4. ANALYSIS OF THE GEOCHRONOLOGICAL DATA

Precise dating of the ridges is hindered by several factors, some related to the samples themselves, or to their chronological relationship with the ridge formation, and others due to specific limitations of the radiocarbon method. It is unavoidable to mention the distinct factors limiting the precision of the age determination of the samples and of the episodes of ridge formation, before establishing chronological correlations between the two sequences.

4.1. The dating and stratigraphic significance of charcoal and shell samples

The ^{14}C activity of marine nearshore carbonates generally does not permit precise "absolute" age determinations. It is commonly assumed that charcoal ages are more accurate than nearshore carbonates because terrestrial plants are more directly related to atmospheric CO_2 than marine biogenic carbonates that are subject to a "reservoir effect". Typically, marine shells yield ^{14}C (normalized) apparent ages that are 200 to 400 yrs older than contemporaneous charcoal samples (Mook & Van de Plassche, 1986). Accordingly, from a geochemical point of view, charcoal fragments intermingled in the pebbles of the Colan ridges, or those collected in hearths on the Chira ridges, should provide more confident results than the marine shells.

On another hand, there is a more direct chronological relationship between the ridge formation and the shells that were presumably alive immediately before they were deposited among the pebbles. At Chira also, the marine shells were eaten fresh, while the wood used to cook them may have been older by several decades (or centuries). So, from a chronostratigraphical point of view, the shells, or at least those selected for their stratigraphic significance, should be more useful than fossil wood of unknown age transformed to charcoal.

Finally, it must also be noted that, particularly at Colan, very small charcoal samples were collected within the sediment. As a consequence of the restricted size of these samples, the radiocarbon results are affected by large uncertainty ranges (Table 1).

All these considerations finally justify that both sorts of material were used for ^{14}C dating. One may even think that the comparison of ^{14}C data on associated shell and charcoal samples should improve the accuracy of the age determination. This would be the case if it were not for some possible variations in time of the "reservoir effect". The variability of the isotopic composition of nearshore sea-water through time, in relation with general circulation patterns and local upwelling phenomena (Toggweiler *et al.*, 1991), is extremely difficult to document. Analyses of present-day shell samples cannot resolve this problem, nor be used for calibration purposes, because of the "post-bomb effects" due to nuclear weapon experimentation in the atmosphere in the last few decades (Broecker *et al.*, 1985).

The "reservoir effect" that affects nearshore marine organisms varies along the coasts of the world. In north-central Peru, a factor of correction "R" of 221 yrs had been estimated previously (Stuiver *et al.*, 1986; Wells, 1988). This correction factor, empirically determined, may well vary (in unknown proportions) both in time and space. Some insight into the range of these variations may be provided by our data from the Chira ridges. In the hearths sampled upon the Chira ridges, where shells and burned wood may be considered as grossly contemporaneous, inconstant differences of apparent ages are observed (Table 2). Normalized

^{14}C age differences in these doublets vary between 90 and 520 years during the second half of the Holocene : the shells systematically appear older, by one to five centuries, with respect to the associated charcoal samples (see factor "S", Table 2). It must be emphasized that these are minimum age differences, because the wood burned in the hearths actually predated the shells.

In the calculation of the "reservoir effect" correction for the shell samples (Tables 1, Fig. 2), we chose to systematically use the previously published value of "R" (rounded off to 220 ±50 yrs), even if we suspect that this correction is inaccurate for time periods previous to the first half of the XXth century.

4.2. Biologic and oceanologic effects

In addition to the "reservoir effect" related to the nearshore chemical environment, there may be some differences in the isotopic fractionation of living organisms ("specific effects"). This means, for instance, that specimens of *Donax* and *Tivela* that co-existed in the same spot of the intertidal zone, might yield distinct apparent ^{14}C ages. As mentioned above, "post-bomb effects" now make difficult any inter-specific calibration on modern shell material. We measured apparent age differences on the order of 200-400 years between *Donax* and *Tivela* shells collected alive in 1987. Without more precise information on specific differences on biological isotopic fractionation, we shall view all the shell data as equivalent.

Besides, it seems that the upwelling phenomena, which are particularly strong on the Peruvian coast, also play some indirect role in the dispersion observed in the radiocarbon data (Toggweiler *et al.*, 1991). In addition, the study area is located in the transition zone between two oceanic domains (Peruvian and southern Panamic areas) and north-south shifts of this oceanic boundary seem to have occurred during the Holocene (Richardson, 1983; Ortlieb & Macharé, 1989b; Díaz & Ortlieb, 1991). The nearshore fauna of the Chira River estuary and Paita Bay was thus probably affected, but in an unknown way, by fluctuations of various geochemical parameters of this particular coastal environment.

4.3. Chronological significance of the dated material

Shell and charcoal fragments sampled in the two areas provide distinct kinds of chronological information with respect to the episodes of ridge formation. In the Chira sequence, the dated archeological samples basically yield minimum ages for each beach ridge. Even though it cannot be discarded a priori that the material sampled on top of the ridges postdate, by several centuries or much more, the episode of ridge formation, the overall results (and the internal consistency of multiple samples from a given ridge) suggest that the elapsed time was of the order of a century (one exception is a *Tivela* sample, from ridge J, which was brought there 1000 yrs after the other samples, Table 2).

At Colan, great care was taken to perform radiocarbon dating only on shell samples that were not obviously reworked. The analyzed marine shells, thus selected among those probably alive shortly before the ridge formation, yield apparent ^{14}C ages that are not significantly different from those calculated from the charcoal fragments sampled in the same sediment (Table 1). The general consistency of the results, within any given ridge as well as throughout the whole sequence (Table 1), supports the interpretation that altogether the well-preserved shells and the charcoal fragments were not much older than the episode of formation of each beach ridge.

4.4. Methodological limitation in the accuracy of the age determination

Radiocarbon measurements were performed following the classical method at the ORSTOM geochronological laboratory at Bondy (liquid scintillation, several days of radioactivity counting). Undoubtly, more analyses (and subsequent increased statistical significance) might have helped in reducing some uncertainties in the age determination of each beach ridge formation. Nevertheless, for all the reasons mentioned here, 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) radiocarbon method, which is technically more accurate and needs smaller samples, should reduce the uncertainty ranges but may not necessarily yield more precise ages for the ridge formation episodes.

Actually the radiocarbon method may never be able to assess the precise age of features and phenomena that, as is the case for El Niño, typically lasted no more than a few months or, at most, two years.

An additional commentary can be made about the relevancy of using "calibrated" results, conventionally expressed in cal. yrs AD and BC. The transformation of radiocarbon ages (expressed as BP) into calibrated dates accounts for former yearly variations in the production of C radioactivity. This kind of correction of the chronological data is specially recommended when dealing with comparison of data from different kinds of samples. A side effect of this correction is that for some specific periods of time it generates its proper range of uncertainty which should be added to those produced by the measurement itself and by the other correction factors (Stuiver & Becker, 1986). Maximum and minimum age estimates for the formation of the beach ridges are expressed in calibrated years (Tables 1 and 2). The time ranges thus indicated (last column of Tables 1 and 2) include all the combined intervals of uncertainty.

5. THE CHRONOLOGIC CORRELATION OF THE TWO SEQUENCES

5.1. Basis of the approach

The starting point of this study lies in the similar number of beach ridges in several sequences of northern Peru, and in the hypothesis that the ridges were formed coevally. Therefore, we first considered, and wanted to check, that for instance the 3rd (or 'n'th) ridge at Colan was formed in the same period than the 3rd (or 'n'th) ridge in the Chira sequence (Fig. 1 and 3). It proved to be less simple. The radiocarbon results needed to be scrutinized.

It appears that a ridge may have been eroded in one sequence and not in the other. Another problem was that some ridges could be composite, and thus be coeval with two clearly separated ridges in the other sequence. In a third case, a composite ridge in one area seems to match a simple ridge in the other area. These difficulties in the correlation between the Chira and Colan sequences were solved with the support of the chronological analyses.

In our approach, the stratigraphic relationships as determined in the field, and morphological criteria as well as geometrical arguments were favoured, and secondarily checked with the radiocarbon data. We do not forget that apparent radiocarbon ages may be misleading or erroneous, for all the reasons reviewed above. With these premices, we constructed a chronological correlation between individual ridges of the two sequences that is shown in Table 3.

Chira ridges	R	Q	P	O (outer)	O (inner)	N (outer)
Colan ridges	shell-line	1	2	3a	3	4
Age range estimate	*1607- -1393 AD*	*1252- -768 AD*	*682- -88 AD*	*417 AD- -161 BC*	*364 AD- -533 BC*	*151 AD- -727 BC*

Chira ridges	N (inner)	M	L	K	J
Colan ridges	5	6	7	8	-
Age range estimate	*295- -1270 BC*	*846- -1510 BC*	*1408- -1510 BC*	*1408- -1895 BC*	*>3140 BC*

Table 3 - Chronological correlation between the beach ridges of the sequences of Chira and Colan (see Fig. 3 for location and identification of the ridges, and Fig. 5 & 6 for geochronological control).

5.2. Ridge-to-ridge chronological correlation and time range estimates

The chronological correlation between Chira and Colan sequences is established together with a time range estimate for the formation of each pair of ridges (Fig. 6, Table 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, expressed in calibrated years (Tables 1 and 2, last columns). We shall examine successively the available data, from the youngest to the oldest features.

The main shell-line at Colan and the next-to-last ridge in the Chira sequence, which are both immediately behind the modern coastal ridge, may be coeval. For these two features where archeological material was used, only minimum ages are available. Chira ridge R and the Colan shell-line, viewed as a former, eroded, sand ridge, would thus have formed prior to 1607-1393 AD (Fig. 5 and6).

A tentative correlation is proposed for the two previous ridges in both areas (respectively ridges 1 and 2 at Colan and Q and P at Chira). For the pair of ridges 1-Q, the confidence interval is set by a minimum age of 1252 AD (Chira) and a maximum age of 768 AD (Colan); a median (theoretical) value can be calculated at 1010 AD. In the case of ridges 2-P, an interval 682-88 AD was determined (median value= 385 AD) (Fig. 5 and 6).

As ridge O appears wider than others and consists of two sub-units, we believe that it corresponds chronologically to two distinct ridges at Colan: ridges 3a and 3. The shells sampled atop ridge O are probably coeval with, or immediately postdating, the formation of Colan ridge 3a. Accordingly, the seaward sub-unit of ridge O and ridge 3a would have been formed between 161 BC and 417 AD (median value= 129 AD) (Fig. 6). Ridge 3 and the inland sub-unit of ridge O would be older by at most a few centuries, but younger than 533 BC (Fig. 5 and 6).

Ridge N also consists in two sub-units that were apparently formed during a short interval. We hypothesize that these sub-units correspond to ridges 4 and 5 at Colan. For the formation of the pair ridge 4-outer sub-unit of ridge O, we infer an interval of confidence

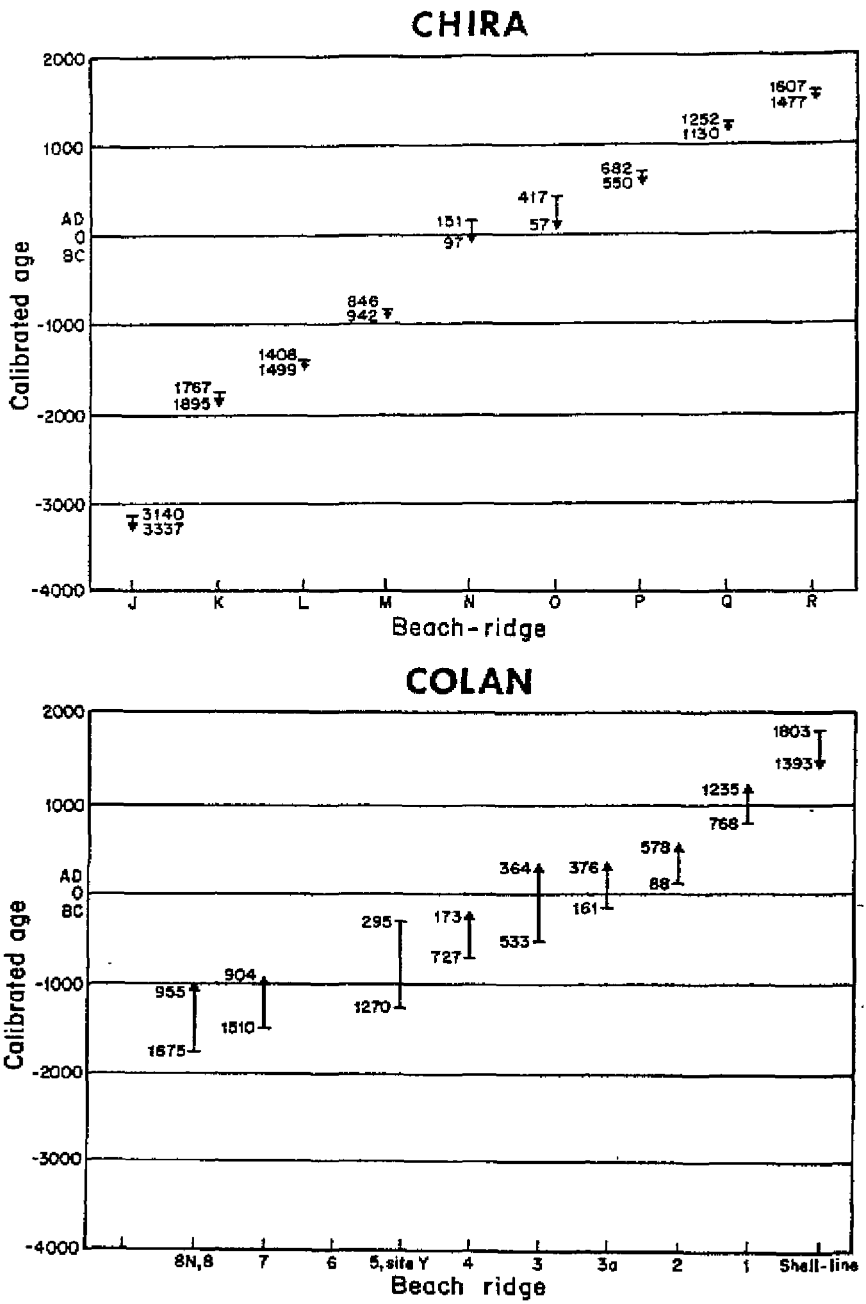

Fig. 5 - Synthesis of radiocarbon data from Chira and Colan beach ridge sequences. At Chira the analyzed (archaeological) samples postdate the episodes of ridge formation, and thus provide minimum age estimates of the ridges. At Colan, most of the analyzed samples predate the ridges, and indicate maximum ages. Ages are corrected for isotopic fractionation and "reservoir effect", and are expressed in calibrated years (BC= before J.C.; AD= after J.C.).

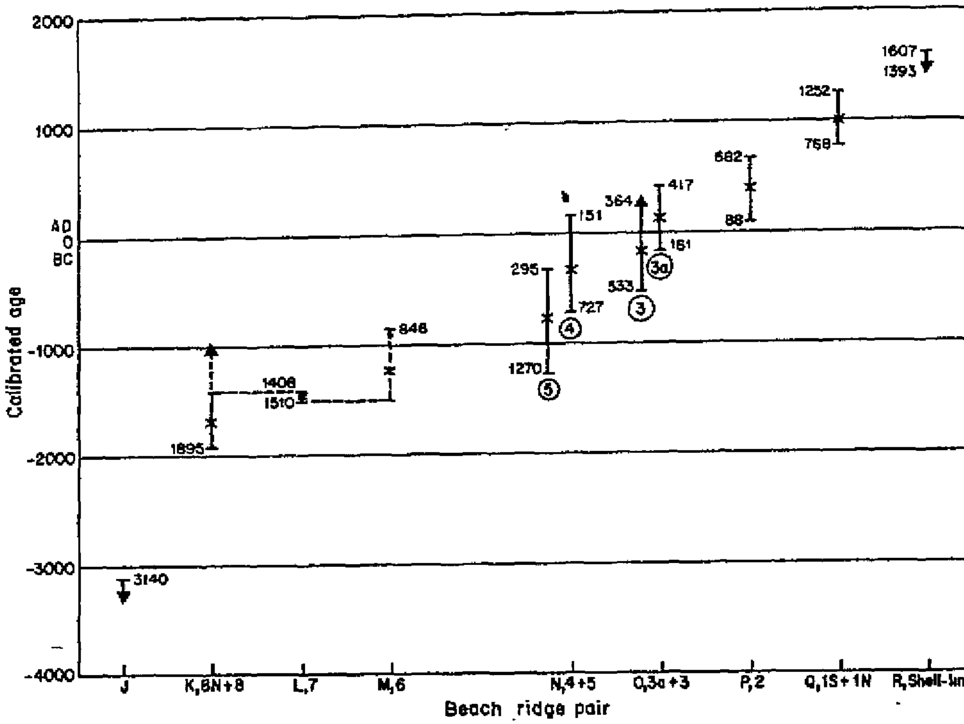

Fig. 6 - Proposed chronological correlation between the Chira and Colan sequences of beach ridges, with indication of estimated age ranges including confidence interval, expressed in calibrated years. For the youngest and oldest ridges only minimum ages (with corresponding confidence interval) are determined. For construction of this chart, and determination of the chronological intervals, see text and refer to Fig. 5 and Table 3.

151 AD-727 BC (median value= 440 BC)(Fig.6). Such a wide range is partly due to the "young" minimum age determined on ridge N (possibly a hearth postdating by several centuries the formation of the ridge). For ridge 5, there is precise chronostratigraphic information from Colan but no counterpart from the inner sub-unit of ridge N. A charcoal fragment collected in the sandy substrate of ridge 5 provides a maximum age for the formation of the ridge (2520 ±490 BP, normalized). Midden shells accumulated on top of a storm deposit associated with ridge 5, called locality Y (Fig. 3), yield a corrected age of 2480 ±250 BP (Table 1). These data suggest that ridge 5 was formed around 2500 BP (normalized/corrected ages). Unfortunately, the uncertainty range (in cal. yrs.) is fairly wide (Fig. 5 and 6), first because of the large standard deviation (1 sigma) value affecting the date on the small charcoal fragment, and secondly because important anomalies in the radiogenic activity of the atmosphere occurred precisely around 2500 BP (Stuiver & Becker, 1986). As a result, and in spite of well-constrained sampling, the age determination is affected by a wider than usual uncertainty interval: 295-1270 BC (Fig. 6).

A correlation between ridge 6 and M is supported by geomorphological considerations. In the Chira area, as at Colan, a relatively wide inter-ridge zone separates the beach-ridge sequences into two parts: an older set of higher (and, at Chira, wider) ridges from a younger set of lower ridges (Fig. 2, 3 and. 4). This large swale is located between ridges 6 and 5 at Colan, and M and N at Chira. Radiocarbon data from ridge M indicate a minimum age of 846-942 BC (Fig. 6). Not enough dating material was found in ridge 6 at Colan, but a maximum age is indirectly deduced from the maximum age (1510 BC, Fig. 5) of the previously formed ridge (L). Ridges 6 and M thus appear to have formed in the interval 846-1510 BC (median value= 1178 BC) (Fig. 6).

A proposed correlation between ridges 7 and L and a combination of their respective minimum and maximum calibrated ages suggest a particularly short interval during which the ridges could be formed: 1408-1510 BC (median value= 1460 BC) (Fig. 6).

The previously formed ridges, respectively 8 and K, are tentatively correlated. Their period of formation is bracketed by the minimum age (955 BC) of shells from ridge 8 and the maximum age (1895 BC) of a charcoal sample from the top of ridge K (Fig. 5). This confidence interval may be reduced by considering that the pair of ridges K-8 cannot be younger than the pair L-7, and thus should be older than 1408 BC (Fig. 6).

Radiocarbon data from ridge J strongly suggest that this ridge is much older than ridge 8 at Colan. Archeological material atop ridge J yields several radiocarbon results with a minimum calibrated age range of 3337-3240 BC (Table 2). Because of the consistency of the ^{14}C data from ridge J (distinct collectors, distinct analysis laboratories, several sampling places), we interpret that this ridge may really be older by as much as 1500 years than Colan ridge 8. We ignore if an equivalent of ridge J was formed at Colan and was subsequently eroded, or if it simply did not formed south of the Chira River estuary.

6. CONCLUSION

The geomorphological setting of the Chira River estuary and surrounding coastal plain, as well as the sedimentary and geometric characteristics of the Chira and Colan beach ridges (*e.g.* sedimentary volume of the ridges, inter-ridge widths, relative heights) suggest that these coastal features were formed episodically in response to a conjunction of meteorologic anomalies and particular oceanic conditions. These recurrent situations must have involved strong rainfall, large sediment supply from the Chira River, high sealevel and rough seas. All these manifestations characterize the El Niño phenomenon in the area. In the case of Colan, at least, we consider that no other process than those related to the El Niño phenomenon can explain the formation of the beach ridges. In the case of the Chira sequence, it seems also well established that only very strong, and episodical, increases in the sediment supply of the Chira River are able to account for the formation of the large sandy beach-ridges.

There is still some uncertainty as to whether each beach ridge of the Colan and Chira sequences is related to single former major El Niño event or to a series of El Niño events. At Colan, the volume of the beach ridges does not preclude that these were formed during single, or several but closely spaced in time, major El Niño events. Actually, in several Colan ridges, stratigaphic observations suggest a two - or threefold episodes of sediment accumulation (Ortlieb *et al.*, 1989b), but it is difficult to determine if these phases were separated by months, decades, or centuries. North of the Chira River estuary, the amount of sediment accumulated in each beach ridge is much larger (about 20 km x 3 m x 100 m = 6.10^6 m^3), and so huge that it may exceed the volume of sand that the Chira River can supply to the nearshore area, even during particularly strong El Niño events. One may assume that the sandy beach ridges observed north of the Chira estuary took several years to form after very strong El Niño events, but the problem is rather to evaluate how much sediment can be carried by the Chira River, in the case of exceptional rainfall on the watershed. The very strong 1982-1983 event cannot be used as a realistic example for past reconstructions because the course and the flow of the river have been largely modified during the last decades (Poecho dam, for instance). We shall leave as an open possibility that each Chira beach ridge was formed after a series of episodes of anomalously high runoff.

The geochronological study conducted in the two sequences had several purposes. We wanted to evaluate the possibility to determine, with some precision, the time of formation of each beach ridge, to try to assess a chronological correlation between individual ridges of the two sequences, and finally to try to fix "absolute ages" of pairs of ridges, as a possible record of major El Niño events during the second half of the Holocene.

Unavoidable limitations of the radiocarbon method generally did not allow precise age determinations of the episodes of formation of each ridge. Through a combination of analyses of charcoal and shell samples, we improved somewhat the accuracy of the age determinations, but the major remaining problem is the excessive interval of uncertainty (several centuries) attached to the dating of the samples. As a consequence, we cannot pretend to determine the age of any ridge with a precision of less than a century.

A time correlation between the ridges of the two sequences is proposed (Fig. 6, Table 3). This correlation, based on geomorphological and geometrical criteria and corroborated by the radiocarbon data, suggests that at least eleven ridge-forming processes occurred in the last 5,000 years, and at least ten in the last 4,000 years. The oldest ridge preserved at Chira, was formed more than 5,000 years ago (minimum age: 3140 BC, cal. yrs). Near Colan, the oldest preserved beach ridge yielded an age of ca. 1650 BC, that is 1,500 yrs after ridge J at Chira. In the last 3,600 years, the time periods elapsed between ridge formation episodes probably varied, but are of the order of a few centuries. A recurrence interval of several centuries of the ridge-forming conditions seems compatible with that of very strong, or 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, and it can be recalled that according to Woodman (1985), the strength of the 1982-1983 event may not have been reached during the last 4 centuries.

Various kinds of evidence for very strong El Niño events recorded in South America during the late Holocene were recently produced at the Paleo-ENSO Records international Symposium (see: Ortlieb & Macharé, Eds., 1992). No record of El Niño events during the last millennia is yet available. We still have to deal with a series of sparse indications (of an archeological, geological, geomorphological, biological, or paleohydrological nature) of major climatic alterations throughout the whole continent. The evidence for former El Niño events comes primarily from northern Peru, but exists also from the Peruvian and Bolivian high Andes and altiplano, Ecuadorian lakes, northern Colombia, Brazilian Amazonia, northern et central Chile, etc. As the chronological framework for all this paleoclimatic information, which depends heavily on radiocarbon dating, is rather inaccurate, it is still out of reach to expect to determine the precise age of occurrence of major Holocene El Niño events and to firmly assess transcontinental teleconnections.

We surmise that at least part of these posible El Niño former manifestations should be correlative with beach ridge formation episodes in the Chira-Colan region. For instance, it has been shown that flooding episodes of archeological sites on the Xingu River, in Brazilian Amazonia, possibly related to El Niño events, occurred ca. 2250-1485 BP, ca. 1200-1090 BP and ca. 840-550 BP (Perota, 1992); these three inferred events might correspond to the pairs of ridges O-3, Q-1 and R-shell-line, respectively. On another hand, core data from the lower Magdalena Basin in Colombia revealed a succession of peat layers that may indicate El Niño-related dryness conditions; the peat layers were dated at: 7000 BP, 5500 BP, 4700 BP, 4000 BP, 2500 BP, 2300 BP, 1400 BP, and 700 BP (Dueñas, 1992), the sixth youngest and the last four peat layers might be coeval with the following pairs of beach ridges: J, inner N-5, outer N-4, P-2 and Q-1, respectively. Other data concern lake level fluctuations of Titicaca in relation with strong El Niño aridity conditions on the altiplano (Martin *et al.*, 1992a; 1992b).

A reassessment of the chronological data on manifestations of El Niño anomalies, in distinct regions of South America, may be one of the most promising ways to establish a record of this major oceano-climatic alteration on a 10^3-year time scale. Such an objective would require, beside careful chronostratigraphical studies, abundant radiocarbon measurements (using the AMS method, whenever possible).

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