Environmental change and economic development in coastal Peru between 5,800 and 3,600 years ago

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Between ≈5,800 and 3,600 cal B.P. the biggest architectural monuments and largest settlements in the Western Hemisphere flourished in the Supe Valley and adjacent desert drainages of the arid Peruvian coast. Intensive net fishing, irrigated orchards, and fields of cotton with scant comestibles successfully sustained centuries of increasingly complex societies that did not use ceramics or loom-based weaving. This unique socioeconomic adaptation was abruptly abandoned and gradually replaced by societies more reliant on food crops, pottery, and weaving. Here, we review evidence and arguments for a severe cycle of natural disasters—earthquakes, El Niño flooding, beach ridge formation, and sand dune incursion—at ≈3,800 B.P. and hypothesize that ensuing physical changes to marine and terrestrial environments contributed to the demise of early Supe settlements.

El Niño | geoarchaeology | Preceramic collapse | Mid-Holocene

Adapted to a coastal desert broken by verdant river valleys and fronted by a productive near-shore fishery, the north central coast of Peru was very different from other centers of ancient development. Although characterized by complex social organization and large centers dominated by stone-faced temple mounds, early coastal Peruvians did not produce pottery or loom-woven cloth. Animal protein came entirely from the sea, not from domesticated or terrestrial animals. Irrigated farming focused on cotton; among the remains of food crops are the tree fruits *guayaba* (*Psidium guajava*) and *pacae* (*Inga feuillei*), *achira* (*Canna edulis*, a root crop), beans, squash, sweet potato, avocado, and peanut. This unique evolutionary experiment thrived for ≈2 millennia (the Late Preceramic Period, *ca.* 5,800–3,800/3,600 cal B.P.) in the Río Supe and adjacent desert drainages (1–3) (Fig. 1). Ending abruptly, this Late Preceramic society was gradually replaced by more typical or normative economies that emphasized plant and animal domesticates while also producing pottery and woven goods.

Eustatic sea level stabilization between 6,000 and 7,000 years ago set the stage for the Late Preceramic developments, both natural and cultural. Rising sea level had inhibited the establishment of sandy beaches, beach ridge formation, and consequent inland sand dune deposition while leading to the development of large, protected bays. When sea level transgression ceased in the Mid-Holocene, this geophysical configuration changed significantly. Approximately 5,800 years ago, the return of El Niño (the warm phase of the El Niño–Southern Oscillation phenomenon, or ENSO) after a hiatus of several millennia (4, 5) coincided with emplacement of the modern fishery dominated by small schooling fish (6, 7) and of the contemporary coastal regime dominated by powerful north-flowing longshore currents and strong daily winds blowing inland NNE off the sea. Establishment of these conditions created the beach ridge and sand dune geomorphic regime that has characterized the north coast of Peru since the Mid-Holocene (e.g., ref. 8). In this tectonically active region, seismic activity produces abundant unconsolidated sediment from earthquake-triggered landslides. Subsequent ENSOs bring torrential rain to the vegetationless desert landscape, transporting massive quantities of the loose sediment into the rivers and down to the coast. ENSOs that follow large earthquakes move particularly large quantities of material. After initial delta formation and sediment spreading to form subsea ridges composed of finer particles along the shoreline, normal longshore littoral processes further develop the sediment into coast-parallel, linear beach ridges (9). Four decades of high-altitude time-lapse images, spanning a major earthquake, 2 El Niño flood events, beach ridge formation, and sand dune incursion have revealed these processes in action during the 20th century at the Santa River (9° S) (8), demonstrating that transport of massive quantities of sediment to the coast leads to beach ridge formation and ultimately to episodic sand dune invasions of inland areas. This ridge-and-dune regime, and the earthquakes and floods that drive it, can have severe consequences for humans in this extreme desert environment.

Early Disasters in Supe—Earthquakes, Floods, and Sand

The north central coast is one of the most seismically active regions on earth, with earthquakes produced by the subduction of the offshore Nasca Plate beneath the South American Plate. Historically, large and great earthquakes [magnitude (M) > 7.5] have occurred along this segment of the plate boundary approximately twice every century on average (10), and similar occurrence rates are expectable prehistorically. Damage of probable earthquake origin is evident at a number of structures excavated by Shady (1, 11, 12); here, we summarize the Late Preceramic cases of 2 platform mounds at 2 different Río Supe sites: one coastal (Aspero) and the other 23 km inland (Caral). The most spectacular wreckage transpired during the penultimate use of the Pirámide Mayor, the main temple platform at Caral, a 66-ha interior monumental center. At the time of impact, the platform base measured ≈170 m by 150 m and rose in steps to a ≈19- to 30-m-high flat summit covered by masonry walled courts, compartments, rooms, and corridors. Pervasive damage to almost all summit structures, expressed in fallen, tilted, or offset walls and displaced floors, is unusually well preserved because the wreckage was not repaired but filled over during final use. In terms of core damage, a large and deep-seated rotational landslide displaced a huge volume of construction material in the southwest quadrant of the temple itself. Near the summit of the temple, structures were disturbed by back-rotational movement in the scarp area of the landslide block (Fig. 2), whereas low down on the south face, the landslide caused a wide area of the

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GEOLOGY

ANTHROPOLOGY

Fig. 1. Map showing location of Caral, north central coast, and major beach ridge sets in northern Peru. The Medio Mundo ridge is coincident with the North Central Coast, from 10.5 to 11.2 S latitude.

pyramid to bulge outward. This bulge was evidently repaired, and the face smoothed over when the summit damage was filled over.

Landslides of this type can be triggered by a variety of causes, but in this hyperarid environment core construction materials of the Pirámide Mayor were presumably dry, implicating an earthquake trigger for this landslide-induced structural collapse. Landslides of the Caral type can occasionally be triggered by earthquakes of only moderate size, but they are typically triggered by the relatively severe and long-lasting ground shaking associated with large earthquakes (13) that are typical of the subduction zone along Supe region coastline (10).

Highly probable earthquake damage also appears in at least 1 of 6 mounds at the 19-ha coastal complex of Aspero. This maritime settlement occupied a northern rocky peninsula forming the headlands of a large crescent bay that extended >3.8 km inland from the modern shoreline in the Mid-Holocene, when sea level transgression abated. The Aspero "Sacrificios" platform (14) measured ≈40 × 34 m at the base and was 10 m high when it was affected or hit. Common people then settled atop the former temple and dumped substantial garbage on its unrepaired surface and sides. The masonry sides and fill exhibit fissures with displacements of as much as 15 cm, whereas the central ceremonial stairway suffered a large near-vertical crack with several centimeters of lateral separation (Fig. 3). As at Caral, the most likely cause of this damage was seismic shaking.

If the Late Preceramic damage at both sites was due to a single seismic event, then this was a relatively large earthquake, estimated at M ≥ 7.2 [see supporting information (SI) *Text*], as is typical of the subduction zone offshore (10). If 2 separate events were involved, the one damaging Caral was probably M 7.2 or larger, and the one damaging Aspero was M 6.9 or larger (see *SI Text*). In any case, seismically induced landslides almost certainly extended over large areas (≈5,500 km^2 for an earthquake of M 7.2) (15) to generate mass wasting of the steep, rocky sides of the Supe Valley and adjacent drainages, resulting in

Fig. 2. Earthquake-damaged and back-rotated structures on the summit of Pirámide Mayor, the main temple platform at Caral. Back rotation is associated with scarp of a large and deep-seated landslide displacing a large volume of material in the southwest quadrant of the temple. Landslide is inferred to have been caused by earthquake shaking.

copious amounts of loose sediment available for transport by postearthquake processes initiated by El Niño-induced rainfall and runoff.

At Aspero, Terminal Preceramic evidence of flooding is also present ≈225 m north of the Sacrificios temple, where people living in simple quarters occupied lower areas of a small topographic basin. In this residential area there are 2 thin layers of silt with ripple marks and other sedimentary structures indicative of significant flooding of a kind historically attributable to El Niño-induced rainfall (Fig. 4). The first inundation transpired atop dense habitation remains and interrupted the occupation. The flood deposit is well preserved because it was covered by ≈15 cm of aeolian sands with little archaeological debris. The aeolian stratum was capped by silt from the second flood after which there is no evidence of continuing occupation or of flooding or sand incursion of comparable magnitude. Because the catchment basin is very small, flooding must have resulted from very substantial local precipitation. Inundation of the residential area is not stratigraphically linked to the Sacrificios temple where flooding may or may not have prompted people to live atop it. If it did, this would be the earliest case of the ethnohistorically (16) and ethnographically (D.H.S., personal observation, northern Peru, 1989–1998) documented pattern of people moving onto *huacas* (temple mounds) during El Niño flooding.

When Aspero was first settled, it lay on a jutting headland on the north side of the large Mid-Holocene Supe bay. The constant onshore winds would have passed over water right up to the edge of the site, so there was no sand to entrain. The lack of windblown sand in excavations predating the first flood deposit is consistent with this early configuration. In contrast, the terminal Preceramic aeolian sand incursion could transpire only if there was an upwind sediment source due to infilling of the former bay. Daily sand blasting makes it intolerable to live in active dune areas, and this curtailed reoccupation of the Aspero residential area. Substantial aeolian sediment blew over the reoccupied summit of the Sacrificios platform and accumulated on its leeward side covering occupation deposits. Although sand survives today only in sheltered areas, it likely swept over the entire settlement as evidenced by 1944 aerial photographs, which show windward remnants of dune formations on the adjacent valley floor that is now leveled for agriculture. Thus, stratigraphically, sand incursion represents the concluding catastrophe that

Fig. 3. Near-vertical cracks with several centimeters of lateral separation inferred to be due to earthquake damage, central ceremonial stairway, Sacrificios platform, Aspero.

affected Aspero after prior El Niño flooding and earlier earthquake impact.

Inland from Aspero, aeolian sands invading the middle Supe drainage originated from coastal beaches to the SSW along the Medio Mundo shore line. From these playas abundant sediment blew inland against and over the low mountains on the south side of the Río Supe. The erosive power of large rivers tends to confine sand sea incursions to southern sides of valleys. However, expansive dune remnants on both sides of the Río Supe demonstrate that this modest river was completely bridged by sand seas. Valley burial was pervasive and extended upstream and inland to Caral where a large linear dune remnant is now gradually deflating, as are other inundated areas.

At Caral itself, we observed substantial sand deposits that cap the final Preceramic occupation and are themselves covered by early ceramic-bearing midden, probably dating to the Initial Period (3600–2800 cal B.P.) based on presence of locally extinct *Mesodesma donacium* clams and *Choromytilus chorus* mussels (17). In 2 nearby Late Preceramic sites (Chupacigarro and Miraya) located, like Caral, on the south side of the valley, sand deposits underlie their final prepottery construction phases. These last structures entailed low labor volume relative to earlier building episodes.

If this massive sand invasion were a single, long-term process with early expressions at Aspero, Caral, and adjacent sites, then

Fig. 4. Terminal Preceramic evidence of flooding in residential quarters at Aspero. Scale, marked in centimeters and inches, spans deposit of aeolian sand ≈15 cm thick. Stratigraphically below is habitation floor covered by a thin layer of silt exhibiting ripple marks and other sedimentary structures indicative of flood deposition. Stratigraphically above the aeolian sand is another layer of silt, also exhibiting ripple marks and sedimentary structures indicative of flood deposition. No evidence of occupation is present at this locality after the second flood event. Both floods are inferred to have been caused by El Niño-induced rainfall.

farming and settlement would have been severely inhibited for centuries before the sand sheets dissipated due to a decline of source material and removal of existing deposits by subsequent wind and river erosion. Such a sand surge would have led to a massive decline in agricultural productivity and population, and permanent loss of the valley's power and prestige.

The Late Preceramic Abandonment

Recent research has shown that Late Preceramic temples of the north central coast were abandoned progressively, perhaps in abrupt stages, between 3,800 and 3,600 cal B.P. (1, 3). In the Huaura and Supe Valleys, the youngest date for Late Preceramic temple sites is ≈3,825 cal B.P. In the Pativilca and Fortaleza Valleys, termination dates range from 3,700 to 3,400 cal B.P., with most falling between 3,700 and 3,600 cal B.P. (3). The north central coast was never again a center for cultural florescence, although there are a small number of later pottery-bearing, Initial Period agricultural sites in the valleys as well as small sites of later epochs. What was different about the north central coast that led to the abandonment of Preceramic lifeways and the less robust presence of Initial Period centers here, as compared with valleys just north and south?

Medio Mundo

The entire coastline of the north central coast is fronted by a massive, sand and cobble beach ridge known as the Medio Mundo formation (Fig. 5). If Medio Mundo originated very late in Late Preceramic times, as is likely, then it would have influenced the ensuing cultural transition. Across >100 km of coastline, Medio Mundo sealed off the Mid-Holocene bays, transforming them into lagoons and sand flats that combined with new beaches in front of the ridge to pump copious amounts of sand into the aeolian transport system.

Applying the 20th century earthquake–flood–ridge–sand incursion disaster cycle described above to Medio Mundo, we hypothesize the following sequence of events: (*i*) The archaeologically detected earthquake and El Niño events at Caral and Aspero were significant contributors to initial construction of the massive Medio Mundo beach ridge through sediment deposition processes; (*ii*) the ridge sealed off the shallow Medio Mundo coastal coves and closed the Supe embayment that once extended >3 km inland from the modern shore. A similar but separate process occurred 250 km to the north, in the Santa Valley, which prograded up to 6 km between sea level stabilization at 6,000 cal B.P. and the present, with most progradation complete by ≈3,000 cal B.P. (18). Infilling of the shallow Medio

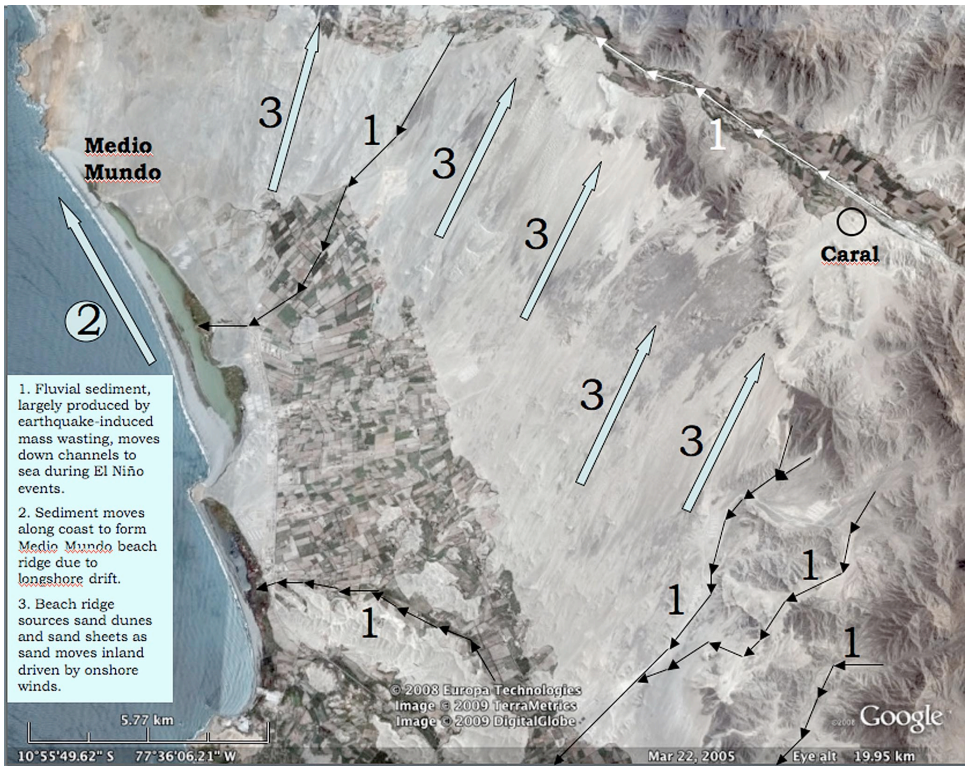

Fig. 5. Satellite image of the sediment cycle at Medio Mundo (adapted from GoogleEarth 2008).

Mundo bays and the deeper Supe Bay exposed sediment for aeolian entrainment, supplying sand for massive sand sheets that blew inland on the constant, strong, onshore breeze and swamped the irrigation systems and agricultural fields of the local farmers in coastal and midvalley environments; the ridge also substantially decreased the area available for near-shore fishing and gathering of mussels, clams, and other staples of the marine diet; (3) Driven by north-trending longshore drift, a Medio Mundo ridge initially created by sediment deposition from a major El Niño, or series of large El Niños, slowly extended from the southern to the northern extreme of the north central coast. As it formed, Medio Mundo thus impoverished both the coastal and valley resources that had sustained Preceramic development on the north central coast.

The Medio Mundo ridge has not been directly dated. However, we can constrain its formation date by examining the broader history of beach ridges along the northern coast of Peru. Medio Mundo could not have been deposited before sea level stabilization, so it is younger than ≈6,000 cal B.P. Given ridge-forming processes identified elsewhere in the region, El Niño must have been active for Medio Mundo to form; that provides a similar maximum limiting date of 5,800 cal B.P. The ≈3,000-year-long hiatus in El Niño activity preceding this date (4, 5) would have provided time for a large volume of sediment to build up in the north central coast valleys, available for transport to the coast with the resumption of El Niño events. The major beach ridge plains of northern Peru (Santa at 9° S, Piura at 5.5° S, Chira at 4.8° S, and Tumbes at 3.5° S) formed on relatively wider sectors of the continental shelf and each consists of 8–9 macroridges. Medio Mundo, running from 11.2° to ≈10.5° S, has only 1 macroridge. Although likely driven by the same processes as the northern ridges, Medio Mundo's history is evidently different, most likely resulting from a steeper offshore seabed slope than the other regions and the attenuation of El Niño with increasing latitude. The dated ridge plains in northern Peru are oldest in the north and become progressively younger toward the south: Chira originated at ≈4,250 cal B.P., Piura at ≈4,000 cal B.P., and Santa at ≈3,825 cal B.P. Following this trend, Medio Mundo would have formed at or slightly later than the Santa ridges, which is also the minimum age for Caral and the beginning of the Late Preceramic abandonment.

Conclusion

As Dillehay and Kolata (19) have written, "climate anomalies and other processes of environmental change of natural and anthropogenic origin have been affecting, and often disrupting, societies throughout history." These authors point to the synergistic effects of convergent events and detail such a case during the mid-first to mid-second millennia A.D. on Peru's north coast (see also ref. 20 for a detailed example of these processes in action in the same region during the 7th century A.D.). Here, we have presented a developing case study of similar interaction between multiple environmental events and emergent complex society. That the evolutionary trajectory of early Supe was derailed by synergies of convergent catastrophes is a testable hypothesis based on modern analogues. It is possible that some evidence of ancient catastrophes, such as seismic and ENSO damage, are conflations of several separate disasters. Fortunately, from littoral Aspero to inland Caral, there are multiple stratigraphic venues to date seismic shock, ENSO wash, and aeolian sand, thereby constraining their ages by radiocarbon and/or other techniques such as luminescence. Dating the Medio Mundo formation will come from coring the bays it closed off, leaving behind stranded shellfish "death assemblages."

Culturally, it is no coincidence that the Medio Mundo ridge is geographically coterminous with the 5-valley north central coast, which saw the rise of one of the earliest expressions of cultural complexity in the Americas. Built on a combination of fishing and agriculture, the dual economic bases of this society were equally vulnerable to the geomorphic consequences of Medio Mundo's formation.

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