed. (ICCROM, 1983), pp. 33–43.
62. G. Calatan, A. Hegyi, C. Dico, C. Mircea, Determining the optimum addition of vegetable materials in adobe bricks. *Procedia Technol.* **22**, 259–265 (2016).
63. E. Christoforou, A. Kylili, P. A. Fokaides, I. Ioannou, Cradle to site Life Cycle Assessment (LCA) of adobe bricks. *J. Clean. Prod.* **112**, 443–452 (2016).
64. B. Rein *et al.*, El Niño variability off Peru during the last 20,000 years. *Paleoceanography* **20**, PA4003 (2005).
65. M. Carré *et al.*, Holocene history of ENSO variance and asymmetry in the eastern tropical Pacific. *Science* **345**, 1045–1048 (2014).
66. C. Perrier, C. Hillaire-Marcel, L. Ortlieb, Paléogéographie littorale et enregistrement isotopique (13C, 18O) d'événements de type El Niño par les mollusques holocènes et récents du nord-ouest péruvien. *Géogr. Phys. Quat.* **48**, 23 (1994).
67. C. F. T. Andrus *et al.*, Response to comment on "Otolith ∂18O record of mid-Holocene sea surface temperatures in Peru". *Science* **299**, 203a–203b (2003).
68. J. Moore, *Architecture and Power in the Ancient Andes. The Archaeology of Public Buildings* (Cambridge University Press, 1996).
69. C. Scarre, "Monumentality" in *The Oxford Handbook of the Archaeology of Ritual and Religion*, T. Insoll, Ed. (OUP Oxford, 2011), pp. 9–23.
70. B. Trigger, Monumental architecture: A thermodynamic explanation of symbolic behaviour. *World Archaeol.* **22**, 119–132 (1990).
71. R. M. Rosenswig, R. L. Burger, "Considering early new world monumentality" in *Early New World Monumentality*, R. L. Burger, R. M. Rosenswig, Eds. (University Press of Florida, 2012), pp. 3–22.
72. H. Brunke *et al.*, Thinking big. Research in monumental construction in antiquity. *J. Ancient Stud.* **6**, 250–305 (2016).
73. C. K. Wentworth, A scale of grade and class terms for clastic sediments. *J. Geol.* **30**, 377–392 (1922).
74. X. Zhou *et al.*, XRD-based quantitative analysis of clay minerals using reference intensity ratios, mineral intensity factors, Rietveld, and full pattern summation methods: A critical review. *Solid Earth Sci.* **3**, 16–29 (2018).
75. S. Gates-Rector, T. Blanton, The powder diffraction file: A quality materials characterization database. *Powder Diffr.* **34**, 352–360 (2019).
76. A. G. Hogg *et al.*, SHCal20 Southern Hemisphere Calibration, 0–55,000 Years cal BP. *Radiocarbon* **62**, 759–778 (2020).