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A REVIEW OF GEOLOGICAL EVIDENCE FOR ANCIENT EL NINO ACTIVITY IN PERU

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Abstract. Geological evidence (geomorphological, sedimentological, paleontological, and archeological) for the occurrence of El Niño events in Peru during the Quaternary has been reevaluated. New data concerning thermally anomalous molluscan assemblages in Holocene deposits of north central Peru are briefly described, as are new data regarding the distribution of warm- and cold-water mollusks in late Pliocene and early Pleistocene deposits of northwestern Peru. No conclusive evidence of prehistoric "El Niño" events was found in the new data or the reviewed literature. Most references to El Niño events are best characterized as descriptions of El Niño-like conditions. These conditions may accurately represent events or only mimic events. Past studies lack evidence of two necessary criteria for proof of an El Niño event: a demonstrably short-lived event, and the advection of warm coastal marine waters into the southeastern Pacific Ocean. The glaciological record of precipitation in the Andes, when combined with historical accounts of El Niño phenomena on the coast, is the sole example of a geological data set that meets both criteria.

Introduction

El Niño is defined by the Scientific Committee on Oceanic Resources (SCOR) Working Group 55 [1983] as the appearance of anomalously warm water in the coastal and equatorial ocean off Peru and Ecuador for at least 4 consecutive months at three or more of five coastal stations between Talara and Callao, Peru (Figure 1). Records of El Niño events over the past few centuries compiled from historical accounts [Quinn et al., 1978, 1986] and recovered from tropical ice cap cores [Thompson et al., 1984, 1986] show long-term changes in variables related to fluctuations in the intensity of the intertropical circulation across the Pacific Ocean, i.e., the Southern Oscillation [Berlage, 1957]. El Niño events prior to A.D. 1500 are poorly documented except in ice cores. Written records are nonexistent, while proxy records lack resolution and are open to alternative interpretations.

Since modern El Niño events are an extreme manifestation of the Southern Oscillation, ancient El Niño-Southern Oscillation (ENSO) events can be viewed as monitors of equatorial Pacific climate and ocean circulation. The usefulness of the monitor depends on matching its sensitivity and resolution with appropriate spatial and temporal scales of climatic and oceanic change. Given the centennial, millennial, or coarser resolution of existing prehistorical records, the changes of interest are those associated with Holocene neoglacial intervals, Pleistocene glacial epochs, the early Pleistocene onset of northern hemisphere glaciation, and Pliocene closure of the Isthmus of Panama.

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The definition of El Niño suggests two necessary criteria by which El Niño events might be recognized in the geological record: an event duration of several months to 2 years, and the advection of warm water along the coasts of Ecuador and Peru. Satisfying one criterion alone is not sufficient to demonstrate the existence of ancient El Niños. The geological record is replete with short-lived events; not all need be related to El Niño. Warmer water may have lain offshore of Peru and Ecuador not for months, but for centuries. Possible combinations involving the presence or absence of warm coastal waters and the existence or nonexistence of short-term events are shown as "alternatives" in Figure 2. The modern situation is represented by alternative III: normally cold upwelled coastal waters off Peru, replaced episodically by warm waters for several months. "El Niño-like conditions" are exemplified by alternative II: warm coastal waters present offshore for centuries, perhaps with associated oceanic productivity and onshore precipitation patterns that resemble patterns of recent El Niño years. Warm-water and cold-water extremes are represented by alternatives I and IV, respectively: El Niño events against a backdrop of regional or global ocean warming, and an absence of El Niño events (and presumably Southern Oscillation activity) despite intensified South Pacific circulation and upwelling.

The following discussion of the geological and paleontological evidence for ancient El Niños in Peru proceeds from the more recent to the more ancient and from records of events to records of conditions. This evidence can be viewed in light of the four alternatives (Figure 2) describing long-term water temperature and event duration. The glaciological record, so well documented by Thompson et al. [1984, 1986], will not be considered in detail.

Holocene Record

Events

Multiple catastrophes. Evidence of ancient tsunamis along the coast of Peru has been published by Bird [1987]. T. J. DeVries and L. E. Wells [Wells, DeVries, and Quinn, 1987] have observed stranded driftwood at several sites (Salinas Chao, area of Casma) inland from the north-central coast of Peru. Radiocarbon dates of wood from several sites suggest that wood was introduced to the ocean during the 1618-1619 El Niño event and soon thereafter was borne inland by a tsunami [Vasquez de Espinoza, 1629; Quinn et al., 1986].

Rare events from a historical perspective, tsunamis and very strong El Niños are to be expected along a convergent margin of the southeast Pacific Ocean. The two catastrophes occasionally must have followed one so closely that freshly floated timber would have been swept inland. Older deposits of driftwood from the

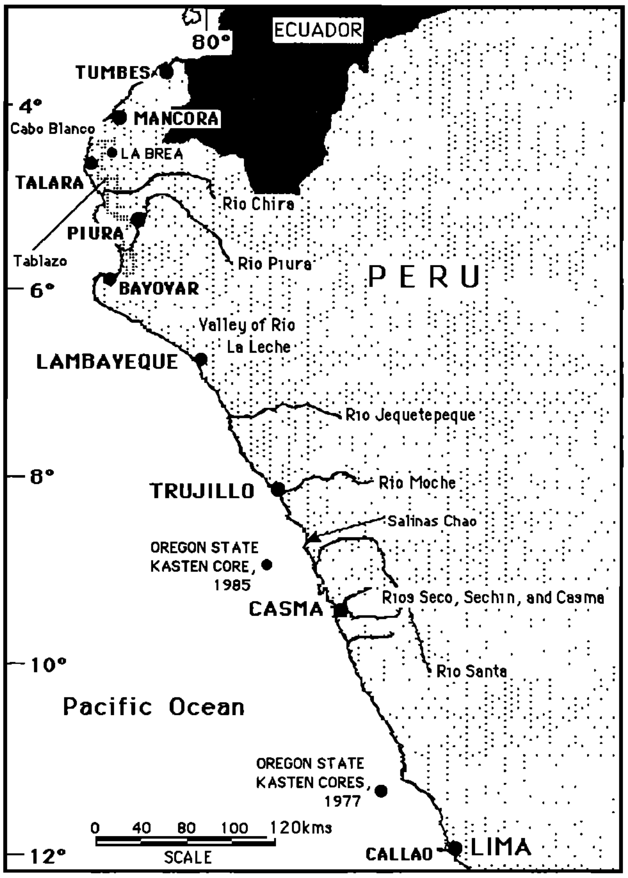

Fig. 1. Map of central and northern coastal Peru, showing the location of cities, rivers, and geographical localities mentioned in the text.

coast of Peru might represent other coincidental catastrophes.

Floods. Floods are the most serious of catastrophes that affect the Peruvian mainland during El Niño events [Murphy, 1926; Philander, 1983]. Because flood waters are agents of erosion and deposition, they can provide a geological record of ENSO-related activity.

Geological evidence of flooding in coastal valleys of Peru includes steep-banked channels, coarse-grained channel-lag deposits, debris flows, sheet sands, and chaotically scattered archeological remains in massive silty sands. Wells [this issue] describes fining-up channel and overbank sequences of cobbles, sand, silt, and clay in the valleys of the Rio Seco, Rio Sechin, and Rio Casma (9°-10°S). Each sequence is ascribed to a single El Niño-related flood. Approximate ages are provided by ^{14}C analyses and archeological debris and are extended to undated sequences by means of stratigraphic correlation. Wells identified at least 21 events in late Pleistocene deposits and 11 events in Holocene deposits, including four in the late Holocene.

Craig and Shimada [1986] observed a massive silty sand in the valley of Rio La Leche (6°30'S) that they thought was formed by an El Niño flood between A.D. 650 and A.D. 1000. Other homogeneous silty sands in the same valley were dated by man-made artifacts at A.D. 650-700. Buildings dated at A.D. 500-600 showed signs of water damage and repair.

Damage to irrigation canals was cited by Nials et al. [1979a, b] and Moseley et al. [1981] as the principal evidence for El Niño floods in the Moche valley (8°10'S). The largest flood, 2 to 4 times greater than the devastating flood coinciding with the El Niño of 1925-1926 [Murphy, 1926], occurred at about A.D. 1100, probably the same time as a major flood inferred by Craig and Shimada [1986].

Great quantities of sediment are carried in flood waters as bed load and suspended load. It being a short distance from Andean watersheds to the coast, flood-borne sediment quickly makes its way to the river's mouth. After the 1982-1983 El Niño, a large delta formed at the mouth of the Rio Jequetepeque (M. E. Moseley, cited by Sandweiss [1986]) and at the debouchment of Quebrada Pariñas (T. J. DeVries, personal observation). In the latter case, in which the canyon (quebrada) had been perennially dry, the delta still extended 1 km seaward 6 months after the rains of 1983 had stopped.

Richardson [1983] and Sandweiss [Sandweiss et al., 1983; Sandweiss, 1986] have proposed that sets of subparallel beach ridges located downcurrent from river mouths in north central and northwestern Peru were created from sediment flushed episodically from Peruvian coastal valleys by El Niño flood waters. In their view, each ridge represents an El Niño event, comprising one or more floods. The spacing of ridges was thought to depend on (1) the amount of sediment delivered by longshore currents during and between El Niño events, (2) the elapsed time between El Niño events, and (3) the rate of beach face reworking of sediments.

Episodic tectonic uplift as a mechanism for beach ridge emergence on the coast of northwestern Peru was recognized by Richardson [1983] but he did not address its relevance to beach-ridge formation. Also, the role of normal progradational processes along an irregular coast [King, 1973] following a mid-Holocene sea level high stand has not been adequately considered (L. E. Wells, personal communication, 1987). Small changes in the rate of sediment input, sediment

	EVENT	NO EVENT
WARM WATER	I Permanently emplaced warm-water mass, with even warmer El Niño events	II Warm coastal waters, no events. Perhaps the case in the Pliocene
COLD WATER	III Present-day situation: Cold water, warm-water incursion during El Niño events	IV Strong trade winds, strong upwelling, no warm-water incursions

Fig. 2. Contingency table for combinations of warm-water El Niño events (or lack thereof) and El Niño-like conditions (warm water) or absence of such conditions (cold water). Geological evidence of cold water off the coast of Peru and warm-water events is needed to demonstrate the existence of past El Niño events (alternative III). The results of most studies do not permit a distinction between alternatives II and III.

transport, and relative sea level change could equally well explain the episodic forming of beach ridges.

An assumption of the aforementioned studies is that all floods in northern Peru are the consequence of El Niño events [e.g., Nials et al., 1979a, b]. (The reverse proposition, that all El Niño events produce flood deposits, is not true [Craig and Shimada, 1986].) For historical time, the assumption (alternative III, Figure 2) is reasonable (W. H. Quinn, personal communication, 1987). For past millennia, the hypothesis has not been tested against alternative II (Figure 2), namely, that flooding was a periodic (even annual) result of atmospheric disturbances over a permanently emplaced warm-water mass off the coast of northern Peru.

Conditions

Onshore evidence. Archeological and geological arguments for El Niño-like conditions during the Holocene are based principally on evidence of increased ocean temperatures. The data consist of species lists of mollusks from middens at 2°-16°S (E. P. Lanning, unpublished report to the National Science Foundation, 1967, cited by Richardson [1973]; Richardson [1973, 1978], Pozorski and Pozorski [1979a, b], Sandweiss et al. [1983], and L. E. Wells, unpublished data, 1986), uplifted embayments at the same latitudes [Hoffstetter, 1954; Moseley, 1975; DeVries, 1986; also L. E. Wells, unpublished data, 1986], and cores of embayment sands at Casma (9°30'S) (L. E.Wells, unpublished data, 1986). The assemblages of mollusks can be characterized as warm-water, cold-water, or transitional, depending on whether constituent species typically inhabit the modern Panamic faunal province (Gulf of California to Cabo Blanco, northwestern Peru [Olsson, 1961]), the modern Peruvian province (6°S to southern Chile [Dall, 1909]), or the Paita buffer zone (4°-6°S, between the Panamic and Peruvian provinces [Olsson, 1961]), respectively.

Warm-water mollusks of the Paita Buffer Zone (and rarely the Panamic Province) undeniably occur in Holocene deposits of north central Peru. Anadara tuberculosa, a pelecypod associated with mangrove forests of Ecuador and northernmost Peru [Peña, 1976], has been reported in middens overlooking emergent Holocene embayments at Talara [Richardson, 1973] and near Lambeyeque [Richardson, 1978]. Cerithium stercusmuscarum and Chione broggi, respectively a gastropod and venerid pelecypod of the Paita Buffer Zone [Pilsbry and Olsson, 1943; Olsson, 1961; DeVries, 1986] are abundant on the surface of Pampa Las Salinas, north of the Rio Santa [Sandweiss et al., 1983].

Richardson [1973] originally proposed that either El Niño events or a permanently emplaced mass of warm water along the north central coast of Peru enabled warm-water mollusks to thrive at such southerly latitudes. A further refinement of midden chronology led Richardson [1981] to identify ~5000 years B.P. as an important date in the evolution of the Peruvian littoral, a time when sea level was reaching its highest elevation and stabilizing after a rapid early-Holocene rise and when the Humboldt Current was extending its influence northward. He noted that many middens older than ~5000 years B.P. often contained warm-water mollusks, whereas younger middens only contained cold-water species. This thermal dichotomy, further supported by data of Sandweiss et al. [1983], coupled with beach ridge data of Sandweiss [1986], led Rollins et al. [1986] to propose that warm water permanently in place prior to 5000 years B.P. was replaced thereafter by colder water and that the advent of this colder water was concomitant with the onset of El Niño events (alternative II followed by alternative III, in the sense of Figure 2).

This interpretation is open to question, for it has not been shown that the distribution of Holocene warm-water molluscan assemblages in north central Peru is controlled by open marine, littoral temperature alone. DeVries [1986] showed that an assemblage that resembles the north central Peru "warm-water" assemblage is typical of modern tidal flats in the Gulf of California [Berry, 1956], emergent Holocene embayments near Bayovar, Peru (5°50'S), and early Pleistocene uplifted embayments with a mixed cobble and siltstone substrate in northwestern Peru (4°15'S). L. E. Wells (unpublished data, 1986) has evidence that a subset of species belonging to the 'warm-water' assemblage of Sandweiss et al. [1983] persisted without change in quiet waters of the Casma embayment from 6700 to 4700 years B.P.

Southward displaced warm-water assemblages of Holocene mollusks invariably include a majority of species adapted to the relatively quiet waters of lagoons or slightly less protected waters of embayments. Few species of warm-water mollusks from exposed sandy beaches and no such species from intertidal and subtidal rocky surfaces have yet been found. To the contrary, all Holocene middens with a representation of mollusks from exposed coasts contain only species from the cold-water Peruvian province [Pozorski and Pozorski, 1979a, b; Sandweiss et al., 1983; DeVries, 1986; also L. E. Wells, unpublished data, 1986]. Most of these midden faunas are younger than 5000 years B.P., which circumstantially supports the theory of Rollins et al. [1986]. Middens near Casma, however, which contain a mixed assemblage of cold-water species from exposed habitats and warm-water species from protected habitats, may be as old as 7000 years B.P. (L. E. Wells, personal communication, 1987). Most middens older than 5000 years B.P. have been drowned beneath the rising Holocene sea [Richardson, 1981]. A presumed early Holocene shell pavement from the midshelf of Peru at about 9°S, sampled by Oregon State University oceanographers in 1985, contains stratigraphically segregated molluscan assemblages of the nearshore and mid-shelf that include only cold-water species.

Archeological data (fish remains in coastal middens) presented by Llagostera [1979] supports a hypothesis that the northern Chilean littoral climate ameliorated from the early Holocene to 4000 years B.P., past the date of 5000 years B.P. when cooling is supposed by Rollins et al. [1986] to have commenced. Llagostera [1979] concluded that the long-term exploitation of warm-water species by coastal populations showed that former El Niño events lasted longer and were stronger or that warm water was permanently emplaced at subtropical latitudes off western South America.

It must be concluded that the distribution of Holocene molluscan and piscean assemblages in north central Peru and Chile (1) offer inconclusive evidence of a 5000-year-B.P. climate change involving a shift from warm to cold coastal waters and (2) no evidence of El Niño events. Beach ridges provide an chronology of events from 5000 years B.P. to the present, but their origin (tectonic, eustatic, climatic) remains in doubt.

Offshore evidence. The search for evidence of Holocene climate change and ENSO activity on the Peruvian margin has been limited to paleontological and geochemical studies of several Kasten cores collected in 1977 and stored at Oregon State University. The cores were collected between 11°S and 13°S at water depths of 180-600 m across the breadth of the upper slope mud lens [Krissek et al., 1980]. Latest Holocene (0-500 years B.P.), late Holocene (2000-4000 years B.P.), early Holocene (5000-8000 years B.P.) and latest Pleistocene (16,000-11,000 years B.P.) sediments were represented in one or more 2- to 3-m cores. DeVries [DeVries and Schrader, 1981; DeVries and Pearcy, 1982] recorded the downcore distribution of fish scales (Engraulis, Sardinops, Merluccius, etc.) and diatoms. Reimers and Suess [1983a, b] measured down-core accumulation rates and elemental ratios of organic carbon and proto-kerogen. Wefer et al. [1983] analyzed the stable isotope composition of planktic and benthic foraminifera.

Most lines of evidence indicate warmer conditions off the central coast of Peru during the late Pleistocene, late Holocene neoglacials (4500-4200 years B.P. and 2700-2200 years B.P. in southern Chile [Heusser, 1974; Mercer, 1976] and similar time intervals in Colombia [van der Hammen, 1974] and North America [Denton and Karlen, 1973]), and/or the Little Ice Age (about 1600-1800 AD [Denton and Karlen, 1973; Mercer, 1976]). During these times, preservation increased of warm-water sardines and oceanic diatoms (e.g., Coscinodiscus nodulifer). Periods of alternating warm and cold water with enhanced productivity preceded and followed the second neoglacial period. A depletion of $\partial^{18}O$ in the benthic foraminifer Cancris oblongus in near-surface sediments suggested to Wefer et al. [1983] warmer bottom waters 250 years B.P. Values of $\partial^{18}O$ similar to today indicated similar conditions during the Hypsithermal interval, 8000-6000 years B.P. A single value of enriched ∂18O at 5000 years B.P. might suggest cooling. Water cooler than now may have existed offshore 13,000 to 11,000 years B.P., while warmer water was present 15,000 years B.P.

Elevated rates of total accumulation, organic carbon accumulation, and low proto-kerogen O/C and H/C values (reflecting rapid burial of organic matter in low-oxygen environments and a consequent lack of aerobic biodegradation at the sediment surface) during periods of latest Pleistocene and Holocene neoglacial cooling led Reimers and Suess [1983a, p. 517] to conclude that those "prolonged periods of deoxygenated waters and high sediment accumulation" might be correlated with El Niño events.

While every group working with Kasten cores from the Peruvian mudlens has suggested that El Niño events might have been more common during the late Pleistocene and during Holocene neoglacials, no group has excluded the possibility of prevalent El Niño-like conditions. There is no clear evidence of El Niño events from the Peruvian shelf or slope. Unfortunately, the possibilities for resolution of single events are less off the coast of Peru than in the Santa Barbara basin off California [Soutar and Crill, 1977] or in the Gulf of California [Baumgartner et al., 1985] because laminated sequences are neither as well preserved nor as thick.

Late Quaternary Record (15,000-5000 years B.P.)

The evidence for climate change and El Niño activity during the late Quaternary comes from paleontological studies of tar seeps in northwestern Peru [Lemon and Churcher, 1961; Campbell, 1982], palynological studies of lake sediments in the Galapagos Islands [Colinvaux, 1972], floral studies in the Peruvian Andes [Vuilleumier, 1971], and theoretical arguments [e.g., Quinn, 1971] often addressed to the theories of Colinvaux and Vuilleumier [Newell, 1973; Houvenaghel, 1974; Simpson, 1975].

The tar pits at La Brea, near Talara, dated at about 12,000-14,000 years B.P. [Churcher, 1966], contain vegetal debris, freshwater pulmonate snails, insects, and bones of amphibians, reptiles, birds, and mammals [Lemon and Churcher, 1961; Churcher, 1966; Campbell, 1982]. The flora and fauna trapped in the tar represent a number of savanna and riparian environments, all indicating a well-watered coastal plain quite different from the tropical algarroba and cactus scrubland of today. Campbell [1982] proposed that attendant seasonal rains were a consequence of strengthened atmospheric circulation during Pleistocene glacial periods, a resultant shift of northeast trade winds across the equator, and a transformation of those winds into moisture-laden northwest winds.

Lake deposits inside a volcanic crater at the summit of a Galapagos island were cored by Colinvaux [1972] to retrieve pollen samples for a record of Quaternary climatic change. Data showed that the modern lake was established at about 10,000 years B.P., after 24,000 or more years of relative aridity. During the Holocene the lake was shallower from 8600 years B.P. to about 3000 years B.P., after which time it reached its present water depth. Colinvaux hypothesized that the thermal inversion (created by equatorial oceanographic divergence) that now maintains low-altitude aridity and prevents all but fog-generated precipitation at high altitudes was equally strong during the late Pleistocene. He also proposed that the annual displacement of the intertropical convergence zone (ITCZ), which presently leads to a temporary breakdown of the thermal inversion and permits seasonal El Niño-like warming, thermal convection, and heavier high-altitude precipitation, did not occur during the late Pleistocene, when lake beds stayed dry. Colinvaux [1972] concluded that the ITCZ must have stayed in its northerly position between 34,000 and 10,000 years B.P.

In response to Colinvaux [1972], Newell [1973] argued that the ITCZ might have existed south of the equator during Pleistocene glacial periods, owing to a thermal gradient steepened more across the northern hemisphere than the southern hemisphere. Asnani [1968] proposed that a southern ITCZ might have formed in addition to a northern ITCZ. Neither Newell [1973] nor Asnani [1968] addressed the evidence of high-altitude aridity in the Galapagos Islands. Houvenaghel [1974] suggested that the dryness could result from a slight intensification of local upwelling (resulting from stronger trade winds during Pleistocene glacial periods) and a consequent cooling of surface waters by as little as 1°C. Cooler waters would have stabilized the thermal inversion that shielded high altitudes from El Niño-related precipitation. The combination of stronger upwelling just north of the equator and a newly developed or southward shifted ITCZ would have allowed El Niño activity to continue without filling Galapagos lakes prior to 10,000 years B.P.

Evidence of greater precipitation on the western slopes of the Andes and dissatisfaction with other theories of Quaternary climatic change in western Peru led Simpson [1975] to suggest

TABLE 1. Southern Retreat of Modern Cold-Water Molluscan Species From Their Late Pliocene/Early Pleistocene Northern Range Limit

Species	Geological Unit[1]	Northern Range Limit Latitude °'S Pliocene/ Pleistocene	Modern	Southward Retreat km
Lithophaga peruviana	Carrizo	04 15	12 00	860
Choromytilus chorus	Carrizo	04 15	06 00	190
Aulacomya ater	Hornillos	05 00	08 00	330
Argopecten purpuratus	Carrizo	04 15	06 00	190
Glycymeris ovata	Carrizo	04 15	06 00	190
Diplodonta inconspicua	Hornillos	05 00	12 30	830
Mesodesma donacium	Carrizo	04 15	06 00	140
Mulinia edulis	Carrizo	04 15	06 00	140
Gari solida	Hornillos	05 00	12 00	770
Ensis macha	Carrizo	04 45	33 00	3110
Protothaca thaca	Carrizo	04 45	12 00	800
Protothaca antigua	Carrizo	04 45	12 00	800
Transennella pannosa	Carrizo	04 15	06 00	190
Tegula luctuosa	Carrizo	04 15	08 00	410
Crepidula dilatata	Mancora	04 15	08 00	410
Turritella cingulata	Mancora	04 30	08 00	390
Priene scabra	Golf Course	04 30	09 00	500
Concholepas concholepas	Golf Course	04 30	08 00	390
Thais chocolata	Carrizo	04 15	05 00[2]	80
Crassilabrum crassilabrum	Mancora	04 45	12 30	850
Oliva peruviana	Carrizo	04 15	06 00	140

1. Names refer to stratigraphic units of DeVries [1986]. From oldest to youngest they are Carrizo, Golf Course, and El Nuro members of Taime formation (late Pliocene to early Pleistocene) and the Mancora tablazo (terrace). The Hornillos formation of the Sechura basin is roughly time correlative with the Taime formation.

2. Occurrence in great abundance; small populations exist farther north.

that Peru's coastal waters were colder during the late Pleistocene than today but that Peru's coastal plain was not colder to an equal degree. The result was a greater contrast between sea and shore temperatures and thus increased thermal instability as ocean air masses moved inland. According to Simpson, the coastal thermal inversion broke down during the late Pleistocene for millennia as it does today for a season. Rapidly rising air along the western slopes of the Andes produced highland rainfall as recorded by the floral data.

In support of the model, Simpson [1975] enlisted the speculation of Quinn [1971], who suggested that lower sea level during the last glacial maximum might have exposed enough of Indonesia to intensify the Indonesian low. Southern Oscillation zonal indices would then have been so high that ENSO activity would have been greatly diminshed.

A well-developed southern ITCZ during the last glacial epoch might account for the wetter climate in northwestern Peru described by Campbell [1982]. An explanation would still be needed for high-altitude humidity [Vuilleumier, 1971; Hastenrath, 1971]. The scenario presented by Campbell [1982] is also consistent with annual El Niño precipitation as far south as 4°30'S. An oceanographic justification for annual El Niños, however, has never been put forth, and any account of annual El Niños must counter the argument of Quinn [1971] that glacial epoch emergence of a broad Indonesian shelf would have stabilized the Indonesian low pressure cell, thereby discouraging El Niño activity.

As yet, no evidence exists for specific El Niño events during the late Quaternary in the coarsely resolved deep-sea oceanographic record [e.g., Molina-Cruz, 1977; Romine, 1982] or on the coast of western South America.

Pleistocene

Recently completed studies of late Pliocene and Pleistocene mollusks in raised marine terraces (tablazos) of northwestern Peru [DeVries, 1986] show a remarkable southward shift of cold-water species since the early Pleistocene (Table 1).

A distinct Pliocene Peruvian molluscan province had extended from southern Chile to the Rio Chira (4°45'S); a zone transitional to a Pliocene Panamic molluscan province had existed between the Rio Chira and Mancora (4°00'S) [DeVries, 1985]. Many of the Pliocene species became extinct by the early Pleistocene, probably not because waters were significantly colder, but because habitats in protected embayments and lagoons on a Pliocene submergent margin were eliminated when the margin began to rise and sea level began to fluctuate between greater extremes.

During the earliest Pleistocene, individuals of cold-water molluscan species predominated farther north than Cabo Blanco (4°15'S). Individuals of warm-water species were generally restricted to tectonically silled lagoons and spit-protected embayments. Between the time when the early Pleistocene Mancora tablazo and the late Pleistocene Lobitos tablazo were formed [Bosworth, 1922; DeVries, 1984], several abundantly represented species of cold-water mollusks were eliminated from northwestern Peru or were greatly reduced in numbers (Table 1). In their stead, an assemblage of tropical Panamic province species appeared, including species that had existed inside older warm-water lagoons at the same latitude (Turritella gonostoma, Oliva incrassata, and others) and rocky intertidal species rarely seen so far south (Cypraea spp., Mazatlania fulgurata, Mitra swainsoni, Eucrassatella gibbosa, Codakia distinguenda, Protothaca columbiensis, and others).

The possible significance of this southern retreat of cold-water mollusks might have been overlooked had it not been for the occurrence of the 1982-1983 El Niño. A body of literature grew following that strong event that described the effects of warm water on cold-water mollusks inhabiting the littoral of Peru and Chile [e.g., Arntz and Valdivia, 1985; Tarazona et al., 1985; Wolff, 1985; Arntz, 1986]. Many of the species affected most deleteriously (Aulacomya ater, Protothaca spp., Gari solida, Mesodesma donacium, and Concholepas concholepas) were also species showing the greatest southward retreat during the Pleistocene. Conversely, those species that flourished in the unusually warm waters of 1982-1983 (Argopecten purpuratus, Thais chocolata) [Wolff, 1985] are known to have a tropical ancestry and Panamic or Caribbean distribution during the Pliocene (see DeVries [1986] for references).

DeVries [1986] proposed that the Pleistocene molluscan range contractions might reflect the onset of El Niño conditions. Earlier, during the Pliocene, meridional thermal gradients had been less steep and circulation probably less intense. During the Pleistocene, meridional thermal gradients steepened, circulation intensified, and corrective circulatory responses (i.e., the Southern Oscillation) may have become amplified. Repeated El Niño-related intrusions of warm water along the northern coast of Peru would have decimated populations of cold-water species. Recolonization by larvae swept northward by the Humboldt Current would have been discouraged by the episodic reappearance of warm water. The northernmost limit of a cold-water species's range would depend on the physiology of that species, its life span, its sensitivity to environmental pressure during various life stages, and the frequency and intensity of El Niño events. Faunal provincial boundaries would correspondingly reflect the summed responses of all species from many habitats.

While this hypothesis is consistent with other data sets showing the advent of warm water along the coast of Peru during periods of global cooling [e.g., DeVries and Pearcy, 1982; Wefer et al., 1983], the alternative of permanently emplaced warm water off northern Peru is also consistent with the coarsely resolved faunal data. So, for the early Pleistocene, as for the late Pleistocene and Holocene prior to 1500 years B.P., no convincing evidence yet exists for "El Niño events" affecting the coast of western South America, but rather there is circumstantial evidence for El Niño-like conditions.

Discussion

Primary or incidental research on prehistoric El Niño activity in the southeastern Pacific Ocean has proceeded on four fronts: archeological, palynological, marine geological, and glaciological. The first front incorporates paleontological, sedimentological, and geomorphological studies of the Peruvian coast. The second includes botanical studies and theoretical models developed to explain botanical and pollen data. The third consists of paleontological and geochemical studies. The fourth is founded upon an understanding of Andean climate. Each research tradition has its own shortcomings, yet each has the potential for unique contributions to the study of ancient El Niños.

The "archeological" record of Peru's arid coast, being terrestrial and largely surficial, suffers from a lack of temporal continuity only partly remedied by the existence of middens. These man-made accumulations of organic and artifactual remains are widely scattered, were sometimes abandoned, and are often far removed from environments affected by El Niño precipitation. Such environments are usually confined to river valleys, where floods are a matter of course. There, the central question is whether every flood deposit represents an El Niño event. The answer depends on knowing the history of regional precipitation. Averaged climatic histories for coastal Peru might be recorded in desert and floodplain soils (J. Noller, written communication, 1987). In the context of Figure 2, climate histories may demonstrate the long-term persistence of warm water (alternatives I and II) or cold water (alternatives III and IV) off the coast of Peru. The probability that floods occur only during El Niño years must then be judged in light of this choice of alternatives.

The principal obstacle to using pollen and ice core time series from highland areas as proxy records of El Niño is a poor understanding of the connection between cordilleran and coastal climate. In the case of snow accumulation on the Quelccaya Ice Cap [Thompson et al., 1984], an empirical correspondence exists with the coastal historical record of El Niño [Quinn et al., 1986]. Lacking a convincing climatic model that applies to the Andes as well as the coast, it would be unwise to presume this correspondence for early Holocene and Pleistocene proxy records, should the proxy records exist. In fact, a dearth of highland lakes and ancient ice caps has impeded the construction of long-term, high-resolution climate records for the Andes, as has an equable tropical climate that discourages the formation of annual growth rings in highland species of trees. Further progress in the search for evidence of ancient El Niños in the Andes depends upon the discovery of such lakes and trees.

A high resolution of climatic records from the Peruvian continental margin is so far hampered by a lack of cores with undisturbed varves. Owing to an open shelf and slope, sediments as well laminated as those of the California borderland basins and the Gulf of California may never be found off Peru. Nonetheless, high organic sedimentation rates off Peru make it probable that long-term (10^2 to 10^3 years) oceanographic changes can be identified and dated and that shorter term events can be identified, if not precisely dated.

Conclusion

Despite many claims that ENSO activity characterized much of the Quaternary, a variety of geological and archeological evidence still cannot verify its existence, particularly with reference to El Niño events. Reliance on evidence of coastal flooding depends heavily on analogy with modern climatic patterns. Paleontological and marine geological arguments based on evidence of ocean warming too often lack evidence of specific events. Further studies must strive to resolve the El Niño event, discover the thermal anomalies associated with the event, and account for aspects of "normal" or between-event conditions that might mimic and/or mask El Niño.

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