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Transformation of maritime desert to an agricultural center: Holocene environmental change and landscape engineering in Chicama River valley, northern Peru coast

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ABSTRACT

Some of the earliest Andean populations settled in the region's arid coastal river valleys, supported by abundant marine life despite having domesticated plant cultigens as early as ~10 ka. In the Chicama River valley, this maritime economy dominated at the Preceramic site, Huaca Prieta, until ~6 ka, after which agricultural production began to increase significantly. This agricultural expansion was motivated in part by the development of arable fine-grained soils along the coast as the result of slowing sea-level rise, enhanced river floods, and unique basin lithology. Local populations made use of the stabilized floodplain and wetland settings to conduct raised-terrace farming. By ~3.5 ka, growth in agriculture and the new fine-grained sediment resources led to several major cultural developments, including the production of fired-ceramic pottery and adobe-brick monument construction associated with the Cupisnique culture. Populations thereafter expanded into the middle valley, where the Salinar and Gallinazo cultures used small water-control structures to farm local ravines. These cultural and technological developments all parallel natural environmental changes driven by increasing ENSO-related water and sediment discharge. By ~1.8 ka, though, further expansion of agriculture —and arable land— was driven primarily by direct human manipulation of the environment. The construction of an ever-expanding network of irrigation canals diverted increasing volumes of water and sediment to distal reaches of the Chicama valley, supporting the great Moche and Chimu civilizations, and persisting through the Inka and Colonial periods. This history of Chicama valley traces strongly coupled interactions between the human and natural environments, supporting significant socio-cultural, economic, demographic, and technological advances.

1. Introduction

Beginning 9–11 ka the world's earliest complex civilizations emerged independently in six regions, including the lower valleys of the Tigris-Euphrates (Mesopotamia), Nile (Egypt), Yellow (China), and Indus (South Asia) river systems, and in the distinctive settings of Mesoamerica and the Central Andes. The Eurasian civilizations were all located within vast, fertile floodplains and were founded solely upon agriculture and/or animal husbandry practices. The Andean civilization stands apart from others being a maritime- and agriculture/husbandry-based culture, taking advantage of fish, birds, plants, and invertebrates in the region's rich coastal lagoon ecosystems (Moseley, 1975). Like other civilizations emerging at this time, early Andeans along the Pacific coast had already learned to cultivate plants for domestic production (e.g., bean, chili pepper, peanut, maize, squash), yet they continued to principally rely on marine resources for thousands of years. In the Chicama Valley and at the Preceramic sites of Huaca Prieta and Paradones, our study area in northern Peru (hereafter referred to as the *wider Huaca Prieta area*; Fig. 1) where we have carried out interdisciplinary archaeological excavations for the past thirteen years (Dillehay, 2017), this pattern changes entirely beginning

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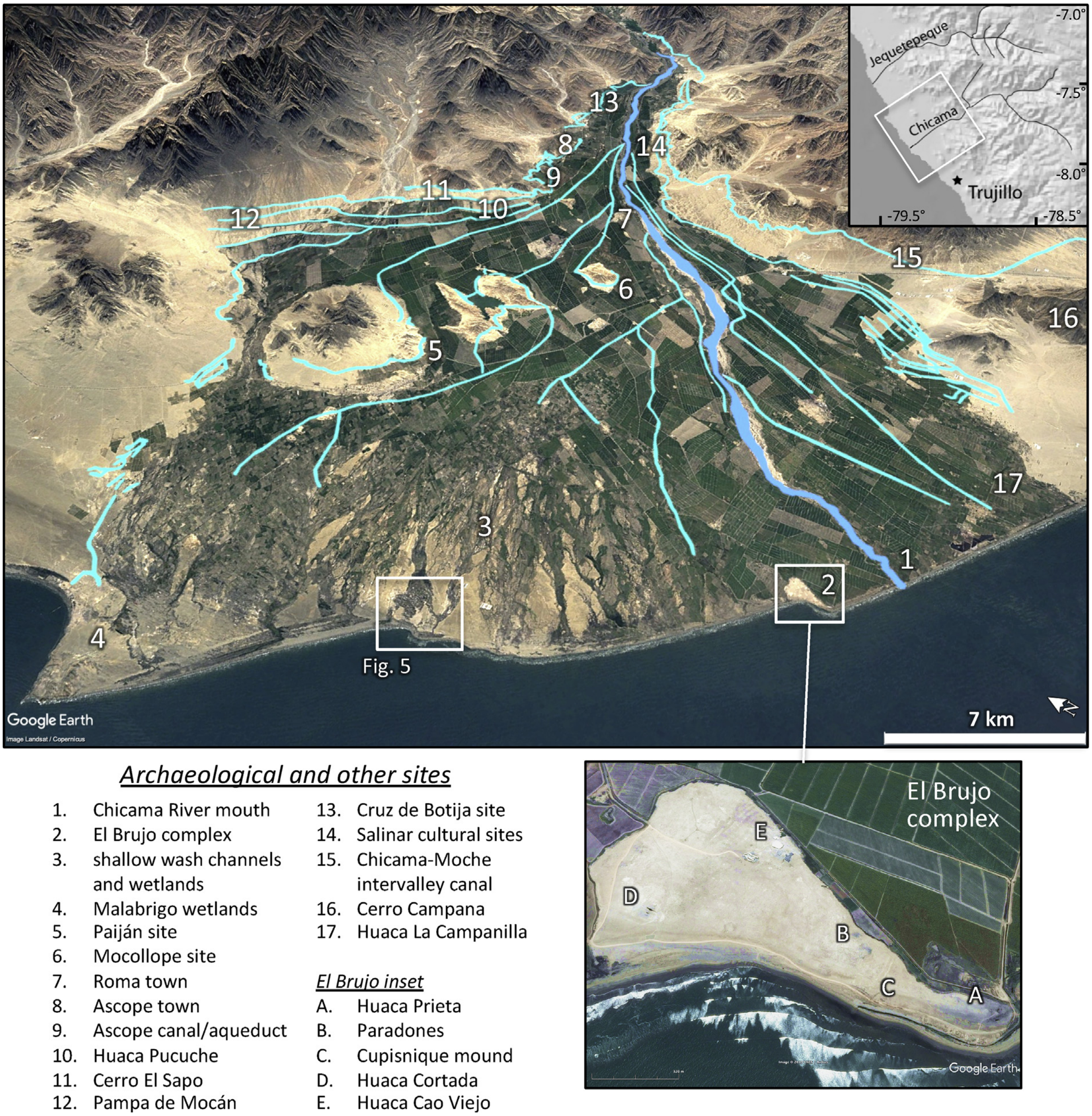

Fig. 1. Oblique east-northeast view of the lower Chicama River valley, north coast of Peru (Landsat image; Google Earth), showing locations cited in the paper and the extent of irrigation canals (aqua blue; after Watson, 1979; Netherly, 1984; Vining, 2018). Thicker blue line shows the Chicama River course. The sites presented here are examples of the type-sites that represent different cultural periods and proto-urban to urban settlement patterns. Also note that the timing of canal construction is diachronous across the valley, and the period of use for individual segments is generally not well constrained, except for a few examples (e.g., Ascope and Chicama-Moche canals). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

6.5–5.0 ka when the population increasingly shifts toward an agriculture-based economy. Why and how did this dramatic shift in resource utilization occur in a coastal desert landscape with abundant marine resources and existing domesticated cultigens?

Centered along the coastal valley and lowland floodplains of the Chicama River, the prominent shift to an agriculture-dominated economy in the wider Huaca Prieta area is concurrent with significant cultural developments, such as ceramic production, growth of population centers, new forms of social organization, large-scale irrigation projects, and adobe-based monument construction (Bird, 1948; Bird et al., 1985; Dillehay, 2017). These trends accelerate after ~4.5 ka, associated with substantial urban population and economic growth that reach their zenith shortly before Europeans arrive. Here, we explore these changes in context of the coupled human-natural system of Chicama River valley, showing that the timing and magnitude of societal advancements correspond with significant environmental changes driven by natural and anthropogenic forcings. For example, why did the great pyramids and cultures of the later Moche, Lambayeque, and Chimu ~1.5–0.5 ka (~500–1500 CE), emerge when they did? Were they motivated by a coupling of social factors – e.g., new technology, socio-political organizations, authority and labor control – with the benefits of an ameliorating environment and evolving physical setting that made possible for the first time a large-scale, agriculturally based economy?

We present data suggesting that growth in power, population, and social complexity (e.g., Chapdelaine, 2011) were motivated by the development of an expansive, arable floodplain across the lower Chicama valley. Furthermore, we show that floodplain development was not driven solely by climate and river response, but rather emerged through a strong coupling of environmental change with human response and engineering (e.g., Dillehay and Kolata, 2004). Early human-environment feedbacks were marked by cultural adaptations to mid-Holocene climate and sea-level change (e.g., Wells and Noller, 1999), but their greatest impacts eventually manifest through direct agronomic and hydrologic engineering of the lower valley coast and floodplain (e.g., Hesse and Baade, 2009). These manipulations are recorded by an ever-expanding irrigation network, beginning with plot-scale raised-terrace farming (i.e., *camellones*), later advancing to local river off-takes, and eventually to large-scale, cross-valley canal systems and aqueducts (e.g., Clément, 2017; Netherly, 1984). Through these evolving technologies, the growing elite administrative units of Chicama valley engineered a veneer of expansive, arable farmland over the desert sands and gravels. This anthropogenically modified landscape supported a much larger population and stronger economy than possible under natural conditions alone.

We suggest that the wider Huaca Prieta area could serve as a Rosetta stone for the role that human adaption to, and control of, environmental change played in the transition of a complex hunter-gatherer civilization to a ‘modern’ agricultural society. We demonstrate the basic tenets of these ideas: (1) that there exists a unique geologic setting and detailed record of local environmental change; (2) that coastal lagoons and alluvial fans transitioned to widespread floodplains through deposition of arable silts; (3) that the onset and expansion of floodplain development is contemporaneous with marked cultural changes in the Chicama valley, including increased population, irrigation systems, and proto-urbanism; and (4) that these environmental and cultural changes are linked through hydrologic engineering systems and recorded in floral and faunal remains and the isotopes of human teeth (Dillehay, 2017).

2. Background

Similar to other rivers along the north coast of Peru, the Chicama River drains an arid, sparsely vegetated highland catchment that yields limited, seasonal water discharge and a high fraction of coarse-grained sediment. These two attributes give rise to a typical braided gravel-bed channel system that is capable of transporting cobble-sized sediment to the coast. The annual water discharge of the Chicama averages ~0.95 km^3, equating to ~20 cm/yr of runoff from the 4800 km^2 catchment (Milliman and Farnsworth, 2011). Although hydrologically similar to adjacent north-coast rivers, the Chicama basin is geologically distinct. Exposed lithologies comprise highly fractured, Mesozoic metasediments, including broad exposures of the fine-grained Chicama Formation (Fig. 2; Institute of Geology and Minerals, 1975). The erodable mudstones (i.e., pelites) of this formation yield a significant fraction of silt-sized sediment to the Chicama River, which is otherwise dominated by the transport of gravels with a smaller fraction of sand. Importantly, the silt component sourced by erosion of the Chicama Formation is key to the construction of a broad, arable floodplain in the late Holocene, which distinguishes the Chicama coastal valley from adjacent river valleys where the channel is incised and arable sediments are restricted near to the channel (Fig. 4).

The Chicama River's lowland reach begins at an elevation of ~200 m as the channel exits the Andean foothills and continues for another ~30 km to the modern coast. Along this lowland reach the river maintains a relatively steep slope of 0.0067, constructing a broad alluvial fan that has aggraded several meters above the adjacent gravel-washed desert (Fig. 4). The fan extends over an area of ~360 km^2 and is principally composed of pebble to cobble-sized gravels and coarse sand. However, over the late Holocene this gravelly fan surface becomes draped by 0.5–3.0 m of fine-grained sediment (silts) associated with changing environmental conditions and human activities discussed in this paper.

Another unique attribute of the Chicama coastal valley is the apparently slower rate of tectonic uplift that favors a gentle, low-gradient shoreline compared with the more typically cliff-bounded coasts north and south of Chicama. For example, the Jequetepeque River just 70 km north is deeply incised (30–40 m) within a narrow valley that extends to the coast, constraining floodwaters and limiting the extent of floodplain deposition (Fig. 4). Similarly, rivers south of Chicama drain to cliffed coasts with high, eroding bluffs. The Chicama valley, in contrast, has a low-lying, relatively gently sloped coastal area of dunes, lagoons, and overbank floodplain.

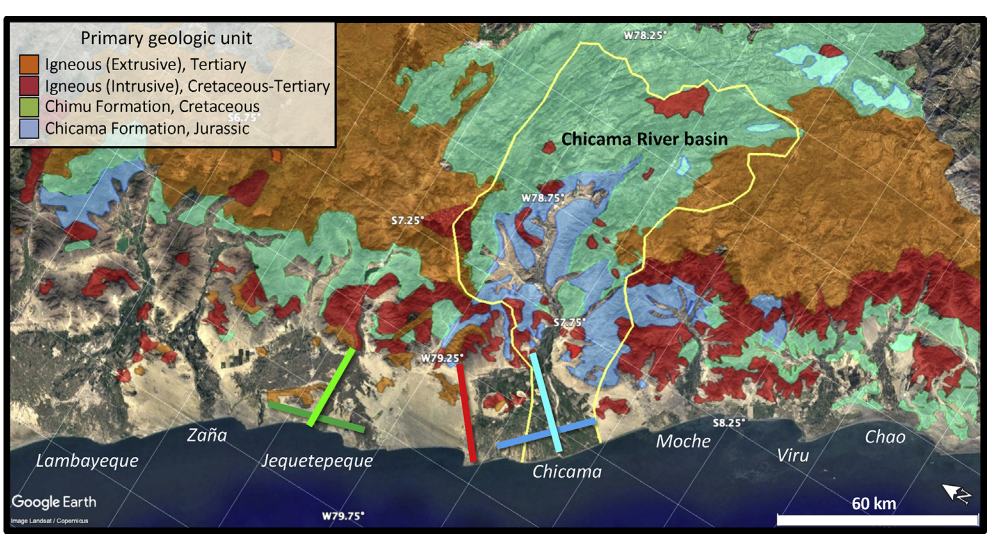

Fig. 2. Northern Peru coast and Andes mountains showing major geological formations (after Institute of Geology and Minerals, 1975) and mouths of the principal river valleys (image: Landsat; Google Earth). Note that the Chicama River basin (outlined in yellow) drains the region's largest exposure of the Chicama and Chimu Formations. The Chicama Formation is composed of metamorphosed mudstones and pelites that yield a relatively high fraction of fine-grained sediment. Also shown are the locations of the topographic profiles in Fig. 4 (green, red, and blue lines). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

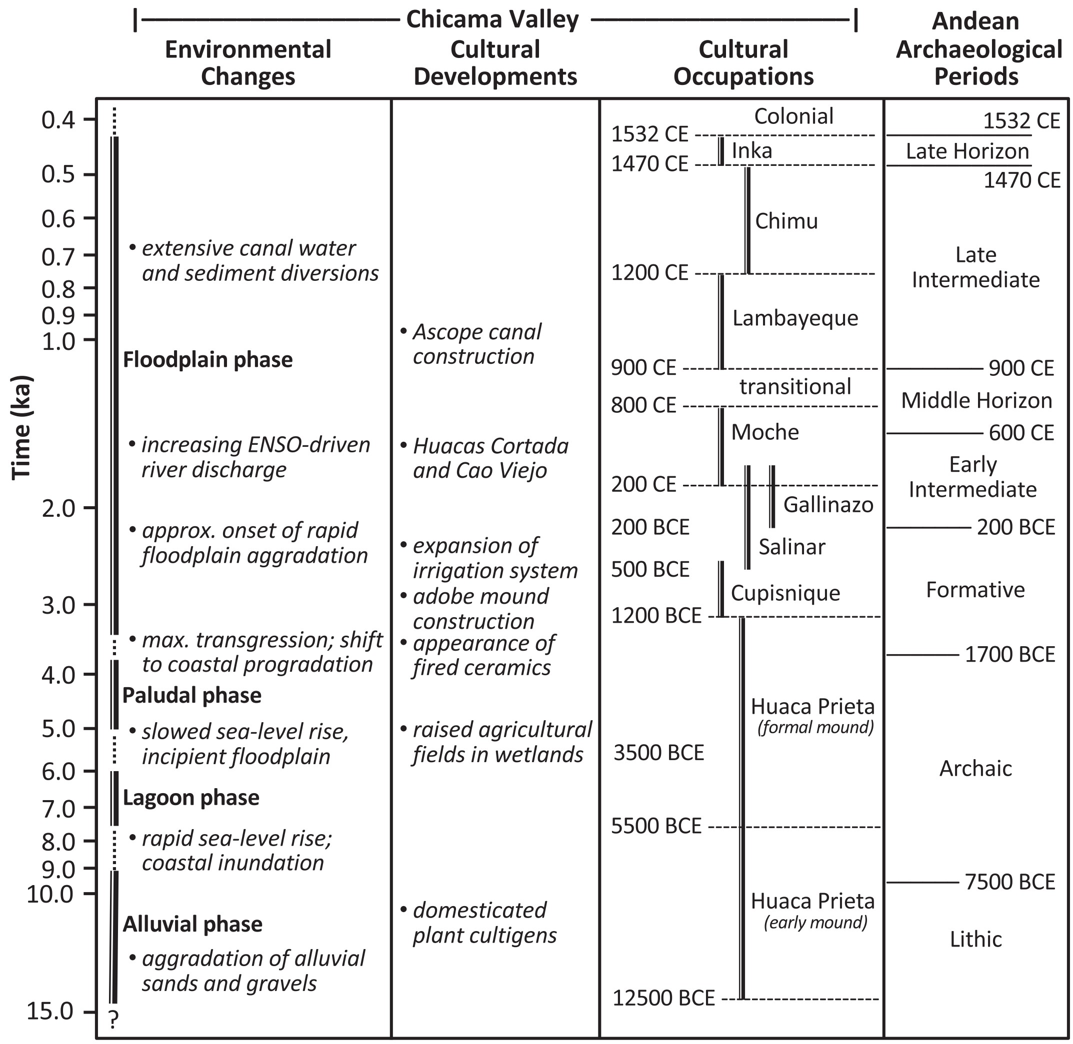

Fig. 3. Regional timeline showing the lower Chicama River valley's major environmental phases, cultural developments, and occupations alongside of the principle Andean archaeological periods. Note log-scale for time.

Here we connect major cultural transitions in the Chicama valley to these physical attributes and the late Holocene evolution of the physical environment, arguing for a strongly coupled human-natural system.

3. Methods

The majority of this geoarchaeological research on the wider Huaca Prieta area and Chicama River valley was conducted during eight major field campaigns from 2006 to 2013, in addition to other less formal excursions before and after this time. The extensive archaeological work was conducted using interdisciplinary methods described in detail in Dillehay (2017). Specific to the findings reported here are systematic archaeological surveys and subsurface testing along the entire coastline and interior from Huaca Prieta to Malabrigo (Fig. 1). Surveys of over 15 km of modern-day drainage trenches (1–2 m wide × 1–3 m deep), extending from the modern shoreline to ~20 km inland, also provided information on stratigraphy, the deposition of cultural materials, and buried agricultural fields. Additional informal surveys of geological and archaeological materials were carried out in the lateral, alluvial ravines (*quebradas*) found alongside the middle Chicama valley as far as 35 km inland (Fig. 1; sites 12 and 13). Data retrieved from these latter investigations provided much of the archaeological information described here.

The geological research was conducted through sampling and descriptions of Holocene stratigraphy throughout the lower Chicama valley, coast, and adjacent alluvial systems (Fig. 1). Stratigraphy was accessed through exposed sections along river cutbanks and within irrigation ditches, as well as through hand-augering of subsurface sediment to depths of 6 m. Much of the environmental history of the region is captured in riverbank exposures and associated subsurface sediments in the lower Chicama River valley and adjacent coastal system. All subsurface samples were hand collected using gouge augers, with further details of the field methods given in Goodbred et al. (2017). Radiocarbon dating was conducted on charcoal and analyzed at the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) in Woods Hole, MA. All ages were calibrated using CALIB 7.1 and the IntCal04.14C calibration dataset (Stuiver et al., 2019). The mean radiocarbon ages are reported as *cal yr BP* (i.e., referenced to 1950) and presented with two-sigma uncertainty. The depositional ages of two sediment samples were determined by the optically stimulated luminescence (OSL) of quartz grains. The single-aliquot regenerative (SAR) dose protocol (Murray and Wintle, 2003) was used to estimate equivalent doses. Quartz aliquots (180–250 μm or 125–180 μm) were

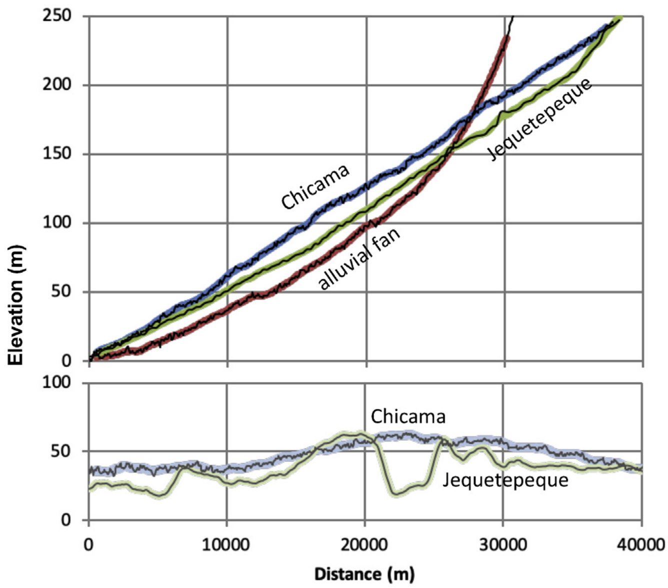

Fig. 4. Along-valley topographic profiles (upper panel) of the Chicama and Jequetepeque river fans, and an intervening alluvial fan system. Note the higher elevation and persistent slope of the aggrading Chicama and Jequetepeque valleys compared with the lower, concave profile of the alluvial fan surface. Cross-valley topographic profiles (lower panel) show broadly convex profiles of the two river fans, but the Jequetepeque River is > 30 m incised in its valley and thus decoupled from its adjacent fan surface. The Chicama River is not incised and can actively disperse sediment to its fan surface during overbank flooding. Profile locations are shown in Fig. 2.

prepared following standard procedures (Aitken, 1998). Luminescence measurements were made using a Risø TL/OSL DA-20 reader equipped with infrared and blue LEDs for light stimulation, Hoya-340 filter for light detection in the ultraviolet band and built-in beta radiation source with dose rate of 0.088 Gy/s for cups. Environmental dose rates were calculated using radionuclides concentrations appraised by high-resolution gamma ray spectrometry. The contribution of cosmic rays to dose rate was calculated according to Prescott and Hutton (1994). The OSL ages are referenced to the year of sample collection (2012 in this study) with one-sigma uncertainty.

4. Preceramic period (~14.5–3.7 ka)

4.1. Alluvial phase

Occupied by at least 14.5 ka, the lower Chicama River valley was a center of early cultural development that later emerges as an agricultural powerhouse and economic center in the region (Fig. 3). The economy of the wider Huaca Prieta area was dominated by maritime fisheries and stone-based mound construction for nearly 8000 years, despite key cultigens such as maize, squash, beans, avocado, and chilis having already been cultivated (Dillehay et al., 2017, 2007). Persistence of the maritime economy over this time is undoubtedly due in part to high productivity of the upwelling coastal ocean, coupled to local wetland and lagoons (Dillehay et al., 2012b). These sites provided persistent harvests of shellfish, seaweeds, fin fish, and occasional marine mammals. Nevertheless, over such an extended time period why should agriculture have not taken a stronger hold in Chicama and other regional coastal valleys, as it did elsewhere in the world? We argue that this may have been due in part to the lack of extensive arable soils along the arid Andean coast, a setting characterized by gravelly alluvial fans and aeolian dunes. Further, persistence of particularly arid, La Niña-like climate conditions during this time (Makou et al., 2010) would also have limited agricultural opportunities (Gálvez and Runcio, 2015).

Unlike many fluvial systems of the region, though, the Chicama River transports a sizeable fraction of fine-grained sediment that is sourced from the basin's unique exposures of mudstone in the Jurassic-age Chicama Formation (Fig. 2). The Chicama valley and coast are also regionally unique in not having experienced major tectonic uplift through the Holocene, resulting in an aggradational land surface and low-relief shore zone. In contrast, the Jequetepeque River valley ~60 km to the north is just 2-km wide and flanked by steep cliffs that confine river floods, leading to scour and erosion of the valley floor (Figs. 2 and 4). In the Chicama valley, however, floodwaters are able to flow overbank, out of the channel, and disperse flood energy, water, and sediment across the fan surface, as observed repeatedly during recent El Niño events (e.g., 2017, 1998). Nevertheless, even the Chicama valley alluvial surface is relatively steep, (slope $= 0.006 \pm 0.001$), driving stream power that favors the deposition of coarser sand and gravel sized sediment over fine-grained grained deposits.

As such, fine-grained suspended sediments are primarily bypassed to the coast, where lagoons and wetlands have served as effective traps for these silts and clays (Goodbred et al., 2017). Thus, it was the margins and shallow reaches of these lagoons that provided at least limited farming opportunities to local populations from the early to middle Holocene (Dillehay et al., 2012a). However, multiple physical factors would have restricted the extent of agricultural production during this time. First, persistent sea-level rise and the continuing lack of El Niño flood discharge (e.g., Moy et al., 2002; Sandweiss et al., 1996) meant that rising water levels were not offset by sediment delivery. The lack of sediment delivery favored persistent transgression of the shoreline and landward reworking of the lagoon systems (Dillehay et al., 2017). Furthermore, open-water lagoons would have remained unfilled and rimmed by water-saturated wetland soils not naturally suited to extensive agriculture. As such, the important role of lagoon settings in the early Holocene remained almost exclusively as wetland and open-water foraging sites.

4.2. Paludal phase

By ~6.5 ka, slowing sea-level rise favored more stable coastal lagoons and wetlands, which in turn provided surface water resources and a trap for fine-grained sediments delivered by the river (Goodbred et al., 2017; Wells, 1996). This latter development of increasing sediment input corresponds with the initial onset of El Niño-phase river flooding and sediment delivery in the region, albeit with weaker, less frequent events than in the late Holocene (Rein et al., 2005; Sandweiss et al., 2009, 2001). Nevertheless, radiocarbon-dated sediment cores near the modern river mouth and adjacent to the Huaca Prieta mound show up to 2 m of lagoon-sediment deposition from 7.5–6.2 ka, comprising alternating units of authigenic carbonates (ostracods, chrysophytes), marsh peats, and fluvial muds (Goodbred et al., 2017).

Thus, with more stable boundaries and increased sediment input, the seasonally wet margins of the lagoons doubled as low-lying, incipient floodplain that could be used for small-scale farm plots. However, preserved faunal and floral assemblages indicate that the lagoon waters were often oligohaline (0.5–5 ppt salinity), presumably from episodic seawater intrusion and wind-blown salts (Goodbred et al., 2017). Thus, to farm the margins of these shallow, slightly saline lagoons, plants had to be cultivated on raised agricultural terraces called '*camellones*'. Built directly within the shallow lagoons or wetlands (Figs. 5 and S1), crops of the raised agricultural platforms were irrigated by the capillary transport of lagoon water, with dissolved salts sorbing onto the terrace soils during transport. However, the soils needed to be periodically replaced as salt content increased with time. Despite such limitations, this small-scale, raised-platform farming is the principal method of agricultural production over several thousand years from ~6.5–3.5 ka, taking advantage of available water and fine sediments around the lagoon margins and wetlands to increase agricultural output (Fig. 1, sites 1–4; Dillehay et al., 2012a).

Toward the end of this phase, the low-lying, saturated, localized farming soils (gleysols) associated with wetlands and lagoon margins begin to change with increased river discharge. First, the authigenic carbonates and peats that reflect open-water and flooded margin settings, respectively, disappear as the lagoons infill. Later, the fluvial muds shift from a slightly reduced bluish-gray color (i.e., subaqueous mud deposition) to a slightly oxidized brown color that indicates increasing oxidation and subaerial exposure as the lagoon infills (Goodbred et al., 2017). Thus, a stable sea level and increased fluvial sediment delivery raised the floodplain surface above the water table for the first time, marking the onset of more productive and increasingly widespread agriculture.

5. Formative period (3.7–1.8 ka)

Beginning ~3.7 ka, the development of new floodplain in the lower Chicama valley is driven, at least initially, by environmental factors such as increasing river discharge from El Niño phase precipitation (e.g., Billman and Huckleberry, 2008; Lagos et al., 2008; Mollier-Vogel et al., 2013; Tapley and Waylen, 1990). The higher discharge and increased delivery of fine-grained sediment from the Chicama Formation (Fig. 2) enhanced overbank sediment deposition (Morera et al., 2017; Romero et al., 2007; Tote et al., 2011; Wells and Noller, 1999), and also led indirectly to the enhanced trapping efficiency of fine sediments near the coast. The latter effect was due to the construction of gravel beach ridges that created an effective backwater trap (i.e., 'dam') at the shoreface for the river's sediment-laden runoff (e.g., Ortloff and Moseley, 2012). Thus, in a region so characterized by gravelly desert outwash, the lower Chicama valley began to be draped with fertile silts that transformed the valley's potential for agricultural production.

It is this onset and expansion of arable floodplain in the late Preceramic and early Formative periods 4.4–3.7 ka (~2400-1700 BCE) that sparks a valley-wide socio-economic transformation. The lower Chicama valley people shift from their long-term maritime-based economy to one dominated by agriculture (Dillehay, 2017), ushering cultural shifts that develop across the Formative period and accelerate in the Intermediate period (Chapdelaine, 2011). The availability of floodplain silts and resulting agricultural revolution also manifests in the conspicuous emergence of adobe-based pyramid construction and the groundbreaking development of fired pottery ~3.5 ka (Patterson and Moseley, 1968). Indeed, early Guañape pottery sherds dating to ~3.5 ka (~1500 BCE) are found in both the earliest floodplain deposits overlying desert gravels and back-dune areas at the coast (Fig. S2; Goodbred et al., 2017; Prieto et al., 2016).

5.1. Environmental change

Reversing a history of coastal transgression that had persisted for the previous 10,000 years of human occupation, the shoreline at the Chicama rivermouth begins to prograde ~3.5 ka for the first time in the Holocene (Goodbred et al., 2017). As the rate of sea-level rise was already relatively low, this seaward progradation of the coast was driven primarily by the increasing frequency of El Niño flood-supplied sediment from the Chicama River. The resulting flux of sediment to the coast led to construction of a high, broad complex of cobble beach ridges overlain by sand dunes, similar to the Santa River beach ridge complex ~120 km south of Chicama (Sandweiss, 1986; Wells, 1996). The Santa beach ridges begin to develop several thousand years earlier than those at Chicama, but the rate of development accelerates after ~4 ka around the same time that the Chicama ridges start to form and the coast progrades. Exact controls on the history of Santa ridge formation remain somewhat debated (e.g., Sandweiss et al., 1998), but uniformly agreed is that the onset of El Niño and increased river sediment discharge was a primary factor (Sandweiss, 1986; Wells, 1996). Consistent with these prior works, our results from Chicama trace early increases in river sediment delivery with the infilling lagoons ~6 ka and the emergence of low-lying floodplain by ~3.5 ka at start of the Formative period (Goodbred et al., 2017).

The Chicama beach ridges extend 3 km from the river mouth north to the Huaca Prieta mound site (Fig. 1), eventually comprising a >100-m wide beach-ridge plain. The development of this feature created a drainage barrier for overland floodwaters and thus an effective trap for fine-grained sediments. After 3.5 ka, we find that enhanced sedimentation behind the beach-ridge plain caused the coastal floodplain to aggrade above the water table for the first time, resulting in more extensive and better-drained soils. This transition is well recorded by the widespread transition in soils from dark, calcic gleysols to lighter-colored cambic fluvisols at this time (Fig. 6) (Goodbred et al., 2017) and would have provided more agricultural area and better growing conditions.

Initially, these more arable floodplain soils were restricted within ~1 km of the coast where overbank floodwaters were trapped behind the beach-ridge plain. However, the expansion of agriculture to the central and middle portions of the valley after this time must have involved human intervention to divert water and

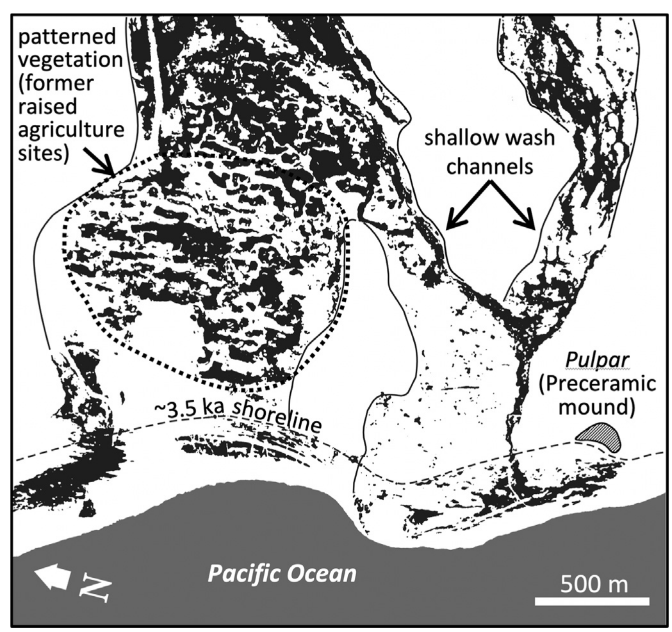

Fig. 5. Rendered image of ephemeral wash channels and raised-agricultural fields from the northern Chicama River valley. The black areas on the image denote vegetation, and location of the image is shown in Fig. 1. These wash channels are only active during the largest flood events and are typically scoured 1–3 m below the adjacent gravelly fan surface. This scour places the channel base closer to the water table, supporting the growth of thick vegetation during the long periods between major floods (decades to centuries). The particular location shown here hosts a large area (~1 km^2) of patterned vegetation that reflects its prior use in raised-field agriculture (*camellones*), which would have been active when this site comprised wetlands and ephemeral open-water habitat (see Fig. S5, for example). These agricultural plots also lie adjacent to a Preceramic mound, Pulpar, that is roughly contemporaneous with early Formative phase of Huaca Prieta (Dillehay, 2017).

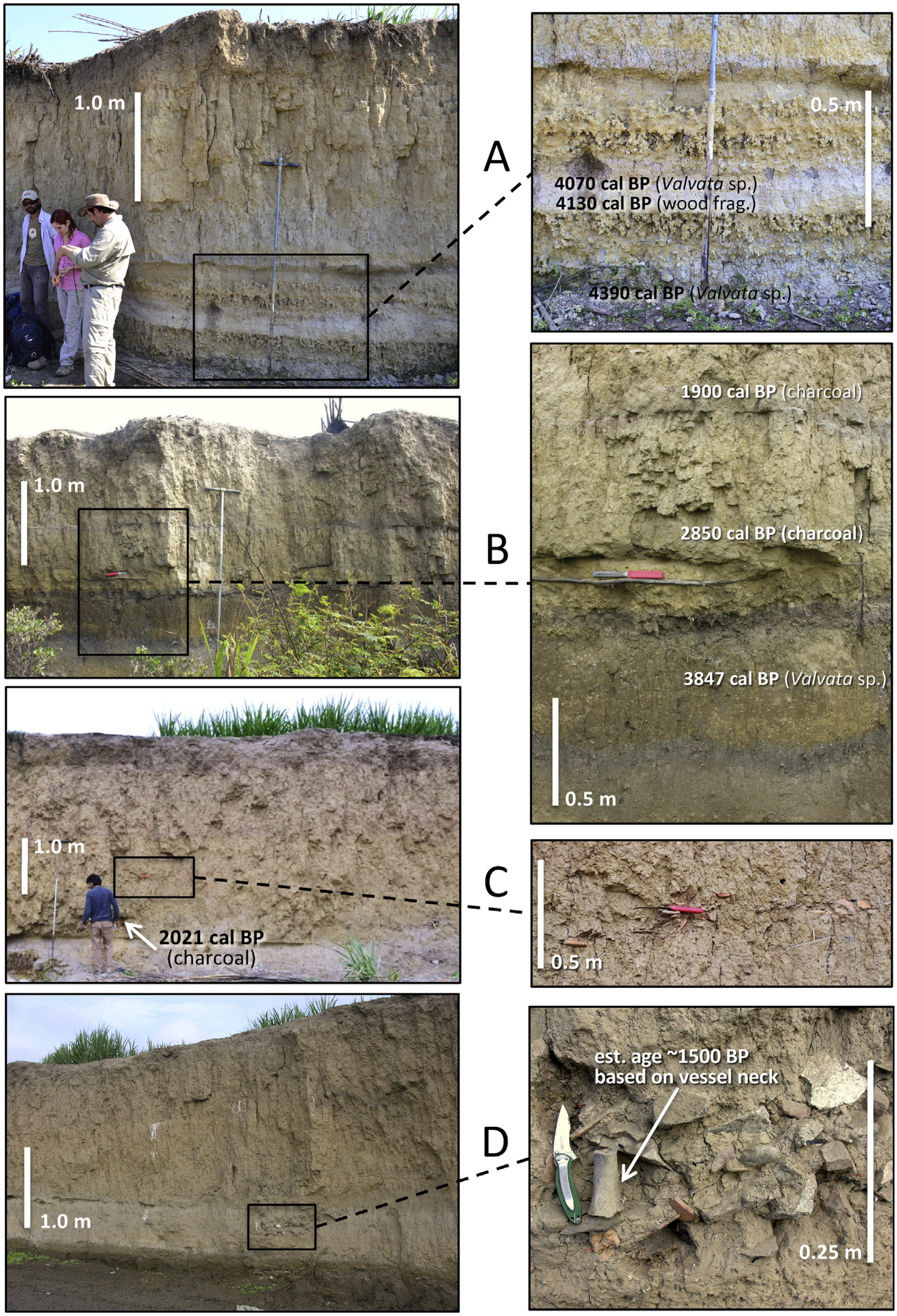

Fig. 6. Field photos showing thick floodplain deposits that have aggraded in the last few thousand years. Image sets A and B are from two locations near the coast and show a transition in soils after ~3.5 ka from slowly accreting calcic gleysols to rapidly accreting mix of natural cambic fluvisols and anthrosols. Image sets C and D are from the middle valley near Roma, ~30 km inland. These sites also show thick, rapidly aggrading floodplain deposits after ~2.0 ka due to increased ENSO-driven river discharge and irrigation diversions. Radiocarbon ages from Goodbred et al. (2017).

sediment to these areas (e.g., Ortloff and Moseley, 2012). Without such engineering controls, overbank floodwaters from the river would simply drain to the coast and lower valley, either eroding or depositing the same sands and gravels that comprise the bulk of the fan stratigraphy. Thus, the 1-3 m-thick silt veneer that now overlies the sloped gravel surface of the middle valley gives evidence for the first canal-based water and sediment diversions upstream of the coast. Indeed, even coastal floodplain in the lower valley would have required irrigation since the land surface had aggraded above the water table, perhaps providing the initial impetus for canal development (e.g., Hesse and Baade, 2009). As for cultigens, the use of small irrigation canals had already been established in the western highlands since at least 6 ka (Dillehay et al., 2005), but their application in the lower Chicama valley would have been largely irrelevant prior to the development of arable floodplain after 3.5 ka, and thus unlikely to be present at this time.

5.2. Cultural change

The expanding footprint of silty floodplain deposits in the middle valley suggests that irrigation technology was adapted to divert not only irrigation water but also suspended sediments that could construct and maintain new arable land surfaces. It is this engineering of the environment during the middle-late Formative period ~3.0–2.5 ka (~1000-500 BCE), following an initial amelioration of the natural environment, that appears to set on course a massive expansion of agricultural capacity. These trends ultimately lead to construction of a vast canal system across the Chicama valley during the Early Intermediate and Middle Horizons (Netherly, 1984; Watson, 1979), including efforts for intervalley linkages, such as the Chicama-Moche aqueduct (Kus, 1984; Ortloff, 2010; Ortloff et al., 1983).

The natural expansion of arable floodplain and agriculture through the Formative period also corresponds with major cultural developments. Fired clay daub first appears in the lower Chicama valley at ~3.5 ka (Goodbred et al., 2017), with ceramic technologies emerging soon thereafter. The first evidence of early ceramic or Initial Period occupation in the lower valley is represented by incised Guañape sherds that date ~3.5–4.0 ka and are buried 1–3 m in floodplain sediments that directly overlie the basal gravel surface (Fig. S2; Dillehay, 2017). These small sherd clusters are associated with development of the first subaerial floodplain deposits (i.e., fluvisols) in the lower valley and probably represent scattered farming households located near the coastal wetlands and river channel.

Over the next millennium both the soils and pottery become increasingly widespread across the central and middle portions of the valley (i.e., from coast to foothills; Fig. 6; Vining, 2018). These later Formative period sherds date to the Cupisnique, Salinar and Gallinazo periods ~3.5–2.0 ka (~1500-0 BCE), appearing less often and recovered from shallower depths ~0.8–1.2 m below surface in the lower valley. Most Salinar and Gallinazo period occupations (Fig. 3) were located along the main river-bank terraces and margins of the adjacent alluvial fans of the lower middle valley. Late Salinar occupations are particularly well preserved in narrow ravines (*quebradas*) that drain elevated terraces along the middle river valley (Fig. 1). Scattered households there host small water management systems in the form of dikes, stone-lined canals and other rock features, indicating opportunistic use of seasonal available water or more permanent humid conditions. Similar agricultural structures linked to local drainages are also described for the Pampa de Mocán at the far north margins of the middle Chicama valley (Caramanica and Koons, 2016). In all, this expansion across the valley of arable sediments, agriculture, and human presence indicates that, for the first time, people are becoming dominant engineers of the environment (Baade and Hesse, 2008; Dillehay et al., 2004). Before this time, the scale and productivity of farming was limited by the availability of naturally arable settings in this arid, coarse-grained desert fan setting.

The emergence of floodplain and pottery also corresponds with a major shift in monument construction and human habitation, as evidenced by all Formative and later structures built of adobe brick rather than the cobble and salt construction of the Preceramic period (Bird, 1948; Dillehay, 2017). One of the first of these adobe monuments in the lower valley is the Cupisnique mound that lies juxtaposed to its cobble-based predecessor, Huaca Prieta, and comprises the dominant Formative period site in the lower valley (Fig. 1). The Cupisnique mound overlies late Preceramic and subsequent early ceramic households dating from about 6.6 ka to 3.2 ka (~4600-1200 BCE). The Cupisnique mound appears to be related to the domestic and ceremonial activities of outlying settlements that were engaged in both agricultural and maritime economic activities. We postulate that the increasing availability of fine-grained muds from floodplain development over this time contributed – both culturally and economically – to the emergence of new construction materials and technology, first expressed in the Cupisnique mound adjacent to Huaca Prieta and the Cruz de Botijas and Huaca Pucuche mounds farther inland near Ascope (Chauchat et al., 1998), each portending the great pyramids Huaca Cortada and Huaca Cao Viejo built in the Intermediate and Middle Horizons ~1.5–1.2 ka (~450–800 CE) (Fig. 1).

In all, (*i*) the development of well-drained, but local, floodplain soils, (*ii*) the appearance and perfection of fired ceramics, and (*iii*) the shift to new adobe-based construction define the Formative period and its transition from a primarily maritime-based economy to one increasingly dominated by agricultural production. These transformations attest to the growing availability and reliance on river-derived silts for food production and monument construction.

6. Early to Late Intermediate periods (1.8–0.4 ka)

The geologic record from 1.8–0.4 ka reveals a continuation of Formative-period patterns, with the deposition of arable sediment in the lower valley and progradation of the coast. Distinct, though, is that rates of sediment deposition continue to increase through the Early Intermediate Period and Middle Horizon ~1.5–1.0 ka (400–1000 CE), with the distribution of fine, arable sediments expanding to more distal portions of the valley. These patterns appear to have been driven by both natural and anthropogenic factors, such as stronger, more frequent El Niño floods (Etayo-Cadavid et al., 2013; Makou et al., 2010; Moy et al., 2002) and the construction of an expansive irrigation-canal system (Clément, 2017; Huckleberry et al., 2017; Kus, 1984). The grand scale of the Chicama irrigation system at this time reflects the magnitude of shift to an agricultural economy; at its peak the irrigation system could have supported cultivation of up to 50,000 ha (500 km^2) (Pozorski, 1987; Watson, 1979).

Culturally, there is rapid growth in social complexity, population, artistry, and monument construction through the Early Intermediate Period (Dillehay, 2001), climaxing with the Late Moche culture and building of the iconic Huaca Cao Viejo (Chapdelaine, 2011). Subsequent shifts in the sociopolitical structure of Chicama valley during the Late Intermediate period brought successive rule by the Lambayeque, Chimú, and Inka cultures prior to European arrival (Chapdelaine, 2011; Haas et al., 1987). Prior research has often associated the strife of these sociopolitical upheavals with increasing intensity and variability of ENSO cycles, driving strong flood and drought cycles (Nials et al., 1979; Salvatteci et al., 2014; Sandweiss et al., 2001; Winsborough et al., 2012). However, there were also significant adaptations to changing environmental conditions, such as taking advantage of increasing water and sediment discharge by constructing a network of massive irrigation structures that operated over hundreds of years (Cerpa et al., 2013; Huckleberry et al., 2017; Netherly, 1984; Ortloff et al., 1983; this study).

6.1. Environmental change

Most proxies from the eastern equatorial Pacific indicate increased strength and frequency of El Niño wet phases through the Early Intermediate period (~last two millennia), as well as correspondingly stronger La Niña dry events (Loubere et al., 2013; Moy et al., 2002; Riedinger et al., 2002; Rodbell et al., 1999). Indeed, much (deserved) attention has been given to the history and impacts of El Niño events on river and coastal flooding and the collapse of marine ecosystems with the loss of upwelling-driven productivity (Andrus et al., 2005; Salvatteci et al., 2014; Waylen and Caviedes, 1986; Wells, 1990, 1987). Particular focus has been given to the most extreme ENSO events and their impact on regional Andean cultures, perhaps in part because these extreme events are the most consistently recorded in the geologic and cultural records (e.g., Manners et al., 2007; Nesbitt, 2016; Nials et al., 1979). Indeed, in the lower Chicama valley near (~1 km) the main Chicama River channel, major El Niño flood events are well recorded in sediment near the coast and along the river channel. In these locations, thickly bedded (15–30 cm) silt units comprise a total of 2–4 m of cambic fluvisol deposits that reflect overbank deposition by major El Niño floods (Fig. S3; Goodbred et al., 2017). Radiocarbon ages from these deposits yield mean sediment accretion rates of 2–3 mm/yr over the last two millennia, considerably higher than the ~0.5 mm/yr longer-term averages (Fig. 7). Taken together, unit thicknesses of 15–30 cm and mean accretion rates of 2–3 mm/yr suggest a 75–100 year recurrence interval for large El Niño floods, comparing well with the 60–80 year return period determined by Rein et al. (2005) from the Peruvian marine sediment record.

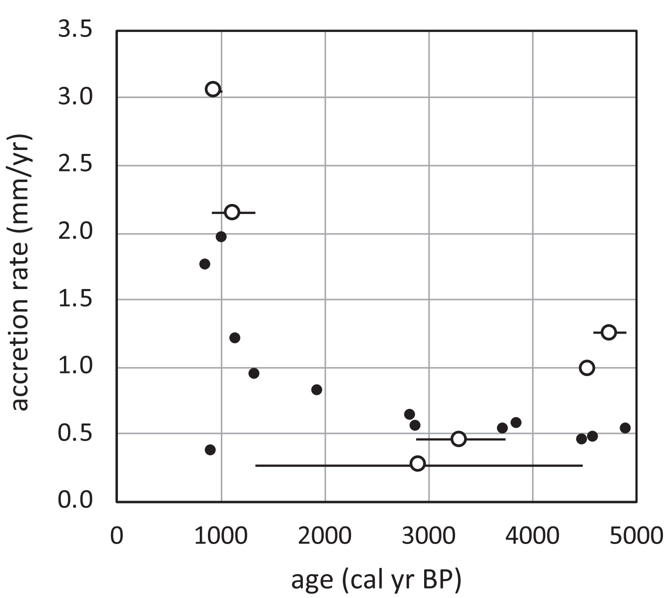

Fig. 7. Plot of long-term floodplain accretion rates over the mid-late Holocene period. Rates are interpolated from radiocarbon ages (Goodbred et al., 2017). Note that accretion rates increase significantly in the last 2000 years in association with more persistent ENSO-driven river discharge and the expansion of irrigation canals diverting sediment to the distal floodplain. Open circles represent rates interpolated between ages as shown by error bars; filled circles are averaged from sample age to present. Note that similar rates between the discrete-period values (open circles) and inclusive-period values (solid circles) indicate that the Sadler effect is not a significant factor in these data (Sadler, 1981).

Building upon the localized expansion of arable lands that occurred in the Formative period, the Early Intermediate Period is characterized by a much greater expansion of floodplain deposits that extend up to 5–15 km away from the river channel. These areas are typically covered by 0.2–1.0 m of weakly developed, cultivated silty soils that overlie the regional base of alluvial sands and gravel (Fig. 6). However, El Niño floods cannot account for such a wide extent of floodplain deposition across the valley, as overbank deposition decays exponentially with distance from a river channel, typically ceasing within 0.2–1.0 km (Allison et al., 1998; Asselman and Middelkoop, 1995; Nicholas and Walling, 1997; Swanson et al., 2008). A natural fluvial system can construct a valley-wide floodplain through distributaries or channel avulsion; however, we find no evidence of avulsion or distributary channels within these distal, late Holocene floodplain deposits across the Chicama valley. Rather, this blanket of silts is devoid of channel cuts or any discernible sand/gravel horizons that would indicate prior channelization; neither are such features expressed in the valley's surface topography. To be clear, there are many older distributaries or channels incised into the Chicama fan surface, but no such channelization is recognized in the Formative period and younger floodplain deposits that overlie this surface. Therefore, explaining the 400–500 km^2 veneer of arable sediments across the Chicama valley requires another mechanism.

Here, we invoke the extensive, yet localized and small scale, irrigation systems first constructed by the Salinar and Gallinazo, and later expanded by the Moche, Lambayeque, and Chimu cultures (Huckleberry et al., 2017; Kus, 1984; Netherly, 1984; Watson, 1979). Historical and field-based reconstructions of the canal system show that its distribution largely coincides with areas where the thin silt horizons are found, suggesting that these sediments were likely transported to distal locations by irrigation water. Such anthropogenically dispersed sediments are well described elsewhere in the region, notably in the Palpa River subbasin of Rio Grande de Nazca in southern coastal Peru. There, researchers document an extensive blanket of irrigation-transported sediment across the river valley, characterizing these soils as irragric anthrosols (Baade and Hesse, 2008; Hesse and Baade, 2009, 2007), which are formed as a result of prolonged sedimentation of silt from irrigation water (Driessen et al., 2001). The irragric soils in Palpa valley have little structure and diffuse horizontal or undulating lower boundaries, and often contain undisturbed deposits of anthropogenic charcoal, artifacts, and stone clasts “whose presence within the fine-grained matrix cannot be explained by fluvial processes” (Hesse and Baade, 2009). Indeed, these irragric-anthrosol descriptions match well the widespread distribution of silty soils that blanket distal portions of the Chicama valley, particularly the regular occurrence of clustered anthropogenic debris (Fig. 6). Chicama anthrosols also regularly display columnar peds, which form from regular wetting-drying cycles typical of irrigated drylands (Jahn et al., 2006).

6.2. Cultural change

The earlier Formative period is characterized by people adapting to naturally expanding floodplains through increased agriculture and renewed monument construction. The subsequent Early Intermediate Period reflects a continuation and intensification of those trends, along with increasing human control of water resources. With larger and more ambitious irrigation structures, Chicama valley polities drove a significant anthropogenic expansion of arable floodplain. The resulting increase in food production supported a growing population, new sources of income and socioeconomic stratification, as well as demands for a larger labor force (e.g., Chapdelaine, 2011).

6.2.1. Irrigation and canal system

With modern alteration of the landscape and antiquities in Chicama valley, the finer details of the prehistoric irrigation system must be approached with caution. Nonetheless, an examination of extant irrigation canals reveals numerous dendritically patterned relic canal networks that distributed water (and sediment) across the valley onto the alluvial desert surface. The canals follow the topographic slope of the land and are generally oriented southeast to northwest. Unfortunately, the course of many canals cannot be charted once they enter the extensive sugar cane fields of the modern era, but based on their size and trajectory at the point they become obscured (e.g., Vining, 2018), it is reasonable that they continued to the coast − perhaps as far as the El Brujo complex and Huaca Cao Viejo. Furthermore, unused, ancient canal segments are located within dune breaks north of El Brujo and in the foothills near Cerro Campana (Fig. 1), a trajectory that puts them in line with the large extant segments located up-valley near Ascope and Roma, further underscoring the size and length of canals in the lower valley. Radiocarbon and OSL ages (this study; Huckleberry et al., 2017) indicate that the construction and use of the large Ascope canal dates to the Middle and Late Horizon from 1.2−0.3 ka (800−1650 CE) (Fig. S4). Construction of this 10-m high canal and aqueduct system extends >20 km from the Chicama River and reflects a massive investment in agricultural infrastructure and labor demand.

Combining maps of Middle to Late Horizon structures (Chauchat et al., 1998; Dillehay, 2017) with digitized topography and SRTM elevation data, segments of remnant irrigation canal reveal an expansive hydrologic network that brought water from the river to the lower valley. The valley-wide canal system initiates upstream of the lower valley between the Ascope and Roma, where it parallels the bedrock-constrained Chicama River and diverted water and sediment via two major routes (Fig. 1). The first route diverted river discharge to the north, beyond Ascope to the small alluvial fans and terrace surfaces associated with local desert drainages. The second main route brought the water around the southern edge of valley near Sausal. These two major irrigation routes can be further subdivided into two different canals and/or aqueduct clusters. These canals dendritically radiate out and provide water to a large portion of the lower valley (Fig. 1).

Intermixed within both canal systems are the likely remains of relic canals associated with present-day sugar cane drainages. While we can question whether or not modern canals that run through or near the major Middle Horizon to Late Horizon sites are truly contemporary relics, and not the result of later occupations, data acquired during recent surveys and excavations tend to refute this. Unfortunately, details related to the use of water for irrigation and agricultural activity in the valley are difficult to discern due to a lack of data on branch canals, feeder canals, and agricultural furrows (*surcos*). Nevertheless, a few well-preserved areas around Mocollope, Paijan, and Cerro Campana demonstrate that this was not the case (Fig. 1). When combining the number, size, and distribution of the main canals with the scattered remains of feeder canals and *surcos*, it is clear that tremendous amounts of agricultural production must have occurred throughout the lower valley from at least the Middle Horizon (Dillehay, 2001; Dillehay and Kolata, 2004).

Estimating the overall area of agricultural production associated with the lower valley is somewhat dubious as the temporal relationship among the canals has yet to be established. It is tempting to consider that all of the canals were in operation simultaneously and that ~40,000 ha (400 km^2) were under agricultural production at any given time (Moseley, 1983). However, this may not have been the case. Watson (1979) performed an agricultural water budget for Chicama valley that suggests this scale of farming would only have been possible in a wet, high discharge year, and that during normal to dry years the river discharge could only have supported successful harvests across half to one tenth of this space, respectively. Furthermore, such an extensive canal system as this represents a tremendous labor effort in the short-term, measured against long-term return through potential agricultural efficiency and the flexibility to respond to changes in the environment (Dillehay, 2001; Dillehay and Kolata, 2004).

6.2.2. Settlement patterns

Interspersed among the Chicama valley irrigation canals are dozens of Early Intermediate Period structures (Vining, 2018), mostly small *huacas*, as well as relict agriculture plots that extend across the valley onto adjacent fan surfaces (Huckleberry et al., 2017). These Chicama valley settlement patterns are unique among the northern Peru coastal communities. For example, other contemporaneous occupations around El Brujo and adjacent coastal areas had either been abandoned (e.g., Malabrigo wetlands in the north) or lacked large-scale irrigation systems and clear evidence for agriculture at this time (e.g., Cerro Campana in the south) (Fig. 1). At the Malabrigo sites, luminescence dating of exposed terrace plots (*camellones*) yield a minimum abandonment age of ~2.4 ka, indicating no reoccupation or reworking of these plots since at least that time (Fig. S5; Table S1). The approximate timing of abandonment of the Malabrigo wetlands coincides with a period of population shift to the lower Chicama valley and growing urbanization in that area.

This contraction of settlement patterns toward the main valley reverses in the Moche period, ~1.8−1.0 ka (~200−1000 CE), when new settlements and secondary *huaca* construction appears across the Chicama floodplain (e.g., mounds at La Campanilla; Fig. 1). This societal growth occurs at a time when sediment deposition was expanding across the lower valley via canal diversions of water (and sediment) from the Chicama River. As noted earlier, these areas were not likely under direct influence of major El Niño floods, as reflected by the distal, non-channelized sediment deposits (i.e., irragric anthrosols). This assertion is also consistent with the relatively dense settlement pattern in these areas (Vining, 2018), which would have been unlikely in case of regular flooding, making it more likely that these structures are related to local farming and canal maintenance activities.

The later Lambayeque to Inka occupations generally follow these earlier Moche settlement and irrigation patterns (Clément, 2017; Netherly, 1984), but expand them with more lateral canals and even massive aqueducts to carry larger volumes of water to more distant areas. These latter engineering structures include the Ascope canal and aqueduct to the north (this study; Clément, 2017; Huckleberry et al., 2017), the operation of which extends through the entire Late Intermediate period (Fig. S4), as well as the Chimu Chicama-Moche Intervalley canal to the south that sought to divert water across river valleys (Farrington, 1983; Kus, 1984; Ortloff, 2010; Ortloff et al., 1983, 1982). Such infrastructure reflects human demographic and urban growth in the valley, as observed with settlements at the Cerro El Sapo (Figs. 1 and S6) in the Pampa de San Jose (Pozorski, 1987). These developments are associated with the expansion of arable fine-grained soils, now primarily driven by anthropogenic diversions of river water and sediment (e.g., Hesse and Baade, 2009).

7. Summary and conclusions

Here we link local geology and Holocene paleoenvironmental change in the Chicama River valley to the area's major culture transformation from a maritime to agriculture-dominated economy, culminating with the Moche civilization ~1.5 ka (~500 CE)

(Dillehay, 2017). Large exposures of Chicama-formation mudstones, regionally unique to the Chicama River basin (Fig. 2), yield a high fraction of fine-grained sediments to the lower valley. This resource of silt-sized sediment, plus a stabilizing sea level and amelioration of the strictly arid climate (i.e., a modest increase in wetness), all helped facilitate significant landscape and cultural transformations beginning ~5 ka. Paleoenvironmental conditions at this time favored the expansion of wetlands and local small-plot farming (*camellones*) during the late Preceramic. The emergence of fired-clay pottery and larger pottery vessels (*tinajas*) during the subsequent Formative period ~3.5 ka (~1500 BCE) reflect the need for food storage driven by excess agricultural production. This increase in production from ~5–3.5 ka grew primarily from the natural expansion of arable floodplain associated with increased wet phases and overbank river sedimentation. Aggradation of the floodplain above the water-table at this time improved soil drainage and reduced the need for less-efficient *camellones*-style agriculture. Start of the Formative period also marks a major shift in monument construction from the cobble-stone structure of Preceramic times to the purely adobe-brick architecture that began with the Cupisnique and peaked with the Moche pyramids (e.g., Huaca Cao Viejo). The use of adobe as a major building material would have been greatly limited prior to the late Holocene deposition of fine-grained floodplain sediments.

These natural paleoenvironmental trends and trailing human responses are reversed by the late Early Intermediate Period and Middle Horizon from ~1.5–1.0 ka (~500–1000 CE). By this time, the Chicama valley has become heavily engineered with an extensive irrigation canal system that comprised 100s of kilometers of water diversions from the Chicama River. As importantly as diverting water for agricultural production, the canals also diverted fine-grained sediments that helped to significantly expand arable land in the Chicama valley. These anthropogenic soils, referred to as irragric anthrosols, extend up to 20 km away from the Chicama River channel. There is no evidence that the Chicama River supported significant distributaries that would have been required to naturally deliver sediment to these distal areas. In the absence of such distributaries, the observed range of floodplain sediments must have been facilitated by the extensive and partially preserved canal system of the Moche and later cultures. These water diversions would have been the primary conduits for fine-grained sediment delivery to an otherwise remote, gravelly desert surface. And, if we assume a typical exponential decay of natural overbank sedimentation, then $\geq$50% of the arable surface in Chicama valley may be anthropogenically built through irrigation canal system. The Moche culture was not only taking full advantage of natural environmental change to expand agriculture, and presumably wealth and power, but also enhancing landscape conversion from coarse-grained desert outwash to fine-grained arable floodplain.

In whole, we find that the necessary technologies (e.g., cultigens, ceramics, adobe) appear either well before or contemporaneous with their need, suggesting that a limiting factor to cultural advancement was not the technology itself but rather the natural resources and paleoenvironmental conditions needed to fuel their demand. Social drivers undoubtedly played a role as well, but at present there is little evidence as to what such social circumstances may have been. Nevertheless, it is clear that once the natural floodplain stabilized and expanded during the later Preceramic period, the regional culture shifts from a maritime to agricultural economy with the emergence of adobe monument construction. These transformations are commensurate with massive water engineering structures and a trend toward increased urbanism, social complexity, and population. Such trends in the lower Chicama valley culminated with the Moche culture and its construction of the grand pyramids of El Brujo. It is not clear whether subsequent declines leading toward the Colonial period were influenced by extreme climate variations (e.g., Nials et al., 1979) or other natural or cultural strife (e.g., Moseley, 1983).

Environmental engineering continues today, with farmers in the Moche and Chicama valleys expanding arable lands into local dune complexes and onto the lower slopes of the Andean foothills. In dune settings, they direct floodwaters into the dune's swales (i.e., depressions) by way of simple excavated canals, with the flowing water readily transporting the sands and leveling the surface, while simultaneously enriching it with river-derived silts. Other desert lowlands have been intentionally flooded to support small xeric forests and lagoons, which ultimately develop more fertile soils suitable for agricultural expansion, as seen today in the Jequetepeque Valley (Sabogal, 2016). The presence of archaeological remains in these areas, in the form of ceramics, small canals, and grinding stones, suggest that similar activities took place in the prehispanic past.

Data availability

Data that informed this study are either included in the current manuscript or can be found in the edited book by Dillehay (2017) and its associated website https://my.vanderbilt.edu/huacaprieta/.

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Appendix A. Supplementary data

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References

Aitken, M.J., 1998. An Introduction to Optical Dating: the Dating of Quaternary Sediments by the Use of Photon-Stimulated Luminescence. Oxford University Press, Oxford, UK.

Allison, M.A., Kuehl, S.A., Martin, T.C., Hassan, A., 1998. Importance of flood-plain sedimentation for river sediment budgets and terrigenous input to the oceans: insights from the Brahmaputra-Jamuna River. Geology 26, 175–178. https://doi.org/10.1130/0091-7613(1998)026<0175:IOFPSF>2.3.CO;2.

Andrus, C.F.T., Hodgins, G.W.L., Sandweiss, D.H., Crowe, D.E., 2005. Molluscan radiocarbon as a proxy for El Niño-related upwelling variation in Peru. In: Mora, G., Surge, D. (Eds.), Isotopic and Elemental Tracers of Cenozoic Climate Change: Geological Society of America Special Paper 395, pp. 13–20. https://doi.org/10.1130/2005.2395(02).

Asselman, N.E.M., Middelkoop, H., 1995. Floodplain sedimentation: quantities, patterns and processes. Earth Surf. Process. Landforms 20, 481–499.

Baade, J., Hesse, R., 2008. An overlooked sediment trap in arid environments: ancient irrigation agriculture in the coastal desert of Peru. In: Sediment Dynamics in Changing Environments: IAHS Publication 325. IAHS Press, Christchurch, New Zealand, pp. 375–382.

Billman, B., Huckleberry, G., 2008. Deciphering the politics of prehistoric el Niño events on the north coast of Peru. In: Sandweiss, D.H., Quilter, J. (Eds.), El Niño: Catastrophism, and Culture Change in Ancient America. Dumbarton Oaks Research Library and Collection, Washington, DC, pp. 111–138.

Bird, J.B., 1948. America's oldest farmers. Nat. Hist. 57, 296–303.

Bird, J.B., Hyslop, J., Skinner, M.D., 1985. The preceramic excavations at the Huaca Prieta, Chicama valley, Peru. Anthropol. Pap. Am. Mus. Nat. Hist. 62, 294.

Caramanica, A., Koons, M.L., 2016. Living on the edge: pre-Columbian habitation of the desert periphery of the Chicama valley, Perú. In: Contreras, Daniel (Ed.), The Archaeology of Human-Environment Interactions – Strategies for Investigating Anthropogenic Landscapes, Dynamic Environments, and Climate Change in the Human Past. Routledge, New York, pp. 155–178.

Cerpa, L.M., Bissig, T., Kyser, K., McEwan, C., Macassi, A., Rios, H.W., 2013. Lithologic

controls on mineralization at the Lagunas Norte high-sulfidation epithermal gold deposit, northern Peru. Miner. Depos. 48, 653–673. https://doi.org/10.1007/s00126-013-0455-6.
Chapdelaine, C., 2011. Recent advances in Moche archaeology. J. Archaeol. Res. 19, 191–231. https://doi.org/10.1007/s10814-010-9046-6.
Chauchat, C., Galvez, C., Briceño, J., Uceda, S., 1998. Sitios arqueológicos de la zona de Cupisnique y margen derecha del valle de Chicama. Instituto Nacional de Cultura, Trujillo.
Clément, C., 2017. The oasis of the Chicama valley: water management from the Chimú to the Spaniards (eleventh to seventeenth Century AD) on the north coast of Peru. In: Lavie, E., Marshall, A. (Eds.), Oases and Globalization. Springer Geography, pp. 73–88.
Dillehay, T., Kolata, A.L., Pino, M., 2004. Pre-industrial human and environment interactions in northern Peru during the late Holocene. Holocene 14, 272–281. https://doi.org/10.1191/0959683604hl704rp.
Dillehay, T.D., 2017. Where the Land Meets the Sea: Fourteen Millennia of Human History at Huaca Prieta, Peru. University of Texas Press, Austin, TX.
Dillehay, T.D., 2001. Town and Country in late Moche times: a view from two northern valleys. Stud. Hist. Art 63, 258–283.
Dillehay, T.D., Bonavia, D., Goodbred, S., Pino, M., Vasquez, V., Tham, T.R., Conklin, W., Splitstoser, J., Piperno, D., Grobman, A., Levi-lazzaris, G., Moreira, D., Tung, T., Titelbaum, A., Verano, J., Adovasio, J., Cummings, L.S., Bear, P., Dufour, E., Tombret, O., Ramirez, M., Beavins, R., DeSantis, L., Rey, I., Mink, P., Maggard, G., Franco, T., 2012a. Chronology, mound-building and environment at Huaca Prieta, coastal Peru, from 13 700 to 4000 years ago. Antiquity 86, 48–70. https://doi.org/10.1017/S0003598X00062451.
Dillehay, T.D., Bonavia, D., Goodbred, S.L., Pino, M., Vásquez, V., Tham, T.R., 2012b. A late Pleistocene human presence at Huaca Prieta, Peru, and early Pacific Coastal adaptations. Quat. Res. 77, 418–423. https://doi.org/10.1016/j.yqres.2012.02.003.
Dillehay, T.D., Eling, H.H., Rossen, J., 2005. Preceramic irrigation canals in the Peruvian Andes. Proc. Natl. Acad. Sci. U.S.A. 102, 17241–17244. https://doi.org/10.1073/pnas.0508583102.
Dillehay, T.D., Goodbred, S., Pino, M., Vásquez Sánchez, V.F., Tham, T.R., Adovasio, J., Collins, M.B., Netherly, P.J., Hastorf, C.A., Chiou, K.L., Piperno, D., Rey, I., Velchoff, N., 2017. Simple technologies and diverse food strategies of the late Pleistocene and early Holocene at Huaca Prieta, coastal Peru. Sci. Adv. 3, e1602778 https://doi.org/10.1126/sciadv.1602778.
Dillehay, T.D., Kolata, A.L., 2004. Long-term human response to uncertain environmental conditions in the Andes. Proc. Natl. Acad. Sci. U.S.A. 101, 4325–4330. https://doi.org/10.1073/pnas.0400538101.
Dillehay, T.D., Rossen, J., Andres, T.C., Williams, D.E., 2007. Preceramic adoption of peanut, squash, and cotton in northern Peru. Science 316, 1890–1893. https://doi.org/10.1126/SCIENCE.1141395.
Driessen, P., Deckers, J., Spaargaren, O., Nachtergaele, F., 2001. Lecture Notes on the Major Soils of the World (No. 94). Food and Agriculture Organization (FAO), Rome.
Etayo-Cadavid, M.F., Andrus, C.F.T., Jones, K.B., Hodgins, G.W.L., Sandweiss, D.H., Uceda-Castillo, S., Quilter, J., 2013. Marine radiocarbon reservoir age variation in Donax obesulus shells from northern Peru: late Holocene evidence for extended El Nino. Geology 41, 599–602. https://doi.org/10.1130/G34065.1.
Farrington, I.S., 1983. The design and function of the intervalley canal: comments on a paper by Ortloff, Moseley, and Feldman. Am. Antiq. 48, 360–375. https://doi.org/10.2307/280458.
Gálvez, C., Runcio, M.A., 2015. Occupation, mobility and subsistence in the desert on the right bank of the Chicama Valley, North Coast of Peru. Archaeobios 9, 246–268.
Goodbred, S.L., Beavins, R., Ramirez, M., Pino, M., Sawakuchi, A.O., Latorre, C., Dillehay, T.D., Bonavia, D., 2017. Holocene geology and paleoenvironmental history of the lower Chicama valley. In: Dillehay, T.D. (Ed.), Where the Land Meets the Sea - Fourteen Millennia of Human History at Huaca Prieta, Peru. University of Texas Press, pp. 48–87.
Haas, J., Pozorski, S.G., Pozorski, T.G., 1987. The Origins and Development of the Andean State. Cambridge University Press.
Hesse, R., Baade, J., 2009. Irrigation agriculture and the sedimentary record in the Palpa Valley, southern Peru. Catena 77, 119–129. https://doi.org/10.1016/j.catena.2008.09.003.
Hesse, R., Baade, J., 2007. Early horizon anthrosols in the Palpa valley, southern Peru. Geo-oko 28, 160–185.
Huckleberry, G., Caramanica, A., Quilter, J., 2017. Dating the Ascope canal system: competition for water during the late Intermediate period in the Chicama valley, north coast of Peru. J. Field Archaeol. 1–14 https://doi.org/10.1080/00934690.2017.1384662.
Institute of Geology and Minerals, 1975. Geological Map of Peru. Ministry of Energy and Mining.
Jahn, R., Blume, H.P., Asio, V.B., Spaargaren, O., Schad, P., 2006. Guidelines for Soil Description, fourth ed. Food and Agriculture Organization (FAO), Rome.
Kus, J.S., 1984. The Chicama-Moche canal: failure or success? An alternative explanation for an incomplete canal. Am. Antiq. 49, 408–415.
Lagos, P., Silva, Y., Nickl, E., Mosquera, K., 2008. El Niño-related precipitation variability in Perú. Adv. Geosci. 14, 231–237.
Loubere, P., Creamer, W., Haas, J., 2013. Evolution of the El Nino-Southern Oscillation in the late Holocene and insolation driven change in the tropical annual SST cycle. Glob. Planet. Chang. 100, 129–144. https://doi.org/10.1016/j.gloplacha.2012.10.007.
Makou, M.C., Eglinton, T.I., Oppo, D.W., Hughen, K.a., 2010. Postglacial changes in El Nino and La Nina behavior. Geology 38, 43–46. https://doi.org/10.1130/G30366.1.
Manners, R.B.B., Magilligan, F.J.J., Goldstein, P.S.S., 2007. Floodplain development, El Niño, and cultural consequences in a hyperarid Andean environment. Ann. Assoc. Am. Geogr. 97, 229–249.
Milliman, J.D., Farnsworth, K.L., 2011. River Discharge to the Coastal Ocean: A Global Synthesis. Cambridge University Press.
Mollier-Vogel, E., Leduc, G., Böschen, T., Martinez, P., Schneider, R.R., 2013. Rainfall response to orbital and millennial forcing in northern Peru over the last 18 ka. Quat. Sci. Rev. 76, 29–38. https://doi.org/10.1016/j.quascirev.2013.06.021.
Morera, S.B., Condom, T., Crave, A., Steer, P., Guyot, J.L., 2017. The impact of extreme El Niño events on modern sediment transport along the western Peruvian Andes (1968–2012). Sci. Rep. 7, 11947. https://doi.org/10.1038/s41598-017-12220-x.
Moseley, M.E., 1983. The good old days were better: agrarian collapse and tectonics. Am. Anthropol. 85, 773–799.
Moseley, M.E., 1975. Chan Chan: Andean alternative of the preindustrial city. Science 187, 219–225. https://doi.org/10.1126/science.187.4173.219.
Moy, C.M., Seltzer, G.O., Rodbell, D.T., Anderson, D.M., 2002. Variability of El Niño/southern oscillation activity at millennial timescales during the Holocene epoch. Nature 420, 162–165. https://doi.org/10.1038/nature01194.
Murray, A.S., Wintle, A.G., 2003. The single aliquot regeneration dose protocol: potential for improvements in reliability. Radiat. Meas. 37, 377–381.
Nesbitt, J., 2016. El Niño and second-millennium BC monument building at Huaca Cortada (Moche valley, Peru). Antiquity 90, 638–653. https://doi.org/10.15184/aqy.2016.70.
Netherly, P.J., 1984. Management of late Andean irrigation systems on the north coast of Peru. Am. Antiq. 49, 227–254.
Nials, F.L., Deed, E.E., Moseley, M.E., Pozorski, S.G., Pozorski, T.G., Feldman, R., 1979. El Nino: the catastrophic flooding of coastal Peru. Field Museum Nat. Hist. Bull. 50, 4–14.
Nicholas, A.P., Walling, D.E., 1997. Modelling flood hydraulics and overbank deposition on river floodplains. Earth Surf. Process. Landforms 22, 59–77.
Ortloff, C., Moseley, M., 2012. 2600-1800 BCE Caral – environmental change at a late archaic period site in north central coast Peru. Ñawpa Pacha 32, 189–206. https://doi.org/10.1179/naw.2012.32.2.189.
Ortloff, C.R., 2010. Canal systems of pre-Columbian Peru: the Chicama-Moche intervalley canal and the Moche intravalley irrigation system, 800-1450 CE. In: Water Engineering in the Ancient World: Archaeological and Climate Perspectives on Societies of Ancient South America, the Middle East, and South-East Asia. Oxford University Press, pp. 11–84.
Ortloff, C.R., Moseley, M.E., Feldman, R.A., 1983. The Chicama-Moche intervalley Canal : social explanations and physical paradigms. Am. Antiq. 48, 375–389.
Ortloff, C.R., Moseley, M.E., Feldman, R.A., 1982. Hydraulic engineering aspects of the Chimu Chicama-Moche intervalley canal. Am. Antiq. 47, 572–595.
Patterson, T.C., Moseley, M.E., 1968. Late preceramic and early ceramic cultures of the central coast of Peru. Ñawpa Pacha 6, 115–133. https://doi.org/10.1179/naw.1968.6.1.006.
Pozorski, Thomas, 1987. Changing priorities within the Chimu state: the role of irrigation agriculture. In: Haas, J., Pozorski, S., Pozorski, T. (Eds.), The Origins and Development of Andean State. Cambridge University Press, pp. 111–120.
Prescott, J.R., Hutton, J.T., 1994. Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations. Radiat. Meas. 23, 497–500. https://doi.org/10.1016/1350-4487(94)90086-8.
Prieto, G., Quilter, J., Dillehay, T., 2016. Early “Guañape” ceramics from the north coast of Peru: new data from Gramalote (Moche valley) and Huaca Prieta (Chicama valley). In: Proceedings of the 81st Annual Meeting of the Society for American Archaeology (tDAR id: 402912).
Rein, B., Lückge, A., Reinhardt, L., Sirocko, F., Wolf, A., Dullo, W.-C., 2005. El Niño variability off Peru during the last 20,000 years. Paleoceanography 20, PA4003. https://doi.org/10.1029/2004PA001099.
Riedinger, M.A., Steinitz-Kannan, M., Last, W.M., Brenner, M., 2002. A ~6100 ^{14}C yr record of El Niño activity from the Galápagos islands. J. Paleolimnol. 27, 1–7.
Rodbell, D., Seltzer, G., Anderson, D., Abbott, M., Enfield, D., Newman, J., 1999. An approximately 15,000-year record of El Nino-driven alluviation in southwestern Ecuador. Science 283, 516–520.
Romero, C.C., Baigorria, G.a., Stroosnijder, L., 2007. Changes of erosive rainfall for El Niño and La Niña years in the northern Andean highlands of Peru. Clim. Change 85, 343–356. https://doi.org/10.1007/s10584-007-9301-0.
Sabogal, J., 2016. Agricultura Tradicional Yunga. Sociedad Geográfica de Lima, Lima, Peru.
Sadler, P.M., 1981. Sediment accumulation rates and the completeness of stratigraphic sections. J. Geol. 89, 569–584.
Salvatteci, R., Gutierrez, D., Field, D., Sifeddine, A., Ortlieb, L., Bouloubassi, I., Boussafir, M., Boucher, H., Cetin, F., 2014. The response of the Peruvian Upwelling Ecosystem to centennial-scale global change during the last two millennia. Clim. Past 10, 715–731. https://doi.org/10.5194/cp-10-715-2014.
Sandweiss, D.H., 1986. The beach ridges at Santa, Peru: El Nino, uplift, and prehistory. Geoarchaeology 1, 17–28.
Sandweiss, D.H., Maasch, K.A., Belknap, D.F., Richardson, J.B., Rollins, H.B., 1998. Discussion of: Lisa E. Wells, 1996. The Santa beach ridge complex. J. Coast. Res. 14, 367–373.
Sandweiss, D.H., Maasch, K.A., Burger, R.L., Richardson III, J.B., Rollins, H.B., Clement, A., 2001. Variation in Holocene El Niño frequencies: climate records

and cultural consequences in ancient Peru. Geology 29, 603–606. https://doi.org/10.1130/0091-7613(2001)029<0603:VIHENO>2.0.CO.

Sandweiss, D.H., Richardson III, J.B., Reitz, E.J., Rollins, H.B., Maasch, K.A., 1996. Geoarchaeological evidence from Peru for a 5000 years B.P. onset of El Niño. Science 273, 1531–1533. https://doi.org/10.1126/science.273.5281.1531.

Sandweiss, D.H., Solís, R.S., Moseley, M.E., Keefer, D.K., Ortloff, C.R., 2009. Environmental change and economic development in coastal Peru between 5,800 and 3,600 years ago. Proc. Natl. Acad. Sci. 106, 1359–1363. https://doi.org/10.1073/pnas.0812645106.

Stuiver, M., Reimer, P.J., Reimer, R.W., 2019. Calib 7.1.

Swanson, K.M., Watson, E., Aalto, R., Lauer, J.W., Bera, M.T., Marshall, A., Taylor, M.P., Apte, S.C., Dietrich, W.E., 2008. Sediment load and floodplain deposition rates: comparison of the Fly and Strickland rivers, Papua New Guinea. J. Geophys. Res. Earth Surf. 113, 2–17. https://doi.org/10.1029/2006JF000623.

Tapley Jr., T.D., Waylen, P.R., 1990. Spatial variability of annual precipitation and ENSO events in western Peru. Hydrol. Sci. J. 35, 429–446. https://doi.org/10.1080/02626669009492444.

Tote, C., Govers, G., Van Kerckhoven, S., Filiberto, I., Verstraeten, G., Eerens, H., 2011. Effect of ENSO events on sediment production in a large coastal basin in northern Peru. Earth Surf. Process. Landforms 36, 1776–1788. https://doi.org/10.1002/esp.2200.

Vining, B.R., 2018. Cultural Niche construction and remote sensing of ancient anthropogenic environmental change in the north coast of Peru. J. Archaeol. Method Theory 25, 559–586. https://doi.org/10.1007/s10816-017-9346-y.

Watson, R.P., 1979. Water Control and Land Use on the Arid North Coast of Peru: Prehispanic Agricultural Systems in the Chicama Valley. The University of Texas, Austin.

Waylen, P.R., Caviedes, C.N., 1986. El Niño and annual floods on the north Peruvian littoral. J. Hydrol. 89, 141–156. https://doi.org/10.1016/0022-1694(86)90148-4.

Wells, L.E., 1996. The Santa beach ridge complex: sea-level and progradation history of an open gravel coast in central Peru. J. Coast. Res. 12, 1–17.

Wells, L.E., 1990. Holocene history of the El Niño phenomenon as recorded in flood sediments of northern coastal Peru. Geology 18, 1134–1137.

Wells, L.E., 1987. An Alluvial record of El Niño events from northern coastal Peru. J. Geophys. Res. 92, 14463–14470.

Wells, L.E., Noller, J.S., 1999. Holocene coevolution of the physical landscape and human settlement in northern coastal Peru. Geoarcheology 14, 755–789.

Winsborough, B.M., Shimada, I., Newsom, L.A., Jones, J.G., Segura, R.A., 2012. Paleoenvironmental catastrophies on the Peruvian coast revealed in lagoon sediment cores from Pachacamac. J. Archaeol. Sci. 39, 602–614. https://doi.org/10.1016/j.jas.2011.10.018.