CHAPTER 17

Beach Ridges and Major Late Holocene El Niño Events in Northern Peru*

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ABSTRACT: Northern Peru is the homeland of the El Niño phenomenon and constitutes one of the key areas for the reconstruction of a chronology of paleo-ENSO events. This is commonly accepted for the last few centuries (QUINN *et al.*, 1987) but may also be true at a longer time scale. In northern Peru, sequences of Holocene beach ridges are restricted to the mouths of the two major permanent streams of the area. We reexamine briefly the geometrical disposition and the available geochronological data from the three series of beach ridges preserved north and south of the Chira River mouth (Chira and Colan sequences), and north of the Piura River mouth (Sechura sequence). Sedimentological and geomorphological characteristics of the three sequences confirm that the formation of the beach ridges required meteorologic and coastal oceanic conditions that would correspond to exceptionally strong El Niño events (stronger than the 1982–1983 event). Radiocarbon data from marine shells and from charcoal fragments, collected either within or upon the ridges, support a ridge-to-ridge chronological correlation between the three sequences. It appears that, in the course of the last 5,000 yr, ridge-forming conditions recurred at time intervals varying from 100 to 600 yr. The eleven beach ridges that were formed in northern Peru are interpreted to have registered the strongest ocean/climate El Niño anomalies that occurred in the second half of the Holocene.

INTRODUCTION

Along the northern coast of Peru, sequences of Holocene beach ridges are scarce. In only four localities, close to the mouth of the three major rivers of northern Peru, series of beach ridges have been preserved (Figure 1). Several authors hypothesized that these coastal remnants may have recorded major El Niño events in the course of the last few thousand years (RICHARDSON, 1983; SANDWEISS, 1986; ROLLINS *et al.*, 1986; ORTLIEB *et al.*, 1989; MACHARÉ and ORTLIEB, 1990). As the El Niño phenomenon is characterized in northern Peru by heavy rainfalls, exceptional river runoff, rough seas and a temporary sea-level elevation (ENFIELD, 1987, 1989; PHILANDER, 1990), it has been suggested that a combination of these climatic and oceanographic effects was responsible for the formation of beach ridges close to major river estuaries. During El Niño years, the sediment that constitutes the ridges would have been carried to the coastal zone by flooded rivers and the beach ridges would have formed in response to the higher than normal energetic conditions observed in the nearshore area. This theoretical scheme has been questioned by certain authors (*e.g.*, CRAIG, 1992) who noted for instance that the recent 1982–1983 El Niño event, one of the strongest observed during the last four centuries (WOODMAN, 1985), did not produce any new beach ridge in the northern Peru sequences. Other authors considered that the beach ridges were related to "El Niño-like conditions" but that they were too voluminous to have been formed coevally with single El Niño events (MARTIN *et al.*, 1992a,b).

The complete geochronological data obtained from the two northernmost beach-ridge sequences, preserved on both sides of the Chira River mouth, the so-called "Chira" and Colan sequences (Figure 1), were recently reexamined (ORTLIEB *et al.*, 1993). Limitations of the radiocarbon dating method (through the traditional—not AMS—measurement technique) hindered a straightforward and precise age determination of the formation of each beach ridge. However, a chronological correlation of the two sequences, partly based upon the geomorphological characteristics of the ridges and their geometric disposition, was proposed.

In this short paper, we recall the geochronological background of the correlation between the ridges of the Colan and Chira sequences, add some data on the Sechura sequence, and discuss the correlation between the ridge-forming episodes and the El Niño phenomenon during the last few millennia.

THE BEACH-RIDGE SEQUENCES OF NORTHERN PERU

Preservation of Series of Beach Ridges

Beach ridges are common features along sandy coasts that experience depositional progradation, especially in areas downdrift from river mouths where large sediment supply is made available. Series of beach ridges generally reflect recurrent processes and intermittent sediment supply that may be related to tectonic, climatic, or oceanographic

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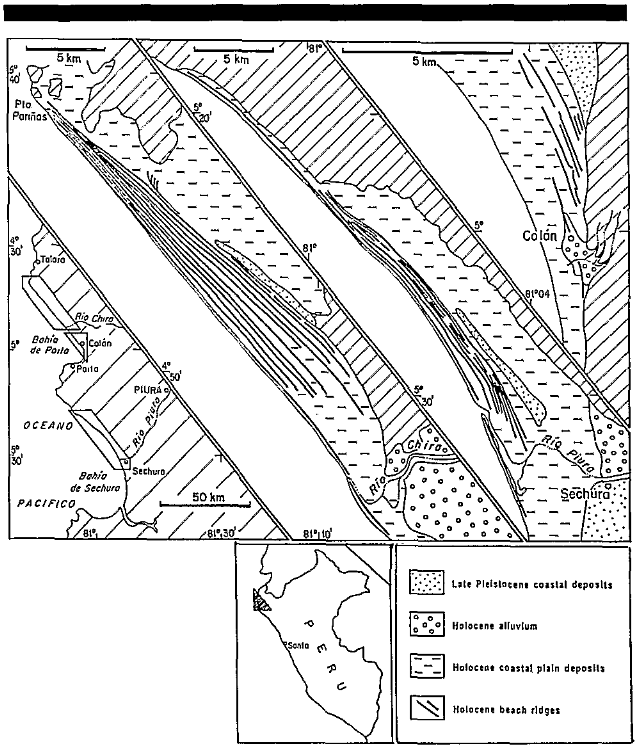

Figure 1. The sequences of Holocene beach ridges in northern Peru: Location and schematic geological setting.

phenomena. As a rule, sequences of beach ridges can be preserved whenever repeated ridge-forming processes do not lead to the destruction of the beach ridges previously built up. More specifically, the preservation of a beach-ridge series is favored in two kinds of circumstances: when a relative lowering of sea level has occurred or when a rapid progradation of the coastal area was combined to a large, episodic, sediment supply. In northern Peru, both conditions were apparently met in the late Holocene; a slight relative fall of sea level since the mid-Holocene maximum highstand seems to have occurred (WELLS, 1988; ORTLIEB and MACHARÉ, 1989a), and some coastal sectors, particularly near the mouth of the Chira, Piura, and Santa rivers did prograde during the last few millennia.

Description of the Peruvian Series of Beach Ridges

The aridity of the coastal regions of northern Peru explains why very few permanent rivers reach the sea. These rivers (Santa, Piura and Chira Rivers) are those which can carry enough sediment to sustain the development of beach-ridge sequences when exceptional rainfalls occur in the area. Because of the northward longshore drift, related to the trade winds system and the Peru Current, the beach-ridge sequences normally extend north of the estuaries of these major rivers (Figure 1).

The northernmost sequences of beach ridges is located immediately north of the Chira River mouth (Figures 1 and 2). It consists of nine ridges which measure up to 20 km long, 100–300 m wide and are 3 to 4 m high (Figures 2 and 3). The ridges are made of unfossiliferous sands directly derived from the Chira River (CHIGNE, 1975). They are widely covered by midden shells spread over the ridges by prehistoric Indian populations. These sheets of midden shells played an important role in preserving the ridges from erosion and deflation. The sequence of beach ridges may be divided into two sub-units: an older one with four well-defined, higher ridges, and a younger sub-unit with fiver closely-spaced, lower ridges (RICHARDSON, 1983). The two sub-units are separated by a relatively wide inter-ridge area which may reflect a long episode during which no ridge was formed. The ridges were numbered I to IX, from the youngest to the oldest by RICHARDSON (1983) and J to R from the oldest to the youngest by ORTLIEB *et al.* (1993).

The Sechura sequence consists of eight wide sandy ridges that extend north of the Piura River estuary (locally called Sechura River) (Figure 1). Like in the Chira sequence, the Sechura beach ridges are made of river-derived sands and extend for about 10 km along the northern shore of the Sechura bay. The southern extremity of the ridges are partly covered with midden shells, but not to the extent of those of the Chira sequence; as a consequence, the ridges suffered some erosion and present less steep profiles than those of the Chira sequence. This sequence of beach ridges is least known and studied, mainly from an archeological point of view (LANNING, 1963; RICHARDSON and MCCONAUGHY, 1987).

Another beach-ridge sequence, located north of the Santa River mouth, that developed in the last 4,000 yr (SANDWEISS, 1986; WELLS, 1988; DEVRIES and WELLS, 1990; PERRIER *et al.*, 1992, 1994) must also be mentioned here. The Santa ridges are made of pebbles carried to the nearshore by the largest of the Peruvian rivers. The Santa River, which drains part of the Cordillera Blanca and Cordillera Negra of the high Andes, is directly influenced by the glacier system and the cordilleran precipitation; thus, its hydrological regime is totally different from the Piura and Chira rivers. Actually, studies of distinct sets of aerial photographs and satellite imagery showed that a poor correlation existed between El Niño events during the last few decades and the episodes of formation of the most recent beach ridges at Santa (WELLS, 1988; MOSELEY *et al.*, 1992). Thus, the Santa beach-ridge sequence appears to record former pulses of coarse sediment supply that were not directly and unambiguously linked to the El Niño climatic anomalies during the last few millennia (ORTLIEB and MACHARÉ, 1993).

The last example, the Colan sequence, is atypical in several ways: the sequence of ridges is located in an anomalous position, south of the Chira River mouth (Figure 1), and the beach ridges are essentially made of pebbles while the deltaic costal plain is exclusively sandy. The pebbles are eroded from conglomerate beds that crop out in an overhanging paleo-seacliff, some 50 m above the coastal plain (Figure 2). The sediment composition varies within the ridges and also from one ridge to the other: the grain-size of the largest clasts diminishes progressively northward and from the oldest ridges to the more recent ones. These gradients indicate that the main source of the pebbles was located at the foot of the seacliff and in the case of the youngest ridges at the base of the small alluvial fan of Colan (Figure 1). At Colan, the beach-ridges are of smaller size than in the other sequences. They measure at most

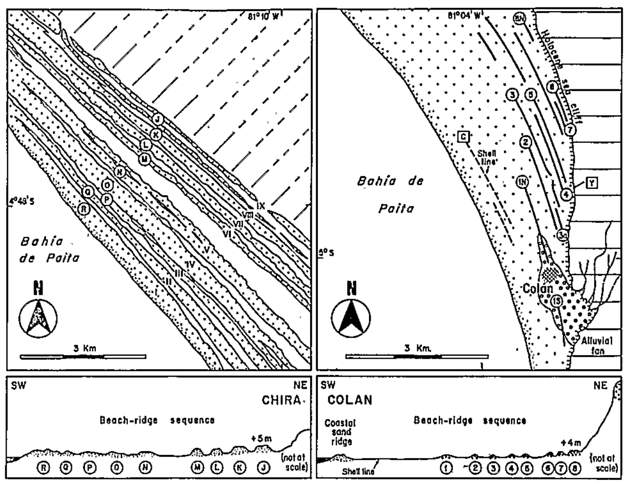

Figure 2. Comparison of the Chira and Colan beach ridge sequences: location sketch and schematic cross section, with identification of the ridges (at Chira, roman numerals refer to the work of Chigne, 1975 and Richardson, 1983). See difference of ridge size between the two sequences.

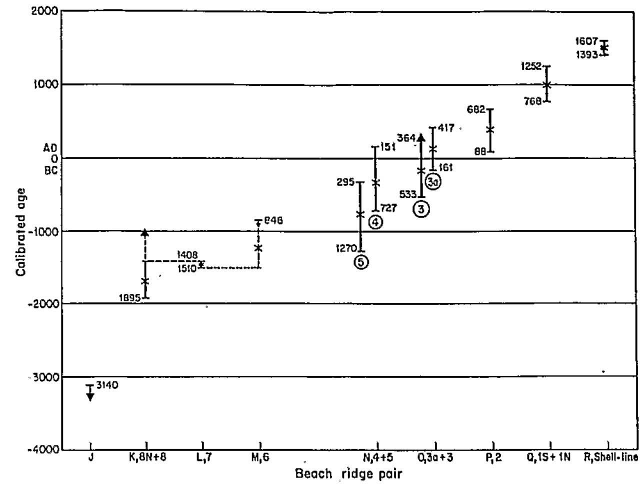

Figure 3. Chronological correlation between the Chira and Colan beach ridge sequences, with indication of estimated age ranges including confidence interval, expressed in calibrated years. The chart was constructed by combining the minimum age estimates of the Chira ridges ("archeological" samples) and the maximum age estimates deduced from the Colan data ("geological" samples).

a few kilometres long, 15 to 50 m wide, and are 1.5 to 3.5 m high over the deltaic plain (Woodman and Polia, 1974; Ortlieb *et al.*, 1989) (Figure 2). The beach ridges of the Colan sequence are numbered according to the previous work of Woodman and Polia (1974), from the youngest (Ridge 1) to the oldest (Ridge 8) (Figure 2).

Genesis of the Ridges at Colan

The coarse lithologic composition of the ridges contrasting with the sandy substrate of the deltaic plain implies that the beach ridge forming processes involved: (1) the erosion of the Plio-Pleistocene conglomerate units, (2) the transport of the eroded shingle to the shoreline, and (3) the formation of the beach ridge by northward longshore drift. The erosion of the conglomerate and the concentration of shingle at the foot of the cliff were interpreted as closely related to the exceptional rainfalls that occur in the area during strong El Niño events (Ortlieb *et al.*, 1989; Macharé and Ortlieb, 1990). The reworking of the shingle along the paleo-coastlines, in the form of supratidal ridges, was probably controlled by temporarily higher-than-normal sea levels (which compare with the +0.50 m anomaly observed during the 1982–1983 event) and by episodes of intense wave energy (also characteristic of El Niño conditions).

At Colan, the modern coastal ridge (Figure 2) is distinct in nature from the Holocene coarse-grained beach ridges. This supratidal ridge, essentially made of coastal and windblown sands, is genetically linked to non-El Niño conditions; during the very strong 1982–1983 El Niño event, for instance, it suffered a severe erosion, as a combined result of increased storminess, sea-level elevation and strong local rainfall.

The Genetic Relationship Between the Beach Ridges Sequences

In each of the three northernmost localities (Chira, Colan and Sechura), eight or nine beach ridges were preserved (Figure 1). This coincidence strongly suggests that the successive ridges were formed coevally, in response to a regional, recurrent phenomenon. As tectonic motions have been disproven in the formation of the ridges (though previously envisaged in the case of the Colan ridges by Woodman and Polia, 1974), one may infer an external geodynamic control in the genesis of these features (Ortlieb and Macharé, 1989; Ortlieb *et al.*, 1989; Macharé and Ortlieb, 1990). Such recurrent conditions might be a series of major episodes of oceanic/climatic changes.

The strong differences in the sedimentologic composition of the ridges and in location with respect to the river mouths do not contradict the hypothesis that the Chira, Colan and Sechura ridges were formed coevally. The unusually strong rainfalls able to erode pebbles in the Colan seacliff were the same that induced tremendous and sudden increases in the Chira and Piura rivers runoff and sediment supply. Under present-day conditions, such meteorologic conditions are strictly limited to the strongest El Niño events.

The very strong 1982–1983 El Niño event did not lead to the formation of any beach ridge in northern Peru, but for different reasons, that are related to: (1) man-made modifications recently made along the course of the Chira and Piura rivers (dams and diversions) and (2) recent progradation of the shoreline in the Colan area. The progradation of the deltaic plain of Chira River explains that at Colan, the source of coarse material which might be reworked in supratidal ridges was totally cut after the formation of Ridge 1 (*ca.* 1,000 BP); in the present configuration of the bay, El Niño conditions like those of 1983 lead to a partial destruction of the modern littoral sandy ridge and a general flooding of the Colan coastal plain. The net erosive action of the El Niño phenomenon in this area, during the last millennium, is documented by two "shell-lines" preserved between the older ridges and the coastline

Table 1. ^{14}C data from the sequence of beach ridges of Colan, with estimates of maximum age of the ridges (charcoal fragments and shells from within the ridge sediment).

Beach-ridge #	Sample (field) #	Lab. analysis # (1)	Nature of sample (2)	Measured C-14 age (BP)	delta C-13 (/PDB)	Normalized C-14 age (BP) (3)	Corrected age (for reservoir effect) (4)	Maximum age of beach-ridge (BP) (5)	Calibrated (BC/AD) max. age of beach-ridge (6)
8N	P.393 P.394 P.395	By 688 By 690 By 686	charcoal *Tivela hians* *Donax* + spp	3340±45 3210±40 3210±50	-26.6 +0.75 +1.34	3310±45 3630±40 3640±50	 3410±90 3420±100	3310±45	1675- 1542 BC
8	P.176 P.174 P.175	By 316 By 331 By 345	charcoal several spp several spp	3170±300 2890±250 3020±250	-27.8 +0.51 +1.26	3130±300 3300±250 3450±250	 3080±300 3230±300	3130±300	1776- 1030 BC 1697- 955 BC
7	P.187	By 380	*Donax* + spp	2760±210	+1.62	3190±210	2970±260	(2970±260)	1510- 904 BC
5	P.189 P.190	By 324 By 350	charcoal *Tivela hians*	2550±490 2510±250	-27.05 +0.47	2520±490 2920±250	 2700±300	>2520±490	> 1270- 68 BC
Locality Y	P.237 P.238	By 410 By 402	*Donax* *Tivela hians*	2430±240 2280±200	+1.16 +0.89	2860±240 2700±200	2640±290 2480±250	<(2480±250)	< 901- 295 BC
4	P.194	By 382	*Donax* + spp	2150±170	+0.49	2560±170	2340±220	(2340±220)	727- 173 BC
3	P.199 P.200 P.197	By 323 By 322 By 349	charcoal charcoal *Olivella* + spp	2080±540 2040±380 2170±300	-26.7 -27.01 +1.56	2050±540 2010±380 2600±300	 2380±350	2010±380	533 BC- 364 AD
3a	P.209	By 381	*Donax*	1660±180	+1.29	2090±180	1870±230	(1870±230)	161 BC- 376 AD
2	P.202	By 379	*Donax* + spp	1450±180	+1.24	1880±180	1660±230	(1660±230)	88- 578 AD
1N	P.207	By 351	*Donax* + spp	960±230	+1.34	1390±230	1170±280		
1S	P.214	By 383	*Donax* + spp	790±210	+0.05	1200±210	980±260	(980±260)	768- 1235 AD
flat *	P.235	By 441	*Donax*	730±190	+0.83	1150±190	930±240		
shell-line & site C	P.181 P.170	By 424 By 320	*Tivela hians* charcoal	180±160 620±290	+0.15 -26.6	590±160 590±290	370±210	(370±210)	1393- 1803 AD

(1) # of analysis from ORSTOM-Bondy geochronological laboratory.
(2) *Donax*: *D. peruvianus* (=*D. obesulus*); *Olivella*: *O. columellaris*; spp: distinct genus and species of molluscs.
(3) Correction for isotopic fractionation (delta C-13= -25 per mil/PDB), according to Stuiver and Robinson (1974) corrected activity= measured activity x $[0.975^2/1 + (\text{delta C-13}/1000)^2]$.
(4) Correction for so-called "reservoir effect", with factor R= 220 ± 50 yr (according to Stuiver *et al.*, 1986); results and sigmas are rounded off to the nearest multiple of ten (Stuiver & Polach, 1977).
(5) Maximum age of beach ridges is given by the youngest available date from charcoal sample collected within the ridge sediments. When no charcoal data are available, the (youngest) shell date is used (results in parenthesis).
(6) Calibrated ages are calculated according the software "CALIBETH", ver. 1.5b (1991) from Stuiver & Becker, 1986.
BC= Before Christ; AD= Anno Domini (after Jesus-Christ).
* In situ shells cored below the surface of the coastal plain, between beach-ridge 1 and modern coastline.

(Figure 1); these features constitute subdued remnants of former sandy ridges that suffered a subsequent and partial erosion.

GEOCHRONOLOGY OF THE BEACH RIDGE SEQUENCES

The Dated Material: Chronological Significance and Relevancy

Radiocarbon dating was performed on marine shells and charcoal fragments sampled either within the ridge sediment, or atop the ridges. Material collected within the sediments, by trench-cutting across the whole ridges as in the case of Colan, has a quite distinct chronological significance than shells or charcoal fragments collected in superficial hearths on top of the ridges (Chira, Sechura). The "archeological" material clearly postdates the ridge building, while shell samples within the ridge sediment necessarily predate the final ridge-forming process.

The molluscan shells embedded in the beach-ridge sediment may be reworked and could be much older than the formation of the ridges. At Colan particularly, we selected small, well-preserved shells (*Donax peruvianus*, occasionally found in paired connection, and *Olivella columellaris*) as this material is the most likely to be contemporaneous with the episode of ridge formation.

In a few instances, at Colan, some tiny charcoal fragments were also collected within the ridge sediment; this material is considered as remains of anthropogenic activity that had been reworked by the waves and deposited together with the pebbles, sand and shell material during the episode of ridge formation. In this case, at Colan, charcoal apparent ages must be considered as maximum ages of the beach ridges (Table 1).

In the Chira area, where the beach ridges are unfossiliferous, the material available for dating purposes consists of midden shells and associated charcoal fragments (hearths) that provide minimum age for the episodes of ridge formation. Some 95% of the shells correspond to two species of pelecypods: *Tivela hians* and *Donax peruvianus*, nearshore species which are still the most abundant today along the coastline. As prehistoric Indians probably ate shellfish close to the shoreline on the last-formed beach ridge, the time elapsed between the beach-ridge formation and its human occupation is assumed to have been short (a few centuries at most).

At Chira, two sets of radiocarbon analyses are available (Table 2): one series of dates from previous archeological studies (Chigne, 1975; Richardson, 1983) and a later series obtained by us (Ortlieb *et al.*, 1993). Most of our samples from the Chira sequence were collected in individual hearths, at a few centimetres below the surface. Hearth sampling was favored because it offers some cross-checking on the dating; one may expect similar ages for the shells and the wood used to cook the shellfish, although the wood may possibly be older (*e.g.*, flotsam material, or old trees).

Table 2. ^{14}C data from the sequence of beach ridges of Chira, with estimates of minimum age of the ridges (archeological material—charcoal fragments and shells—sampled upon the ridges).

Beach-ridge # this study	Beach-ridge # Richardson, 1983	Sample (field) #	Lab. analysis # (1)	Nature of sample (2)	Measured C-14 age (BP)	delta C-13 (/PDB)	Normalized C-14 age (3)	Shell/charcoal data: forced correlation	Shell/charcoal data: factor "S" (4)	Corrected age (for reservoir effect) (5)	Minimum age of beach-ridge (BP) (6)	Calibrated (BC/AD) min. age of beach-ridge (7)
J		P.293 P.294 P.264	By 667 By 693 By 562	*Tivela* charcoal *Tivela*	4210±40 4570±50 3230±40	+0.6 -26.6 +0.42	4630±40 4540±50 3640±40	4540±90 4540±50	90±90	4410±90 3420±90	] 4540 ± 50	3337- 3140 BC
	IX		SI-1450 SI-1420 SI-1456	charcoal charcoal charcoal	4485±80 4255±65 3985±80							
K		P.295 P.296 P.269	By 668 By 648 By 549	*Tivela* charcoal *Tivela*	3310±40 3520±50 3060±30	+0.31 -26.6 +0.58	3720±40 3490±50 3480±30	3490±90 3490±50	230±90	3500±90 3260±80	]] 3490 ± 50	1895- 1767 BC
	VIII		SI-1421	charcoal	3490±80						]	
Inter-ridge		P.300A P.300B	By 671 By 672	*Donax* * *Tivela* *	3410±40 3370±40	+1.15 +0.72	3840±40 3790±40			3620±90 3570±90		
L		P.298 P.299 P.268 P.267	By 669 By 691 By 670 By 525	*Tivela* charcoal *Tivela* *Donax*	3210±35 3190±45 2610±35 2600±150	+0.04 -26.6 +0.06 +1.3	3620±35 3160±45 3020±35 3030±150	3160± 80 3160± 45	460±80	3400±90 2800±90 2810±200	] 3160 ± 45	1499- 1408 BC
	VII		GX-1565	*Tivela*	3500±160							
M		P.305 P.306	By 678 By 689	*Tivela* charcoal	2540±40 2760±40	+0.23 -26.6	2950±40 2730±40	2730±80 2730±40	220±80	2730±90	]] 2730 ± 90	942- 846 BC
	VI		SI-1422 SI-3184	charcoal charcoal	2685±105 2485±70							
N	V		SI-1423	charcoal	1955±100						(1955 ± 100)	97 BC- 151 AD
O	IV		GX-1566	*Tivela*	1550±110		(ca.1990)			(ca.1770)	(1770 ± 110)	(57- 417 AD)
P	III		SI-1424A SI-1424B	charcoal charcoal	1405±75 1305±100						(1405 ± 75)	550- 682 AD
Q	II		SI-1457	charcoal	805±60						(805 ± 60)	1130- 1252 AD
R	I	P.301 P.303	By 673 By 647	*Tivela* charcoal	460±40 380±40	+0.48 -26.6	870±40 350±40	350±80 350±40	520±80	650±90 350±90	] 350 ± 90	1477- 1607 AD

(1) Analysis # of geochronology lab of ORSTOM-Bondy (By), Cambridge, Mass. (GX) and Smithsonian Inst. (SI).
(2) *Tivela*: *T. hians*; *Donax*: *D. peruvianus* (=*D. obesulus*). Shaded data concern samples from archeological hearths, in which charcoal and shells may be considered as penecontemporaneous.
(3) Correction for isotopic fractionation (delta C-13= -25 per mil/PDB), according to Stuiver & Robinson, 1974): corrected activity= measured activity x $[0.975^2/1 + (\text{delta C-13}/1000)^2]$.
(4) Associated charcoal and shell samples from single hearths, thus of similar ages, should provide useful data for the evaluation through time of the reservoir effect that affected the nearshore shells. An empirical factor "S" is thus determined by the difference between the shell normalized age and the charcoal normalized age. "S" varies from 90 to 520 years.
(5) Correction for the "reservoir effect", with factor R= 220±50 yr (according to Stuiver *et al.*, 1986). Results (and sigmas) are rounded off to the nearest multiple of ten (Stuiver & Polach, 1977).
(6) The minimum age of the beach-ridges is given by the (most significant or youngest) C-14 age of charcoal fragments collected atop the ridge. The selected data are indicated by "]". When no charcoal data are available, shell dates are used (data in parenthesis).
(7) Calibrated C-14 ages, according calculation with software "CALIBETH", ver. 1.5b (1991) from Stuiver & Becker, 1986. BC = Before Christ; AD = Anno Domini (after Jesus-Christ).
* In situ shells cored, below the surface, in inter-ridge swale.

In the Sechura area, only a few preliminary ^{14}C results are available. *Donax peruvianus* shells from the oldest Holocene ridge indicate an apparent ^{14}C age of 4,320 ± 40 BP (= 4,520 ± 90 corrected, By 666), while fossil shells from the third youngest ridge provided a 2,770 ± 40 BP age (= 2,970 ± 90 corrected, By 663) (both are subsuperficial, "geological", not "archeological", samples). Previous archeological surveys mentioned the following dates: 1,370 ± 80 BP (ISGS-1233) for a large occupational site (PV10-30, Lanning, 1963) on the last pre-modern ridge, 3,020 ± 70 BP (ISGS-1238) for another shell midden (PV10-75) on the fourth youngest ridge, and 4,700 ± 70 BP (ISGS-1236) ("geological" imbedded Donax shells) for the oldest (eighth) ridge (Richardson and McConaughy, 1987). New radiocarbon data from this area should be produced soon (Richardson, *personal communication*, 1991).

From a methodological point of view, charcoal ^{14}C ages are theoretically more accurate than measurements from nearshore carbonate samples; terrestrial plants are more directly related to atmospheric CO_2 than marine biogenic carbonates that are subject to a "reservoir effect". As a result, marine shells yield ^{14}C (normalized) apparent ages that are generally 200 to 400 yr older than contemporaneous charcoal samples (*e.g.*, Mook and Van De Plassche, 1986). But on the other hand, from chronostratigraphical point of view, shell apparent ages are much more tightly related to the time of the animal's death (shellfish cooking), or to the beach-ridge formation (shells being alive immediately before the ridge formation), whereas the charcoal ages which are derived from wood fragments (which can be of any age) that were used in a fireplace at some (unknown) time after the ridge was build up. In a way the combination of data from shell and charcoal samples reduces the uncertainties corresponding to each kind of material.

Methodological Limitations

Precise dating of the ridges is hindered by several factors, some already mentioned, related to the samples themselves and to their chronological relationship with the ridge formation and others due to specific limitations of the radiocarbon method. We shall only comment on some of the limitations inherent to the chronological method (see more extensive discussion in Ortlieb *et al.*, 1993).

The "reservoir effect" maybe compensated for by an empirically determined factor of correction "R" which, in north-central Peru, would be of 221 yr (Stuiver *et al.*, 1986; Wells, 1988). This correction factor varies, in unknown proportions, both in time and space. Some insight into this matter was provided by our data from the hearth material collected upon the Chira ridges; if shells and burned wood are considered as grossly contemporaneous, differences of apparent (normalized) ages vary between 90 and 520 years (see parameter "S", Table 2). The shells appear systematically older, by one to five centuries, with respect to the associated charcoal samples, and it can be noted that these are minimum values, since the wood burned in the hearths may have actually predated the shells. These values compare with those calculated in charcoal/mollusk pairs from the San Francisco Bay area, during the period 2,000–5,000 BP, and which vary between 230 and 900 years (INGRAM and BERRY, 1993). Variations in time of the reservoir effect may be important in some upwelling areas. However, the correction for the reservoir effect indicated in Tables 1 and 2 was conservatively calculated with the previously published value of "R" (rounded off to 220 ± 50 yr).

Besides the reservoir effect, some "specific effects" related to differences in the isotopic fractionation of organisms from distinct taxa may alter the accuracy of the dating. Specimens of *Donax* and *Tivela* which co-existed in the same spot of the intertidal zone might yield distinct apparent ^{14}C ages. We measured apparent age differences on the order of 300 (± 100) years between *Donax* and *Tivela* shells collected alive in 1987, but these data from the modern, "post-bomb", period may not be readily extrapolated into the past.

Finally, it seems that upwelling phenomena, which are particularly strong on the Peruvian coast (TOGGWEILER *et al.*, 1991), and effects of the mixing of equatorial and Peruvian waters, also play some indirect role in the dispersion observed in the radiocarbon data. The three beach-ridge sequences are precisely located in the transition area ("Paita buffer zone" of OLSSON, 1961) between two oceanic domains (Peruvian and southern Panamic areas). The nearshore fauna of the Chira River estuary, Paita Bay and Sechura Bay has been most probably affected, but in an unknown way, by fluctuations of various biogeochemical parameters of the coastal environment during the Holocene.

Radiocarbon measurements were performed following the classical method (liquid scintillation, several days of radioactivity counting) at the ORSTOM geochronological laboratory at Bondy. If more analyses might have helped in improving the accuracy of the age determination of each beach-ridge formation, we consider that, for all the reasons and unsolved problems mentioned above, there is little hope to obtain a precision much better than a few decades in the dating of the episodes of ridge formation. The AMS (Accelerator Mass Spectrometry) technique should reduce the uncertainty ranges but may not necessarily yield more precise ages for the ridge formation episodes. The assessment of precise age of features and phenomena that, as is the case for El Niño, typically lasted between a few months but at the most two years still remains out of reach.

Internal Consistency of the Radiocarbon Data from Chira and Colan

At Colan as well as north of the Chira River mouth, the radiocarbon results for the successive ridges, from the oldest ones inland to the more recent ones near the modern shoreline (Figure 2), yield progressively younger ages (Tables 1 and 2). This concordance supports the assumption that the archeological material collected on the Chira beach ridges is as useful as the faunal remains within the ridge sediments for the reconstruction of the chronology of the ridge formation. Another test of the internal consistency of the radiocarbon data is provided by the comparison of apparent ages of midden shells from ridge K and *in situ* shells from the substrate of the K-L inter-ridge area (respectively, *ca.* 3,600 BP and *ca.* 3,500 BP, corrected ages, Table 2). Similarly, at Colan, *in situ* shells from beneath the wide coastal flat, in a locality behind the modern coastal ridge, appear as younger (930 BP, corrected) than ridge 1 material (1,170 and 980 BP, both corrected) (Table 1).

Chronological discrepancies between distinct samples from a given ridge are of a limited amount in most of the cases (Tables 1 and 2); apparent age variability within a ridge is of the order of 150 years at Colan, and a little more at Chira (where the analyzed charcoal fragments and shells may reflect longer episodes of human occupation of the ridges or the use of pieces of wood of distinct ages). From an analytical point of view, it is emphasized that no discrepancies were found between results from distinct laboratories (see for instance results from charcoal fragments sampled in separate localities along ridges J, K and M in the Chira sequence, Table 2).

CHRONOLOGICAL CORRELATION OF SEQUENCES OF BEACH RIDGES

Basis for the Correlation of Sequences

One of the arguments put forward for a correlation between the northern Peru sequences of beach ridges is their similar number of ridges. But at first glance, a general comparison of the apparent ages obtained in the two sequences preserved north and south of the Chira River estuary does not readily show clear-cut ridge-to-ridge correlation. This is due in part to the difference of nature of the samples (charcoal and shells) and to the chronostratigraphical significance of the data material ("archeological" *vs.* "geological" material). It also reflects the fact that some ridges are composite; and thus may be coeval with two clearly separated ridges in the other sequence or that some ridges may have been eroded in one sequence and not in the other one.

The correlation between the sequences of beach ridges of Chira and Colan was determined on the basis of chronostratigraphic relationships (as determined in the field), morphological and geometrical criteria, and finally radiocarbon data. A chronological correlation could not be attempted by simple comparison of radiocarbon data but rather through an integration of minimum ages provided by the archeological samples of the Chira ridges and of maximum ages yielded by the Colan "geological" samples. In the integration process, an estimate was made of the time interval during which each ridge was formed.

Geochronological data from the Sechura sequence are too sparse to permit a meaningful comparison with the two other series of beach ridges. As the number of ridges is similar to that of that of the two other series and as two radiocarbon dates from the oldest Sechura ridge (4,700 BP and 4,320 BP, uncorrected) compare with the chronological data from Chira ridge J (Table 2), there is a good probability that the Sechura sequence correlates with the Chira and Colan sequences.

Ridge-to-Ridge Correlation and Time Range Estimates

The chronological correlation between Chira and Colan sequences involved the calculation of time-range estimates for the formation of each pair of ridges (Figure 3). The time-range estimate is figured by the confidence interval between the youngest limit of the minimum age and the oldest limit of the maximum age, both expressed in calibrated years (Tables 1 and 2, last columns). The scale in calibrated years is more appropriate for comparison of samples of distinct nature. The proposed correlations will be briefly reviewed, from the youngest to the oldest features (for details, see ORTLIEB *et al.*, 1993).

The main shell-line at Colan, viewed as a former eroded sand ridge, and ridge R of the Chira sequence, which are both located immediately behind the modern coastal ridge, are probably coeval and appear to have been formed between 1,393 and 1,607 AD (arithmetic median value = 1,500 AD) (Figure 3, Table 3).

The two previous ridges in both areas, respectively ridges 1 and 2 at Colan, and Q and P at Chira, were correlated. The pair of ridges [1,Q] yielded a minimum age of 1,252 AD (at Chira) and a maximum age of 768 AD (at Colan) (median value = 1,010 AD). For the pair of ridges [2,P] an age-range estimate 88–682 AD was determined (median value = 385 AD) (Figure 3, Table 3).

Ridge O consists of two sub-units that may chronologically correspond to two distinct ridges at Colan: ridges 3a and 3. The seaward sub-unit of ridge O and ridge 3a would have been formed between 161 Bc and 417 AD (median value = 129 AD). Ridge 3 and the inland sub-unit of ridge O would be older by a few centuries, but are younger than 533 BC (Figure 3).

Ridge N also consists of two sub-units that were apparently formed during a short interval. We hypothesized that these sub-units correspond to Ridges 4 and 5 at Colan. The formation of the pair [4, seaward sub-unit of ridge N] probably occurred between 151 AD and 727 BC (median value = 288 BC) (Figure 3, Table 3). The wide range of the confidence interval is possibly biased by a "young" hearth on ridge N that postdates (by several centuries?) the formation of the ridge. Ridge 5 material provides useful chronostratigraphic information for Colan area, but no counterpart is available from the inner sub-unit of ridge N. Ridge 5 was apparently formed around 2,500 BP (Table 1), but the uncertainty range is fairly wide: 295–1,270 BC (Figure 3); the unusually wide uncertainty interval is due to sampling problems (too small charcoal fragments) and to important anomalies in the radiogenic activity of the atmosphere that occurred precisely around 2,500 BP (STUIVER and BECKER, 1986).

A correlation between ridges 6 and M is supported by several geomorphological considerations (wide swales between Ridges 6 and 5 at Colan and M and N at Chira that separate each beach-ridge sequences into two sub-sequences, Figure 2). Radiocarbon data from Ridge M indicate a minimum age of 846–942 BC (Figure 3). Although no dating material was found in ridge 6 at Colan, a maximum age is indirectly deduced from the maximum age (1,510 BC) of the previously formed ridge (L). Ridges 6 and M thus appear to have formed in the interval 846–1,510 BC (median value = 1,178 BC) (Figure 3, Table 3).

Table 3. *Chronological estimates, with uncertainty range, of the beach-ridge forming episodes in northern Peru deduced from data of the Chira and Colan sequences. The age estimates expressed in calibrated years correspond to the midpoints (crosses) figured in Figure 3.*

Chira ridges	R	Q	P	O (outer)	O (inner)	N (outer)	N (inner)	M	L	K	J
Colan ridges	shell-line	1	2	3a	3	4	5	6	7	8	-
Age estimate	1500 AD	1010 AD	385 AD	130 AD	95 AD	280 BC	785 BC	1180 BC	1460 BC	1650 BC	>3140 BC
Confidence interval	±110	±240	±290	±290	±460	±440	±490	±330	±50	±245	

A proposed correlation between Ridges 7 and L and a combination of their respective minimum and maximum calibrated ages suggest that the ridges were formed between 1,408 and 1,510 BC (median value = 1,460 BC) (Figure 3, Table 3).

The previously formed ridges, respectively 8 and K, were tentatively correlated. Their period of formation is bracketed by the minimum age (955 BC) of shells from ridge 8 and the maximum age (1,895 BC) of a charcoal sample from the top of ridge K. Considering that the pair of ridges [K,8] cannot be younger than the pair [L,7], the confidence interval is reduced to 1,408–1,895 BC (median value = 1,651 BC) (Figure 3, Table 3).

Radiocarbon data from ridge J (minimum calibrated age range of 3,337–3,240 BC, Table 2) strongly suggest that this ridge is much older than ridge 8 at Colan, by as much as 1,500 years. The oldest beach-ridge of the Sechura sequence (shell ages: 4,700 and 4,320 BP, uncorrected) is assumed to be coeval with the oldest Chira ridge.

The ridge-to-ridge correlation between the sequences of Chira and Colan is substantiated by the available radiocarbon data. The wide confidence intervals which were calculated for each ridge-forming process are due to the addition of all the uncertainties related to the sampling, the measurement technique, and the distinct corrections (including the conversion to calibrated ages) applied to the radiocarbon results.

CONCLUSIONS

The El Niño Link

The geomorphological setting of the Chira and Piura river estuaries and their respective prograding coastal plains favored the formation and preservation of beach-ridge series. The sedimentary and geometric characteristics of these beach ridges (*e.g.*, volume of sediment, inter-ridge widths, relative heights) suggest that these coastal features were formed episodically in response to a conjunction of meteorologic anomalies and unusual oceanic conditions. As these recurrent situations involved heavy rainfall, exceptional sediment supply from the Chira and Piura Rivers, higher than normal sea level and storminess, there is little doubt that they correspond to El Niño manifestations. In the case of Colan, we stress that no other processes than those related to the El Niño phenomenon could explain the formation of the successive beach ridges. For the Chira and Piura sequences, the very strong, episodical increases in the river discharges are also logically related to El Niño conditions.

Some uncertainty remains as to whether each beach ridge is related to a single, or to several, major El Niño events. At Colan, the relatively small volume of the beach-ridge sediment does not preclude that these were formed during single major El Niño events. Nevertheless, there are indications in several Colan ridges of two- or threefold episodes of sediment accumulation (ORTLIEB *et al.*, 1989), and these successive phases may be separated by weeks/months or even by decades/centuries. North of the Chira River estuary, the amount of sediment accumulated in each beach ridge is much larger (20 km × 3 m × 100 m = 6.10^6 m^3) and may exceed the volume of sand that the Chira River could supply to the nearshore area, even during particularly strong single El Niño events. Accordingly, one may assume that these sandy beach ridges, like those at Sechura, took several months (even years?) to form immediately after very strong El Niño events. The evaluation of the amount of sediment that the Chira (or Sechura) River may have carried cannot be based on present measurements because of the major man-made modifications made on the course and the flow of both rivers. In short, we hypothesize that each beach ridge is basically related to single El Niño events of exceptional strength but cannot discard the possibility that Chira and Sechura beach ridges were formed after several episodes (closely spaced in time) of anomalously high runoff.

Recurrence of Strongest El Niño Events

Largely because of intrinsic limitations of the radiocarbon method, precise age determinations of the episodes of formation of each ridge could not be obtained (Table 3). In many cases, the interval of uncertainty of the age determination is of the order of several centuries. The correlation between the ridges of the Chira and Colan sequences was based on geomorphological and geometrical criteria and corroborated by the radiocarbon data. It is concluded that some eleven ridge-forming processes occurred in the last 5,000 years. The oldest Holocene ridge preserved at Chira (ridge J) was formed more than 5,000 years ago (minimum age: 3,140 BC, cal. yr). At Colan, the oldest preserved beach ridge yielded an age of *ca.* 1,650 BC, that is 1,500 yr after Ridge J at Chira. During the last 3,600 years, the time periods elapsed between ridge-forming episodes varied between 100 and 600 years. A recurrence interval of several centuries of the ridge-forming conditions seems compatible with that of very strong, or rather exceptional, El Niño events. The intensity of the events responsible for the beach-ridge formation is estimated to have been at least as strong as that of the 1982–1983 event (possibly the strongest in the last four centuries, according to WOODMAN, 1985).

No complete record of former El Niño events during the last few millennia is available yet. Some useful indications of short-term climatic alterations, produced by distinct kinds of studies, are beginning to be gathered from different parts of South America (see ORTLIEB and MACHARÉ, 1992, 1993). For instance, flooding episodes of archeological sites on the Xingu River, in Brazilian Amazonia, that occurred *ca.* 2,250–1,485 BP, *ca.* 1,200–1,090 BP and *ca.* 840–550 BP were tentatively correlated with former El Niño events (PEROTA, 1992); these three flooding episodes may be coeval with the pairs of ridges [0,3], [Q,1] and [R,shell-line], respectively. On another hand, some peat layers cored in the lower Magdalena Basin, in Colombia, possibly indicate El Niño-related dryness conditions (DUEÑAS, 1992); the peat layers dated at 4,700 BP, 2,500 BP, 2,300 BP, 1,400 BP, and 700 BP might be coeval with, respectively, the Chira Ridge J and the following pairs of beach ridges: [inner N,5], [outer N,4], [P,2] and [Q,1]. Former water level fluctuations of Lake Titicaca may register strong El Niño aridity conditions on the altiplano (MARTIN *et al.*, 1992b); the few lake level drops that occurred in the last 4,000 years may also be coeval with the northern Peru beach-ridge forming episodes. Another series of chronological correlations are being studied within northern Peru, between the beach-ridge sets and archeological evidences of large floods like the Naylamp, or "Chimu", flood around 1,100 AD (NIALS *et al.*, 1979; Wells, 1990; MACHARÉ and ORTLIEB, 1993).

The historical chronology of El Niño events was essentially based on records of anomalous rainfalls in northern Peru (QUINN *et al.*, 1987; HOCQUENGHEM and ORTLIEB, 1992). The beach-ridge sequences preserved in the same region seem to constitute a record of the El Niño events with the strongest intensity for the last 5,000 years. Fortunately, the ridges offered organic material that could be dated and thus assess the general chronology of the ridge formation. For now, the chronology of the ridge-forming episodes lacks desirable accuracy for diverse reasons related to sample nature and heterogeneity, technical limitations of the traditional counting method, and other methodological limitations. In the future, a better understanding of the local variation of the upwelling system and an assessment of the reservoir effect in the past, combined with systematic AMS radiocarbon measurements, should enhance the precision and the accuracy of the age determinations, and should provide a reliable chronological scale of the major late Holocene El Niño events.

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