Geoarchaeological Evidence from Peru for a 5000 Years B.P. Onset of El Niño

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For the tropical west coast of South America, where El Niño/Southern Oscillation (ENSO) is most pronounced, archaeological and associated paleontological deposits in northern Peru revealed a major climate change at about 5000 years before the present (yr B.P.). The data implied the presence of stable, warm tropical water as far south as 10°S during the early mid-Holocene (about 8000 to 5000 yr B.P.). These data suggest that ENSO did not occur for some millennia preceding 5000 yr B.P., when global and regional climate was warmer than today.

ENSO is characterized by interannual climate variability in the Pacific basin and beyond and by elevated sea surface temperatures in the eastern Pacific near western South America. Analyses of pollen from sites throughout the southwest Pacific basin have suggested that ENSO-like variability began only in the late Holocene (*1*, *2*). Unfavorable conditions and limited research on the desert coasts of Chile, Peru, and Ecuador have resulted in a lack of pollen data from this key region (*3*). Mid-Holocene sediments from nearshore cores, which might provide such a record, were either not deposited or were eroded (*4*), or have not yet been studied in detail (*5*). Quaternary soils along the Peruvian coast indicate long-term hyperaridity south of 12°S and much greater precipitation north of that point (*6*), but this phenomenon could be explained by quasiperiodic ENSO rain throughout the late Pleistocene and Holocene or by variation in annual rainfall. Archaeological and paleontological deposits could fill this gap in current knowledge of Holocene climatic conditions in South America. Initial studies of the Peruvian geoarchaeological record (*7*) suggest that ENSO did not occur for some period before 5000 yr B.P. We synthesized new geoarchaeological data from Peru that support the mid-Holocene onset of ENSO.

The presence or absence of ENSO is crucial in understanding the economies and development of past cultures wherever ENSO affects resource abundance and distribution. It is also important in the reconstruction of Holocene climate across the Pacific basin and in the determination of conditions under which an ENSO-dominated climate will arise.

Today, the coast of Peru south of 4°S is characterized by the warm temperate (hereafter "temperate") waters of the north-flowing Humboldt Current, with little seasonal variation except during quasiperiodic ENSO years. ENSO is expressed in Peru as an incursion of warm tropical (hereafter "tropical") waters with a consequent depression of the thermocline and temperatures ranging from 2°C to as much as 10°C warmer than the mean temperature of the Humboldt Current. During ENSO events, some tropical species of fish, crustaceans, and to a lesser degree, mollusks invade the Peruvian coast and survive for the duration of the event or, at most, for the lifespan of the ENSO-recruited cohorts in the case of the mollusks; at the same time, many temperate species retreat southward or suffer high mortality (*8*). Such short-term anomalies have been noted in archaeological faunal assemblages dating to the last 5000 years. In levels of the Salinar culture at Puemape (~2350 to 2050 yr B.P., at 7°30′S), the presence of some tropical species has been used as an indicator of ENSO events (*9*); at El Paraíso (~3750 to 3450 yr B.P., at 12°S), changing frequencies through time of temperate mollusk species reflect the effects of several ENSO events on local molluscan communities (*10*).

Faunal inventories at archaeological sites on the Peruvian coast dating from the first human occupation (~11,000 yr B.P.) to about 5000 yr B.P. demonstrated that warmer sea surface temperatures persisted north of 10°S (Tables 1 through 3 and Fig. 1). The archaeological record for this period is complicated by the effects of sea level rise (*11*). Where the continental shelf is wide, substantial shoreline transgression has occurred and ancient nearshore sites are now submerged. The early maritime sites have thus been discovered where the shelf is narrow (near Talara at 4°30′S and south of the Paracas Peninsula at 14°S). Elsewhere, preserved maritime sites first appear at 7000 yr B.P. when the sea level approached modern elevation. Near Talara, the Amotape campsites are surface scatters of lithic debris and tropical mangrove mollusks; radiocarbon dates on mangrove mollusk shells range from ~11,000 to 8000 yr B.P. (*12*). These species indicate that the climate was more tropical (warmer and wetter) than it is today, as do the avifauna and insect fauna found in the adjacent Talara Tar Seeps, which dated to approximately 14,000 yr B.P. (*13*). South of Paracas, early Peruvian maritime sites include Quebrada Jaguay (~11,000 to 7500 yr B.P.) and the Ring Site (~10,500 to 5000 yr B.P.). Excava-

Table 1. General characteristics of faunal assemblages from early (11,000 to 7000 yr B.P.), middle (7000 to 5000 yr B.P.), and late (5000 to 3500 yr B.P.) Preceramic sites in coastal Ecuador and Peru.

Site (latitude)	Age	Assemblage	Fauna analyzed	Reference
Las Vegas (2°15′S)	Early	Tropical	Vertebrate and invertebrate	(*30*)
Amotape (4°40′S)	Early	Tropical	Invertebrate	(*12*)
Siches/Siches (4°30′S)	Middle	Tropical	Invertebrate	(*14*)
Siches/Honda (4°30′S)	Late	Temperate	Invertebrate	(*14*)
Quebrada Chorrillos (6°00′S)	Middle	Tropical	Invertebrate	(*16*)
Avic 2 (6°00′S)	Late	Temperate	Invertebrate	(*16*)
Alto Salaverry (8°15′S)	Late	Temperate	Vertebrate and invertebrate	(*31*)
Los Morteros (8°40′S)	Late	Temperate	Invertebrate	(*32*)
Ostra (8°55′S)	Middle	Tropical	Vertebrate and invertebrate	(*33*)
Huaynuná (9°20′S)	Late	Temperate	Invertebrate	(*20*)
Almejas (9°30′S)	Middle	Tropical	Vertebrate and invertebrate	(*18*)
Paloma (12°30′S)	Middle	Temperate	Vertebrate and invertebrate	(*34, 35*)
Quebrada Jaguay (16°30′S)	Early	Temperate	Invertebrate	(*14*)
Ring Site (17°40′S)	Early/Middle	Temperate	Vertebrate and invertebrate	(*15*)

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tions at Quebrada Jaguay indicated that the molluscan assemblage was dominated by the temperate wedge clam *Mesodesma donacium* (*14*). The vertebrate and invertebrate fauna from the Ring Site were temperate taxa from top to bottom of the deposit (*15*).

Four maritime sites or complexes north of 10°S have been confidently dated at 7000 to 5000 yr B.P.: Siches (*12*, *14*), Quebrada Chorrillos (*16*), Ostra (*7*, *14*, *17*), and Almejas (*18*). The fauna recovered from each of these sites is dominated by tropical taxa that today characterize the waters north of 4°S. At Ostra, a stranded embayment had individuals of the same tropical molluscan species in living position (*7*). All of the above sites except Siches were abandoned by 5000 yr B.P. In each case, nearby sites containing temperate taxa were occupied shortly after that date: Honda complex sites, including the late component at the Siches type site (*14*, *19*), Avic 2 near Quebrada Chorrillos (*16*), Los Morteros near Ostra (*7*), and Huaynuná near Almejas (*20*).

The molluscan fauna at the Siches type site (PV 7-19) near Talara (4°30′S) change at about 5000 yr B.P. The basal level of area I, dated at 5790 ± 90 yr B.P., contains a purely tropical molluscan assemblage, as do all levels in area II, dated between ~6340 and 6680 yr B.P. The upper levels of area I, which date between ~5260 and 4780 yr B.P., have a mixed tropical and temperate assemblage.

Peruvian coastal sites located north of 10°S and older than 5000 yr B.P. consistently contain tropical marine taxa, whereas all sites south of 10°S and all post–5000 yr B.P. sites, regardless of latitude, contain temperate species. The proxy paleotemperature data for the Huascarán glacier in the eastern cordillera of the Andes at 9°S show higher than present temperatures between 8400 and 5200 yr B.P., with the highest temperatures from 6500 to 5200 yr B.P. (*21*). These dates coincide with the occupation of the Siches, Quebrada Chorrillos, Ostra, and Almejas sites. We interpreted these data to indicate that oceanic conditions were tropical along northern Peru in the early and mid-Holocene. As noted previously (*7*), other paleoenvironmental records such as beach ridges, glacial deposits, phosphorite deposits, and fish scale and diatom distributions also support this hypothesis.

Alternatively, DeVries and Wells (*22*) have suggested that tropical mollusks were able to live in the Ostra Embayment before 5000 yr B.P., because a large beach ridge isolated the embayment from the open ocean and allowed solar heating to warm the bay (*23*). In this model, the Ostra mollusks were tropical species brought south in the larval stage by sporadic ENSO events and carried over the ridge by unusual ENSO

Table 2. Radiocarbon dates and molluscan assemblage types for early and middle Preceramic sites in coastal Peru north of 9°S. Sample sources are Siches (*14*), Amotape (*12*), Quebrada Chorrillos (*16*), Ostra (*32*, *33*), and Almejas (*19*). Laboratories involved were Jaan Terasmae Radiocarbon Lab., Brock University (BGS), Smithsonian Institution (SI), and Pontificia Universidad Católica del Perú (PUC). Dashes indicate sample material unknown.

Context	Age	Sample	Lab number	Assemblage
	Siches/Honda component (4°30′S)			
I-B-3a	4,930 ± 80	Charcoal	BGS-1835	Mixed
I-A-4	5,150 ± 110	Charcoal	BGS-1832	Mixed
I-B-7	5,060 ± 80	Charcoal	BGS-1836	Mixed
I-B-8b	4,860 ± 80	Charcoal	BGS-1830	Mixed
I-B-9bi	4,990 ± 80	Charcoal	BGS-1833	Mixed
	Siches/Siches component (4°30′S)			
I-B-9b2	5,790 ± 90	Charcoal	BGS-1828	Tropical
II-B-2	6,450 ± 110	Charcoal	BGS-1834	Tropical
II-B-3	6,450 ± 80	Charcoal	BGS-1831	Tropical
II-B-4	6,590 ± 90	Charcoal	BGS-1827	Tropical
	Amotape camp (4°40′S)			
PV 8-29	11,200 ± 115	Shell	SI-1415	Tropical
PV 8-26	8,125 ± 80	Shell	SI-1414	Tropical
	Quebrada Chorrillos (6°00′S)			
A-B	6,920 ± 140	—	PUC-33	Tropical
A-B	7,540 ± 90	—	PUC-18	Tropical
	Ostra collecting station (8°55′S)			
Test pit: middle	5,160 ± 60	Shell	SI-4955	Tropical
Test pit: base	5,400 ± 60	Shell	SI-4954	Tropical
1-A-3	5,680 ± 90	Charcoal	BGS-1535	Tropical
	Ostra base camp (8°55′S)			
I-2-C/D-2	5,450 ± 110	Charcoal	BGS-1552	Tropical
V-1-C-1b	5,830 ± 80	Charcoal	BGS-1539	Tropical
V-1-C-4	5,830 ± 90	Charcoal	BGS-1540	Tropical
I-2-A-2	5,860 ± 110	Charcoal	BGS-1551	Tropical
III-2-A-6	5,975 ± 90	Charcoal	BGS-1538	Tropical
III-2-A-2	6,000 ± 90	Charcoal	BGS-1536	Tropical
III-2-A-5	6,010 ± 80	Charcoal	BGS-1537	Tropical
V-1-C-5ii	6,250 ± 250	Charcoal	BGS-1541	Tropical

Table 3. Percent of the minimum number of individuals (MNI) of tropical versus temperate vertebrates, without mixed habitat species, from early (11,000 to 7000 yr B.P.), middle (7000 to 5000 yr B.P.), and late (5000 to 3500 yr B.P.) Preceramic sites, by latitude from south to north.

Site (latitude)	Tropical (%)	Temperate (%)	MNI (%)	Age	Reference
Las Vegas-OGSE-80 (2°15′S)	91.3	8.7	23	Early	(*30*)
Paiján (7°30′S)	97.3	2.6	113	Early	(*36*)
Alto Salaverry (8°15′S)	6.8	93.2	58	Late	(*31*)
Ostra base camp (8°55′S)	64.2	35.8	120	Middle	(*17*)
Paloma: grab samples (12°30′S)	6.0	94.0	235	Middle	(*35*)
Paloma: probability samples (12°30′S)	1.8	98.2	112	Middle	(*34*)
Ring Site (17°40′S)	3.6	96.4	308	Early/Middle	(*15*)

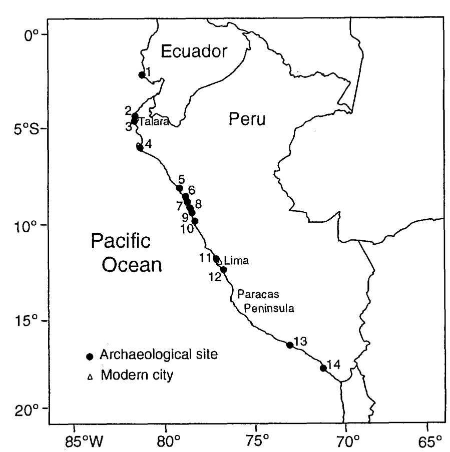

Fig. 1. Location map showing sites and geographic features. 1, Las Vegas; 2, Siches; 3, Amotape campsites and Talara tar seeps; 4, Quebrada Chorrillos and Avic 2; 5, Paiján; 6, Alto Salaverry; 7, Los Morteros; 8, Ostra; 9, Huaynuná; 10, Almejas; 11, El Paraíso; 12, Paloma; 13, Quebrada Jaguay; and 14, Ring Site.

storm activity. We reject this model because (i) mollusks could not reproduce in the salinity of an enclosed lagoon; (ii) Reitz (*18*) has identified estuarine fish species from the Ostra site that spend part of their life cycle in the open ocean; (iii) there is no evidence for a subaerial ridge before 4500 yr B.P., although a beach ridge plain does now separate the stranded embayment from the open ocean (*24*); (iv) faunal data indicating warmer coastal waters are present at the Siches, Quebrada Chorrillos, and Almejas sites in Peru; (v) thermally anomalous molluscan assemblages are present at mid-Holocene sites throughout the world, such as the Atlantic coast of Argentina (*25*), Greenland (*26*), and the Siberian coast of the Sea of Japan (*27*), which suggests that the changes in the paleocirculation we have postulated for the Pacific basin were global in scale; and (vi) independent evidence from northern Australia also suggests that ENSO became active only after 5000 yr B.P. (*28, 29*).

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Organic Optical Limiter with a Strong Nonlinear Absorptive Response

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Molecules with weak ground-state absorption that form strongly absorbing excited states can be used in optical limiters, which can protect sensors or human eyes from optical damage. Phthalocyanine complexes bearing heavy atoms or paramagnetic groups or in solvents containing heavy atoms show optical limiting enhanced by excited triplet-state absorption. A nonhomogeneous distribution of indium tetra(*tert*-butyl)phthalocyanine chloride along the beam path substantially enhances the excited-state absorption, yielding an optical limiter with a linear transmittance of 0.70 that can attenuate 8-nanosecond, 532-nanometer laser pulses by factors of up to 540.

Optical limiters are devices that strongly attenuate intense optical beams while exhibiting high transmittance for low-intensity ambient light levels. These nonlinear optical devices are currently of significant interest (*1–3*) for the protection of human eyes and optical sensors from intense laser pulses, which pose a considerable hazard both in the laboratory and in the field. However, most efforts to develop optical-limiting devices based on various mechanisms including nonlinear absorption and refraction in semiconductors (*4*), optical breakdown–induced scattering in carbon particle suspensions (*5*), thermal refractive beam spreading (*6*), and excited-state absorption (*7–10*) have fallen short of the blocking level needed (attenuation of 10-mJ pulses by a factor of 10^4 or higher) to protect the human eye by two orders of magnitude or more.

Recent work suggests that high levels of blocking at a reasonable linear transmittance, even in highly convergent optical systems, may be possible with high-performance, excited-state absorber materials. Perry *et al.* have shown (*10*) that metallophthalocyanine (M-Pc) complexes containing heavy central metal atoms exhibit enhanced excited-state absorption and optical limiting of nanosecond-duration laser pulses at a wavelength of 532 nm, because of an increased rate of intersystem crossing from the lowest excited singlet state (S_1) to the triplet state (T_1) and the concomitant increase in the population of the strongly absorbing T_1 state during the laser pulse. Moreover, analyses (*11, 12*) of the performance of optical-limiting devices that utilize excited-state absorbers indicate that large enhance-

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