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AN ALLUVIAL RECORD OF EL NIÑO EVENTS FROM NORTHERN COASTAL PERU

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Abstract. Overbank flood deposits of northern coastal Peru provide the potential for the development of a late Quaternary chronology of El Niño events. Alluvial deposits from the 1982-1983 El Niño event are the basis for establishing a type El Niño deposit. Sedimentary structures suggesting depositional processes range from sheet flows to debris flows, with sheet flood deposits being the most common. The 1982-1983 deposits are characterized by a 50- to 100-cm-thick basal gravel, overlain by a 10- to 100-cm-thick sand bed, grading into a 1- to 10-cm-thick silty sand bed and capped by a very thin layer of silt or clay. The surface of the deposit commonly displays the original shear flow lines crosscut by postdepositional mud cracks and footprints (human and animal). Stacked sequences of flood deposits are present in Pleistocene and Holocene alluvial fill, suggesting that El Niño type events likely occurred throughout the late Quaternary. A relative chronology of the deposits is developed based on terrace and soil stratigraphy and on the degree of preservation of surficial features. A minimum of 15 El Niño events occurred during the Holocene; a minimum of 21 events occurred during the late Pleistocene. Timing of the Holocene events is bracketed by isochrons derived from the archaeologic stratigraphy. Corrected radiocarbon ages from included detrital wood provide the following absolute dates for El Niño events: 1720 $\pm$ 60 A.D., 1460 $\pm$ 20 A.D., 1380 $\pm$ 140 A.D. (error overlaps with the A.D. 1460 event; these may represent a single event), and 1230 $\pm$ 60 B.C.

Introduction

Episodic El Niño events bring torrential flooding and elevated sea levels to the northern coast of Peru. The flood-induced sedimentation and erosion, which cause severe and rapid landscape changes, provide a stratigraphic record of El Niño events extending throughout the Holocene and possibly into the late Pleistocene.

The desert climate of the Peruvian coast allows for a direct correspondence of flood events with El Niño events. Annual precipitation in the study area (Figure 1, latitudes 9°S to 10°S) has averaged 4.2 $\pm$ 2.0 mm for the past 20 years (data from El Servicio de Meteorologia e Hidrologia Peruano). During 1983 an annual precipitation of 42.4 mm was recorded at Buena Vista, the highest annual precipitation in the last 20 years; during the years of 1974 to 1980, annual precipitation was zero. In this hyperarid environment, alluvial overbank flooding occurs only during El Niño episodes because only then is there significant precipitation.

As the sedimentary record of flood events is extended further into the past, the reliability of correlating these events with oceanographically defined El Niño events necessarily decreases. For most of the later Holocene, after about 5000 B.P. archaeologic midden remains suggest that the coastal environment has remained relatively constant, supporting the same biota that it supports today [Pozorski, 1976; Feldman, 1980]. Rollins et al. [1986] have argued that warm-water marine fauna present in now-stranded embayments of the Holocene maximum transgression (around 5-7000 B.P.) record a major coastal current reorganization at around 5000 B.P., and a climate change, from savannah to hyperarid, at this time as well. L. Wells and T. DeVries (unpublished data, 1986), however, have found that these molluscan fauna are species common to quiet restricted marine environments (lagoons and estuaries) and that they occur in association with cold-water open-marine fauna (rocky headland or beach environment) in early lithic archaeologic sites near Casma (most likely pre-5000 B.P., based on stratigraphic order of the sites). It seems likely then, that during the time of the maximum Holocene marine transgression, the coast was characterized by warm protected embayments between stretches of rocky coastline and sandy beaches. The change in fauna along the coast is facies rather than current controlled; warm-water mollusks disappear coincidentally with coastal progradation and infilling of the marine embayments. Little is known of the Pleistocene climate or environment in this region. Quinn [1971] argues that during glacial stages the Southern Oscillation would have been locked into a high index phase, as a lower sea level would preclude circulation between the western Pacific and the Indian Ocean. These conditions would result in a hyperarid coastal zone lacking even episodic El Niño precipitation (the low index phase of the Southern Oscillation). Although the long-term climate history of the region is not well understood, the sedimentologic evidence presented here suggests that, for the Holocene and possibly for parts of the Pleistocene, a hyperarid climate with episodic heavy precipitation has predominated. As the latitude of the area precludes the formation of hurricanes and their related rainfall (low Coriolis forces and cold surface waters) and as the zone is isolated form Amazonian rainfall by three Andean mountain ranges (elevations range from 4000 to 6700 m),

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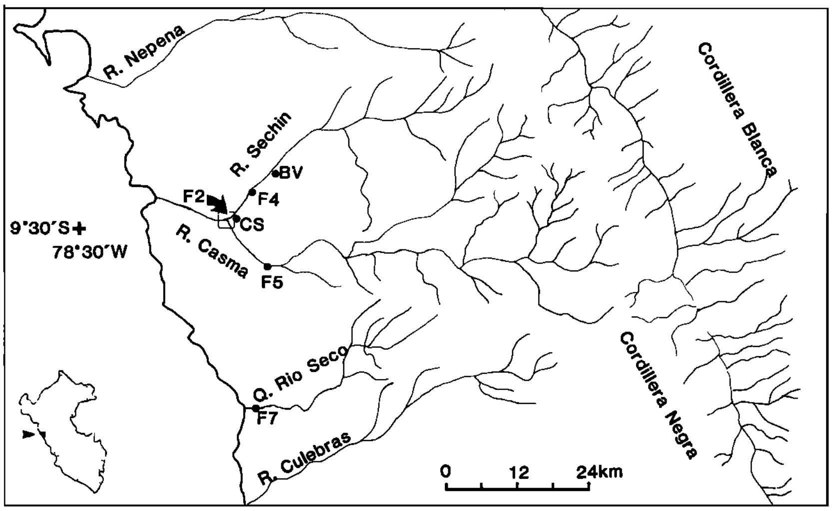

Fig. 1. Study area location, northern coastal Peru. The weather stations in the Rio Sechin valley are marked by the symbols BV, the Buena Vista station, and CS, the location of the Cerro Sechin weather station and the Cerro Sechin archaeologic site. The map shows the areas and outcrops referred to in other figures: F2, Figure 2; F4, Figure 4; F5, Figure 5; and F7, Figure 7.

then El Niño like events seem the most likely cause of the episodic flooding.

The frequency of flood-producing El Niño events is dependent on the latitude of the area in question. The oceanographic dynamics of an El Niño are such that the magnitude of the event defines the southerly extent of the incursion of the warm coastal waters and the concurrent rainfall [Cane, 1983]. In the northern areas of the Peruvian coast (e.g., the Lambayeque region at 7°S), smaller-scale events, with a frequency of 7 to 10 years, can cause flooding; the same events may not show any effects farther south (e.g., the Supe region at 11°S). Events of the magnitude of the 1982-1983 El Niño cause significant overbank flooding and deposition in all drainages north of 11°S. In the study area (9.5°S) some overbank flooding occurs at least once every 50 years, based on the estimate that the 1982-1983 El Niño was a 50-year event (from data of Quinn et al. [1986]); however, flooding of a significant magnitude to produce enough sediment to leave a long-term depositional record appears to occur only about once every 500 years, based on the stratigraphy developed below.

The floods of 1983 caused a reworking of 20% to 30% of the surface of the Holocene floodplain (Figure 2). The major overbank floodplain (see Figures 2 and 3) is 2 to 10 m above the active river thalweg; during flood years the streams overflow onto the overbank terraces due to both increased discharge as well as temporarily elevated sea (base) level. The incision of this surface is primarily the result of differences in the stream potential between flood and nonflood years. Although often cited as a cause of stream disequilibrium in Peru [e.g., Nials et al., 1979a, b], I have found no geomorphic evidence for Quaternary uplift along the central coast, between Lambayeque and Pisco (7° to 13.5°S). In this region of shallow subduction, the absence of Quaternary marine terraces, along with the presence of actively subsiding basins (e.g., the Salaverry basin at 9°S) just offshore [Hussong et al. 1984; Ocean Drilling Program, 1987], suggests that the coastal zone in this region has been either subsiding or stable throughout the later Quaternary. This is confirmed by a middle-Holocene maximum transgression shoreline which, although stranded 4 km from the present shoreline

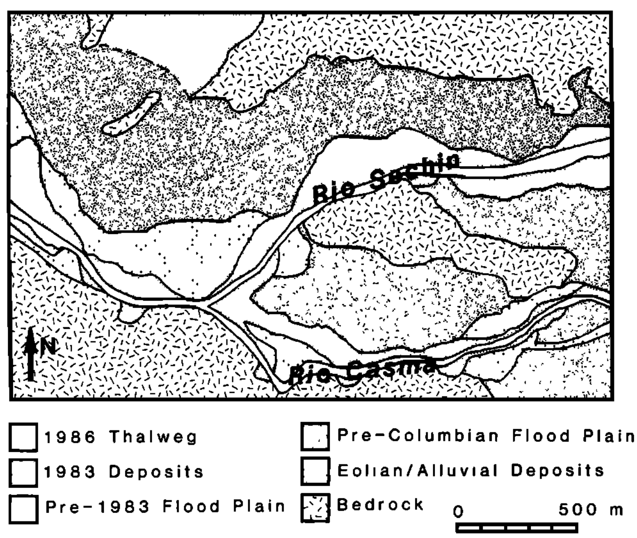

Fig. 2. Holocene alluvial deposits at the confluence area of Rio Sechin and Rio Casma (see Figure 1 for location). The map shows the surficial distribution of (1) the deposits of the 1982-1983 El Niño event, (2) the pre-1982 but recently active floodplain (based on the relatively poor agricultural development on this surface), and (3) the pre-Columbian floodplain (sediments include pre-Columbian artifacts). Area was first mapped at a scale of 1:10,000 from areal photographs taken early in 1982 (about 9 months prior to any flooding); subsequently, the 1982-1983 deposits were added to the map in the field.

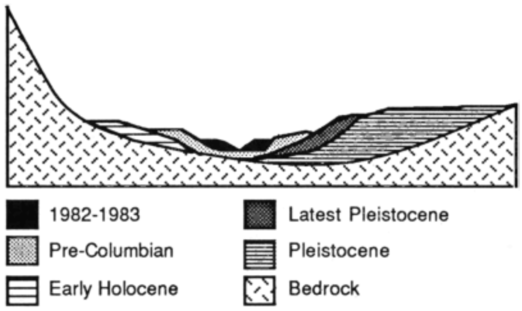

Fig. 3. A schematic alluvial fill model for Rio Casma and Rio Sechin. The diagram represents a cross section perpendicular to the main axis of the valley. The alluvial fill forms inset cut-and-fill terraces which can be correlated throughout the region.

due to rapid coastal progradation, is within a meter of present mean sea level (D. Sandweiss, unpublished topographic data, 1986). As the major floodplain terrace has been active within the last 1000 years (based on included human artifacts), and since there is no evidence for base level change (tectonic or eustatic) during this time, then these floodplain deposits must have resulted from flood discharges much larger than the 1982-1983 floods.

Deposits of the high floodplain (Figure 3, pre-Columbian floodplain) have a relatively high preservation potential. During large floods, with overbank deposition onto this high floodplain, most of the material near the active thalweg is reworked, and therefore long-term preservation of the deposits of smaller flood events (i.e., deposits on or below the 1982-1983 floodplain of Figure 3) is unlikely. As would be expected given the greater opportunity for reworking in the oldest sediments, the resolution of the record decreases with age. Deposits of the largest events (very strong or greater using the scale of Quinn et al. [1986]) make up the majority of the stratigraphy presented here; it should, however, be noted that, because of the resolution problems, the younger record likely includes events of lesser magnitude.

El Niño induced overbank flooding leaves a sheet of sand and some gravel on the floodplain. In the dry years, between major El Niño events, fluvial incision exposes these overbank deposits. The 1982-1983 El Niño sediments of the Rio Casma, Rio Sechin, and Quebrada Rio Seco valleys are described below and compared with the deposits of older floods. These data are then used to develop a chronology of major flood-producing El Niño events.

El Niño Flood Deposits

The 1982-1983 Deposits

Flood sediments of the 1982-1983 El Niño event were studied to characterize an El Niño deposit. Sedimentary structures indicate that depositional

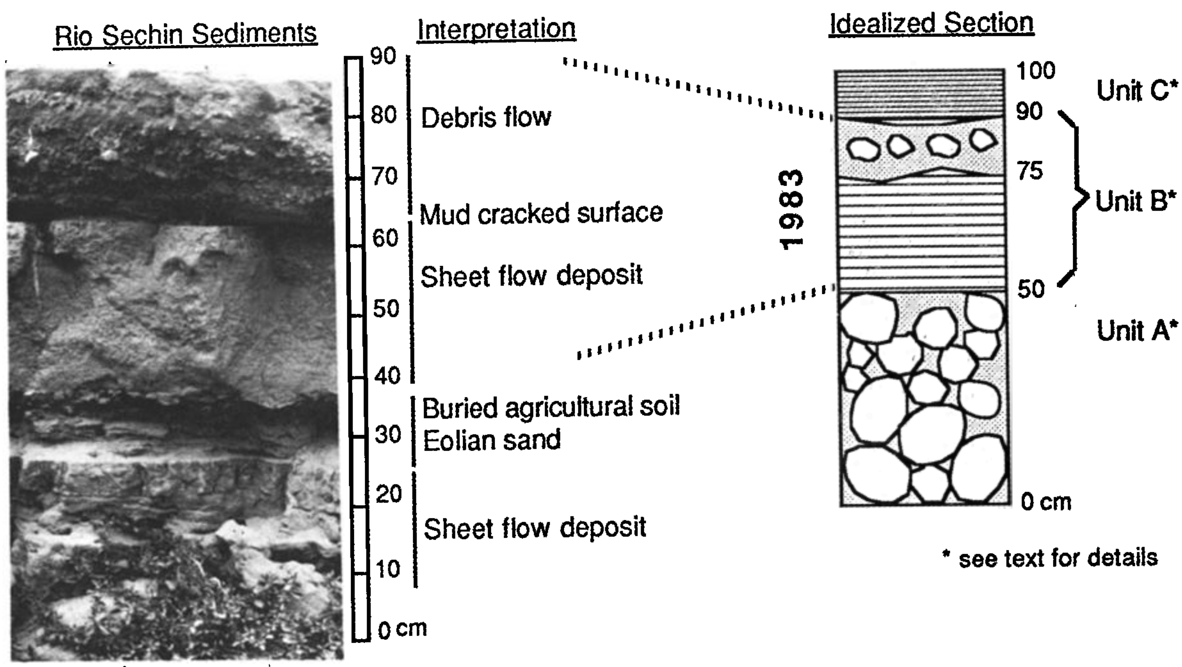

Fig. 4. A typical El Niño deposit. (Left) An idealized synthesis, from numerous outcrops of the 1982-1983 El Niño flood deposits.(Right) A photograph of one of the outcrops (for location see Figure 2). In the synthesis, unit A is a basal-cobble gravel with a clean sand matrix, unit B is composed of one or more sand sheets, unit C is a silty sand bed, unit D (not shown in the figure) is a very fine layer of silt or clay that generally caps the deposits. In the photograph, a pre-1983 flood sheet (0-28 cm) buried by an eolian sand on which an agricultural soil is present (28-38 cm), in turn buried by the deposits of the 1982-1983 El Niño (the base of the 1982-1983 deposits was determined by lateral correlation with a buried tree). The 1982-1983 deposit is made up of two separate flood sheets, a basal sheet flow deposit overlain by a debris flow deposit. Mud cracks on the surface of the sheet flow suggest that sufficient time passed between the two flood events to dry the surface.

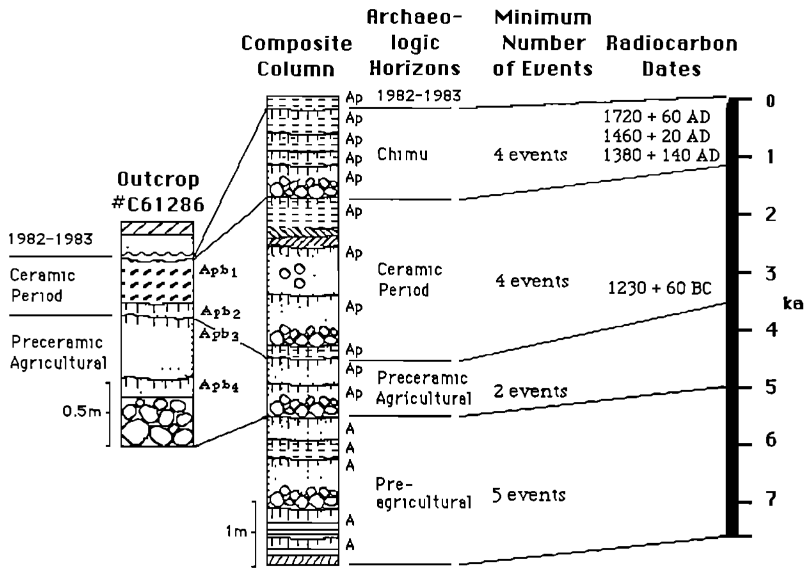

Fig. 5. Holocene stratigraphy of the Rio Casma and Rio Sechin valleys. From right to left are shown a sketch of a single outcrop, a composite stratigraphic column, the archaeologic stratigraphy as based on included artifacts and superimposed archaeologic sites, the minimum number of El Niño events for any given time period, and the absolute chronology as based on radiocarbon dates from detrital wood. The composite stratigraphic column was developed from numerous outcrops of the Holocene sediments. Note the scale change between the sedimentary columns. Ap horizons are agricultural soils, A horizons are nonagricultural soils. The minimum number of events is developed from the alluvial stratigraphy and archaeology. In the radiocarbon stratigraphy there is an overlap in the error margin of the two center dates; they may represent the same event.

processes ranged from sheet flow to debris flow. Sheet flow deposits occur throughout the valleys, whereas debris flow deposits tend to be concentrated near the confluences of small tributaries which were active during this event. Not all tributaries were active; the distribution of active tributaries suggests that flash flooding was local and sporadic.

An idealized El Niño deposit (composed from a synthesis of many descriptions of individual outcrops of the 1982-1983 deposits) is shown in Figure 4 and described below from base to top. A typical deposit of the 1983 floods is also shown in Figure 4.

Unit A. A 50- to 100-cm-thick basal-cobble gravel with a matrix of clean sand. These basal deposits are most common near the main active channel and are absent on the overbank floodplain. The gravels are thickest and coarsest upstream and become progressively thinner or are absent in the lower reaches of the stream.

Unit B. One or more 10- to 150-cm-thick sand sheets. Unstructured sands, planar-, wavy-, and cross-laminated sands are all present, but the structures are indistinct, defined only by very thin planes of heavy minerals (cross laminations) or silt (wavy laminations). In areas near active tributaries, debris flows have added a coarse component to these sands; this results in reverse to normally graded sand sheets with a concentration of pebbles in the center of the bed.

Unit C. A 1- to 10-cm-thick planar- and wavy-laminated or unstructured silty sand or silt bed.

Unit D. A very thin layer of silt or clay capping the deposit.

The base of the 1982-1983 deposits is marked by the root zone of live-buried trees, or by the burial of agricultural soils and very recent human artifacts. Multiple sand sheets of unit B likely record different flood surges during the El Niño event. Units C and D are deposited from suspended materials as the waters recede. The upper surface of the deposit commonly displays the original shear flow lines crosscut by postdepositional mud cracks, and with human and animal footprints. By 1986, farmers were beginning to reclaim the 1982-1983 flood sands, and agricultural soils are beginning to form.

Earlier Holocene El Niño Events

The Holocene floodplain is easily recognizable in the study area owing to a lack of significant soil development and the inclusion of human artifacts within the sediments (see Figure 2). Holocene sediments fill entire valley widths and generally are deposited against the bedrock walls of the valley (except where the valley is very wide and the Holocene fill is deposited against Pleistocene alluvial deposits). Earlier Holocene flood deposits are exposed in many river cuts and locally in small wells. The base of the Holocene section is here placed at about 7500 B.P., as that is about the time of the local maximum shoreline transgression (unpublished radiocarbon dates on marine shell in coastal middens; T. Pozorski and S. Pozorski, personal communication,

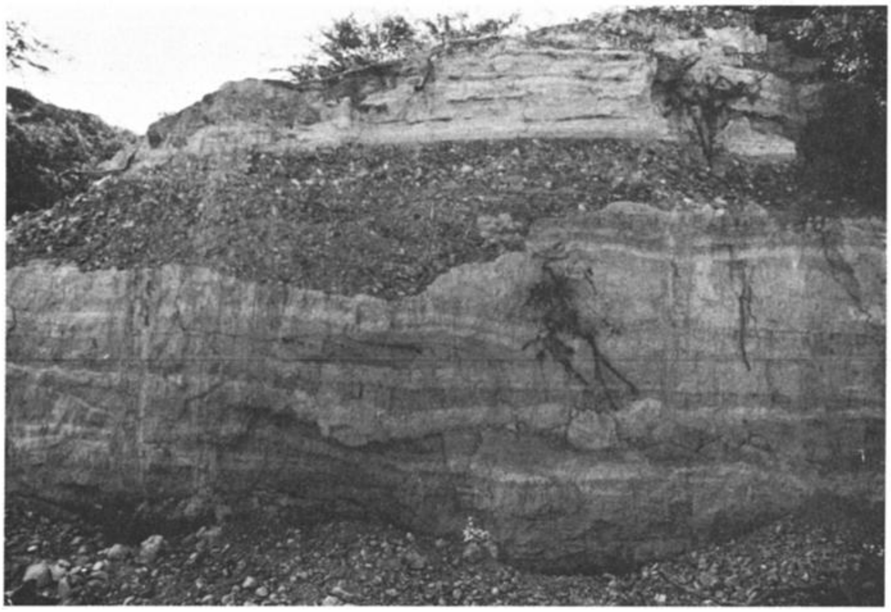

Fig. 6. Late Pleistocene fluvial deposits exposed in Rio Sechin just downstream of Buena Vista. A large gravel-filled channel is present in the upper portion of the river bank exposure. Overbank flood deposits are present in the lower portion of the exposure. The color banding, in the silts, is due to the development of Bw soil horizons (cambic horizons with incipient color change due to iron oxidation) within the deposits. The exposure is about 15 m high.

1986), and it is likely that the Holocene alluvial filling of the river valleys began near this time as well. The stratigraphy (Figure 5) is composed of stacked beds of sand, silt, and gravel. A maximum of eight distinct flood deposits are present in a single outcrop.

Sedimentary structures exposed in Holocene deposits are like those in the type deposit described above. Not every deposit includes all of the individual units described, but most include units B and C (sand sheets fining upward to a silty sand). Basal gravels are common but not always present; they are probably most common in the area near the thalweg just prior to flooding. The upper surfaces of many late Holocene sand sheets are reworked by agricultural plowing, and buried agricultural soils (Ap horizons) are present. The human reworking of the floodplain has provided much of the potential for absolute dates on these deposits owing to the addition of an organic component to the soils.

Pleistocene Deposits

Late Pleistocene floodplain deposits are exposed in river cuts where the main valley is very wide, at confluences with major tributaries. These sediments are distinguished from the Holocene sediments by the degree of soil development on terrace surfaces. (Earlier and late Pleistocene are used here to refer to the relative ages of the deposits, as no absolute chronology is available for these deposits.) The late Pleistocene deposits (Figure 6) are composed of flood sands and silts sedimentologically identical to those seen in the Holocene deposits. Buried soils (A and Bw horizons) in these flood deposits are similar to buried and relict soils in the early Holocene deposits (pre-agricultural), suggesting that soil formation processes, in the overbank environment, have not changed significantly during this time. This similarity of soils and sediments suggests that a similar climate was present during the late Pleistocene. A minimum of 21 flood events are recorded in the late Pleistocene section.

Twenty meters of earlier Pleistocene playa sediments are exposed in the Quebrada Rio Seco valley. These sands and silts are comprised of two facies: (1) planar- and ripple-laminated sands overlain by silt beds with common contorted bedding and mud curls and (2) planar and eolian cross-bedded sands (Figure 7). These facies may be interpreted as playa deposits, resulting from sporadic rainfall and flooding, in a ponded basin (facies 1), with subsequent drying of the surface (mud curls) and burial by eolian deposits (facies 2). There is no longer any evidence for the mechanism of ponding of this drainage, and it is suggested that a large sand dune may have at one time blocked the lower end of the valley. This mechanism of damming valleys is common in this hyperarid desert today, and the rapid erosion that would take place once the stream breached the dune would destroy any long-term evidence of the dam, besides the ponded sediments themselves. Over 100 mud-cracked silt layers are preserved at Quebrada Rio Seco, recording sporadic Pleistocene rainfall in a hyperarid environment. A small fragment of detrital wood was found near the top of the playa sediments. This wood yielded an age beyond radiocarbon-dating potential (SMU-1687), implying that El Niño like events may have occurred more than 40,000 years ago.

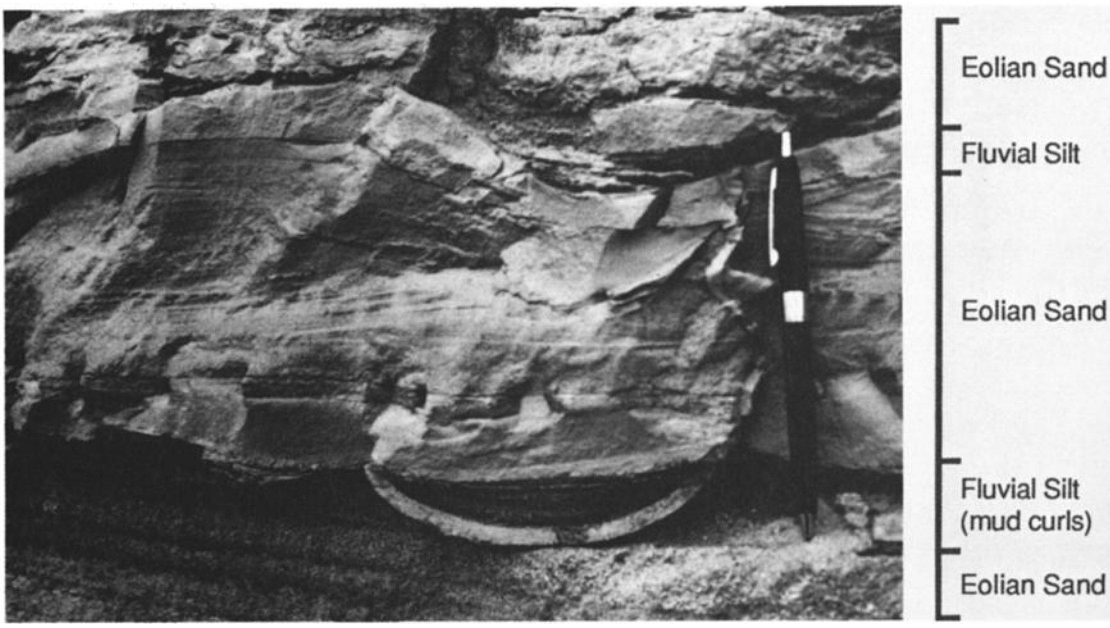

Fig. 7. Pleistocene playa sediments now exposed in the lower Quebrada Rio Seco Valley. The deposits are comprised of interbedded eolian sand (planar and cross laminated) and fluvial sands and silt. The deposits record Pleistocene flood events in an arid environment.

Development of a Holocene Chronology of El Niño Events

The development of a Holocene chronology of El Niño events from the floodplain stratigraphy depends on relative and absolute dating methods. Geomorphology and surficial geology provide the relative chronology, while archaeology and radiocarbon dating provide absolute dates within the relative chronology.

Geomorphology and Surficial Geology

The Holocene valley fill forms inset cut-and-fill terraces (see Figure 3). Relationships among terraces and associated deposits establish a chronology among near-surface flood sediments. Unfortunately, the complex stratigraphic relationships preclude simple correlations between exposures of the subsurface deposits. Individual beds do not necessarily correlate between outcrops because (1) only the largest events affect the entire floodplain, whereas smaller events will cause erosion and deposition on seemingly random parts of the floodplain, and (2) the largest events cause flooding to occur over the top of all earlier deposits and leave a drape of sediments over the entire floodplain. Some isochrons can, however, be established within the deposits based on the archaeology discussed below.

At Quebrada Rio Seco, discharge presently occurs only during major El Niño events. The valley therefore lacks the incision which occurs between flood events in the larger valleys. The surface of a number of different-aged deposits, however, has been preserved on small interfluves. Degradation of mud cracks and mud drapes over boulders, and a discoloration of the surfaces through time, allows for a relative chronology of these deposits to be established. Three distinct events were recognized solely on this basis, and the chronology was confirmed by radiocarbon dating of detrital wood fragments included within the deposits (see Figure 5). The presence of a 3200-year-old interfluve (see below, SMU-1692) within just 50 cm of the surface of the 1982-1983 deposits suggests relative stability of this drainage for at least the latest Holocene.

Archaeology

The rich history of human occupation in the Casma valley [Tello, 1956; Fung and Williams, 1977] provides much potential for dating the fluvial stratigraphic column: (1) the initiation of agriculture and the preservation of early prehistoric agricultural soils provide an isochron within the deposits, (2) the initiation of the use of ceramics provides a second isochron within the deposits, (3) detrital ceramic shards and stone tools, of known age, must predate the sediments in which they are included, and (4) superimposed archaeologic sites must postdate the deposits on which they are built.

Flood deposits ponded within archaeologic sites can provide very precise dates for El Niño events if the stratigraphy of the site is well known. The deposits are trapped in rooms or other artificially closed basins. One such date has been derived from sediments ponded within the Cerro Sechin archaeologic site in the Rio Sechin valley. The well-developed stratigraphy at Cerro Sechin [Samaniego et al., 1985, pp. 179-182] includes many distinct flood deposits. The alluvial fill of the south passage contains a distinct flood sheet (a bed fining upward from sand to silty sand to silt) with human footprints preserved in the upper surface, and which is dated at 1200 B.C. by correlation of archaeologic artifacts (site curators, personal communication, 1986); this date corresponds with one of the radiocarbon-dated events (see below). The ponded areas present within archaeologic sites provide the potential for recording events of a much smaller scale than would generally be preserved within the floodplain.

A combination of the fluvial terrace stratigraphy with the archaeology provides a more detailed chronology. A minimum number of El Niño events within time spans defined by the archaeologically based isochrons is now known for the Casma region. There have been a minimum of 15 Holocene El Niño events large enough to leave significant flood deposits (see Figure 5). Five of these events occurred between 5000 and 7500 B.P., prior to any human agricultural development. Two events occurred between 3500 and 5000 B.P., between the development of agriculture and the beginning usage of pottery. One event occurred around 3200 B.P. (see the description of the Cerro Sechin site above). One event occurred between 2500 and 3000 B.P.; distinctive ceramic shards at many localities define this date. Two events occurred between 1100 and 2000 B.P., between isochrons defined on the basis of ceramic styles. Four events occurred between 500 and 900 B.P., postdating the isochron defined by the introduction of Chimu style ceramics to the valleys.

Absolute Dating

The flood sediments commonly contain detrital carbon. In 1986, 24 detrital charcoal samples, four detrital wood samples, three peat samples, and two shell samples were collected; these samples have been submitted for radiocarbon dating. Detrital charcoal from sediments deposited during agricultural times has a high potential for providing accurate dates on El Niño events. The detrital charcoal comes primarily from reworking the surface of burned fields. In general, the charcoal must have been relatively fresh when reworked, as older charcoal, from earlier burns, is rapidly broken down by subsequent plowing, irrigation, and plant growth. In rare cases, charcoal and plant debris from a burnt surface were actually buried in place by an overbank flood sand, thus providing a very precise potential date for the overlying deposit. A few of the charcoal samples appear to come from sediments which predate agricultural development of the valley, but this is not definite, as they may come from areas of the floodplain which were not agriculturally developed at the time of flooding. It is expected that the dates will cluster and that discrete flood events may thereby be recognized.

From work completed during 1985, a minimum of three, and possibly four, El Niño events are absolutely dated (see Figure 5). Dates are from detrital wood samples from flood sands in Quebrada Rio Seco and Rio Casma and are calibrated to the Irish Oak chronology of Pearson [1986]. The known dates are (1) 1720 ± 60 A.D. (average of two dates: 1730 ± 80 A.D. (SMU-1694) and 1700 ± 100 A.D. (SMU-1696)), (2) 1460 ± 20 A.D. (SMU-1693), (3) 1380 ± 140 A.D. (SMU-1669) (may be the same flood event as date 2 above), and (4) 1230 ± 60 B.C. (SMU-1692).

Conclusions

The unique climate on the northern coast of Peru allows for a direct correlation of Holocene flood events with El Niño climatic events, and a very likely correlation of late Pleistocene flood events with El Niño events. These deposits have been used to develop a chronology of El Niño events based on numerous different lines of evidence. Figure 5 summarizes the El Niño chronology established here. With the above-mentioned absolute dates and the one known date from an archaeologic site, a total of four late Holocene El Niño events have been absolutely dated, and a minimum of 15 Holocene events are relatively dated. The stratigraphy exposed in the late Pleistocene fluvial deposits suggests that there were a minimum of 21 El Niño type events during the late Pleistocene, and possibly over a hundred El Niño type events occurred over 40,000 years ago.

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