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A review of recent paleoclimatic studies in Peru

ABSTRACT

Studies on geomorphological and sedimentological aspects of Quaternary deposits have been for a long time the main source of information on past climatic changes in Peru. Because of their inherent discontinuous character and of a poor chronologic control only relative stratigraphic frameworks have thus been obtained. Most of the recent paleoclimatic contributions involve radiocarbon dating, and consequently deal with those events that occurred within the last 50 kyr. A few pollen studies and the assessment of paleobiological impacts of climate changes constitute valuable complementary information. The late Quaternary fluctuations of Andean glaciers are confidently well correlated along the chain and show two stages of the Last Glaciation as well as tardi- and neo-glacial readvancements; however, many doubts still remain about older glaciations. Paleontological, paleoceanographic, and paleoecological data suggest that the climatic conditions prevailing along large segments of the coast, have undergone El Niño-type variations during at least the second half of the Holocene. Amazonian rivers' dynamics appear to be only in part related to past climate variations; the hypothesis of glacial aridity and of youthfulness of the present-day forest are now better supported. Finally, some previous interpretations and models are briefly discussed.

RESUMEN

Desde hace tiempo, los estudios de los aspectos geomorfológicos y sedimentológicos de los depósitos cuaternarios constituyen la principal fuente de información sobre los cambios climáticos ocurridos en el Perú. Dados su inherente carácter discontinuo y la falta de una buena calibración cronológica, solamente se obtuvieron esquemas estratigráficos relativos. La mayoría de contribuciones recientes en paleoclimatología involucran datación por radiocarbono y por lo tanto tratan sobre los eventos ocurridos en los últimos 50.000 años. Unos pocos estudios palinológicos y evaluaciones sobre impactos paleobiológicos de los cambios de clima constituyen una información complementaria muy útil. Las fluctuaciones de los glaciares andinos en el Cuaternario tardío han sido correlacionadas con cierta confianza a lo largo de la cadena, mostrando dos estadios de la Ultima Glaciación así como los reavances tardi y neoglaciales; sin embargo, quedan aún muchas dudas respecto a las glaciaciones más antiguas. Múltiples datos paleontológicos, paleoceanográficos y paleoecológicos sugieren que las condiciones climáticas prevalecientes en grandes segmentos de la costa han sufrido pequeñas variaciones tipo El Niño durante por lo menos la segunda mitad del Holoceno. La dinámica de los ríos amazónicos muestra estar relacionada sólo en parte con las variaciones paleoclimáticas; las hipótesis sobre la aridez glacial y sobre la juventud de la actual selva amazónica han sido mejor sustentadas. Finalmente, se presentan brevemente algunas de las interpretaciones y modelos generales que se han propuesto sobre los paleoclimas cuaternarios en el Perú.

INTRODUCTION

Since the beginning of the century, geomorphological and sedimentological observations were used to infer past climatic changes in Peru. Thus, Bowman (1916) in southern Peru, McLaughlin (1924) in the central region, and Bosworth (1922) in the northwestern part of the country contributed the pioneer papers on paleoclimatic research. This approach which was followed up to the seventies and afterwards, constituted the foundation upon which lie most of the interpretations on climatic change in the past. The occurrence of short-lived periods of rainfall and reduced aeolian activity on the present-day arid coast (Dollfus, 1964, 1965; Tricart, 1970; Laharie, 1970; Teves, 1976, 1982, Sébrier & Macharé, 1980), as well as past extension of glaciers greater than today (Oppenheim, 1945; Heim, 1947; Fenner, 1948; Clapperton, 1980) was inferred from the study of characteristic landforms and sediments. This chronostratigraphic framework on the Peruvian Quaternary suffered strongly from a lack of geochronologic control. During the last 25 years, the major improvements made in the regional chronostratigraphy are linked to the application of geochronometric methods, and specially radiocarbon dating. Consequently, the contributions deal chiefly with glacial and coastal geology and concern only the last fifty thousand year period.

The purpose of this note is to outline the main results of recent and on-going paleoclimatic studies in Peru placing them within the previously proposed stratigraphic sketches. As will be shown, the uneven distribution of data still hampers chronostratigraphic correlations and the elaboration of a general framework for Quaternary climates. Besides, this review addresses a few key problems that still need to be solved for a better understanding of the general trends of climatic changes in Peru.

MAIN CHARACTERISTICS OF PRESENT-DAY CLIMATES

The distribution of climates in Peru strongly depends on two main factors: a) The high Andean relief, which trends NNW-SSE and separates the zones of influence of the Pacific and Atlantic high-pressure centers, and b) The Peruvian (Humboldt) cold oceanic current, which flows northwards along the South American coast up to 4°S. As a result, the distribution of climates is a function of altitude (i.e. longitude) more than of latitude (Peñaherrera, 1969). Hoffman (1975), Johnson (1976), and I.G.N (1989) have summarized the present day climatic characteristics presented hereafter in a schematic W-E traverse.

The narrow coastal zone of Peru is a hyper-arid land, with precipitation being commonly ≤ 50 mm/yr, and entirely devoid of vegetation. It is considered as a rain-shadow desert related to the high elevation of the Andes (Bowman, 1916; Fenner, 1948; Rauh, 1979). Despite its location within intertropical latitudes, the nearby oceanic current gives to this zone mild temperatures, fluctuating typically between 14° and 25°C, and a very high air-moisture associated with a dense fog which disappears only during the summer months. The adjacent Pacific Andean slopes also are arid up to 3000 m above sea-level (a.s.l), however, their air is dryer, and they receive more sunshine than the coast. Above this altitude, summer rainfalls appear and lead to the development of small trees characteristic of the "Andean forest" (Rauh, 1979).

In the upper Andean region, high plateaus ("punas"), lying around 4.000 m a.s.l, form the base level upon which rise fault-bounded or volcanic cordilleras culminating over 6.500 m. These areas are subject to a long dry winter that lasts from April to December contrasting with a short summertime during which the precipitation is concentrated. On the "punas", rainfall is as common as snowfall whereas the latter predominates on the cordilleras. The resultant snowline is located from 4.800 to more than 5.800 m a.s.l., and its east-west and north-south gradients show the greater influence of temperature in central Peru and of precipitation in southern Peru (Seltzer, 1990).

The eastern Andean slopes and the Amazonian lowlands are permanently subject to typical tropical conditions, i.e. high rainfall (around 3,000 mm/yr), and zonal circulation fluctuations (Peñaherrera, 1969; IGN, 1989). Several forest belts characterize the different altitudinal stages of this region.

GLACIAL EVENTS IN THE ANDEAN CORDILLERA

Recent neotectonic studies have shown that, apart from some local areas, the elevation of the Peruvian Andes has not significantly increased during the Quaternary (Sébrier **et al.**, 1982, 1985). Therefore, the past climatic changes that occurred in this area should rather reflect atmospheric and oceanic phenomena of regional or global significance, and particularly the widespread glaciations.

The relatively early onset of glacial climates in the central Andes,

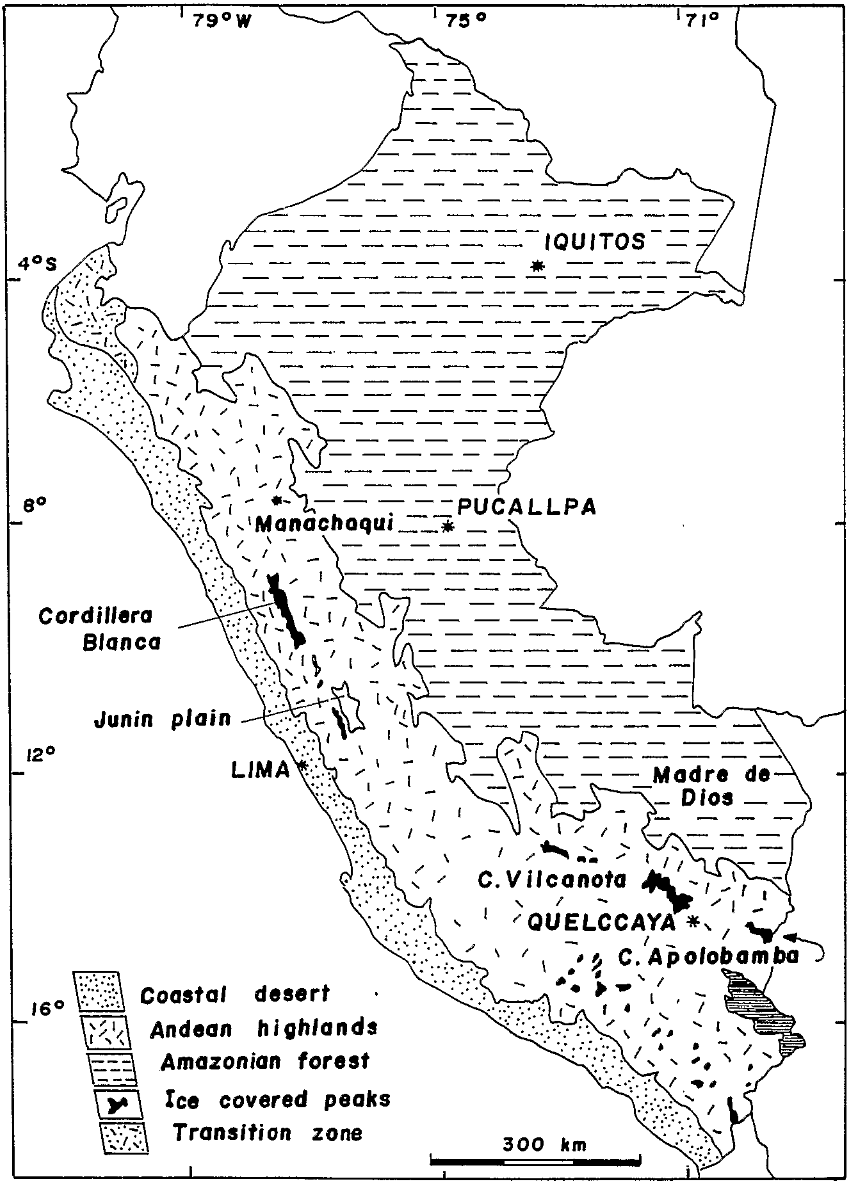

Figure 1.- Morphoclimatic sketch map of Peru, indicating the localities cited in the text.

proposed by Clapperton (1979) and discussed by Thouveny & Servant (1990), has obtained support from the existence of several outwash sequences intercalated within the upper part of Pliocene beds (base dated K/Ar = 4.6 Ma), outcropping west of the Cordillera Blanca (Bonnot, 1984; Bonnot **et al.**, 1988) (Fig. 1).

The occurrence of early and middle Pleistocene glacial events remains poorly documented. The stratigraphic position of Dollfus' (1965) "Mantaro Glaciation" deposits, that would have spread down to 3.600 m a.s.l. on the Puna surfaces in central Peru, has not been reassessed by recent studies. On another hand, two fluvio-glacial formations younger than the Pliocene but predating the moraine systems of Cordillera Blanca, have been assigned early and middle Pleistocene ages (Bonnot, 1984).

The "no unequivocal occurrence of a penultimate glaciation" as discussed for the northern Andes (Schubert & Clapperton, 1990) appears to apply also in Peru. The only glacial deposits likely to represent a penultimate glaciation (ca. 150,000 yr) are reported in the Cordillera de Apolobamba (Fig. 2) where two morainic arcs containing huge blocks are related to the "Limata Glaciation" (Bonnemaison **et al.**, 1985; Fornari **et al.**, 1988). The Unchus till once described by Heim (1947) in the Cordillera Blanca (Fig. 4) may also relate to such event .

In the Peruvian Andes, the last glaciation often shows deposits indicating two different stages (Fig. 4). The oldest one is well distinguished in the northern flank of the Cordillera de Vilcanota (Fig. 3) where Mercer (1984) proposed an age corresponding to that of Isotopic Stage 4 (ca. 70 ka). Glacial deposits attributable to this event are found at the foot of the Cordillera de Apolobamba ("Ancocala Glaciation") (Fig. 2), in Cordillera Blanca (Bonnot **et al.**, 1988), as well as in the Junín Plain ("Rio Blanco Glaciation", Wright, 1983).

All the available data on the younger stage of the last glaciation have recently been summarized by Seltzer (1990). This event is well represented:

- in the Cordillera de Apolobamba, by glacial drift that extends widely on the floor of the Ananea basin ("Chaquiminas Glaciation") (Fornari et al., 1988);
- in the Cordillera Blanca area, by inner morainic arcs which indicate an ice cover smaller than that of the previous stage;
- in the Cordillera de Vilcanota, where it reaches its maximum development around 19,500 BP (Mercer, 1984);
- in the Junín Plain, where this glacial episode ("Punrún Glaciation") extends between 24,000 and 12,000 BP (Wright, 1983);
- in the Cordillera de Huaytapallana (Blanc, 1984).

The deposits related to this event have been morphostratigraphically correlated, and most authors coincide to recognize there the later phase of the last worldwide glaciation, which culminated by 18,000 BP ($\approx$21 ka, according to Bard **et al.**, 1990).

A rapid deglaciation took place between 14,000 (or 12,000) and 10,000 BP (Mercer, 1984; Seltzer & Wright, 1989; Seltzer, 1990; Rodbell & Hansen, 1990). During this interval, two or three "tardiglacial" readvances were recognized in almost all the studied

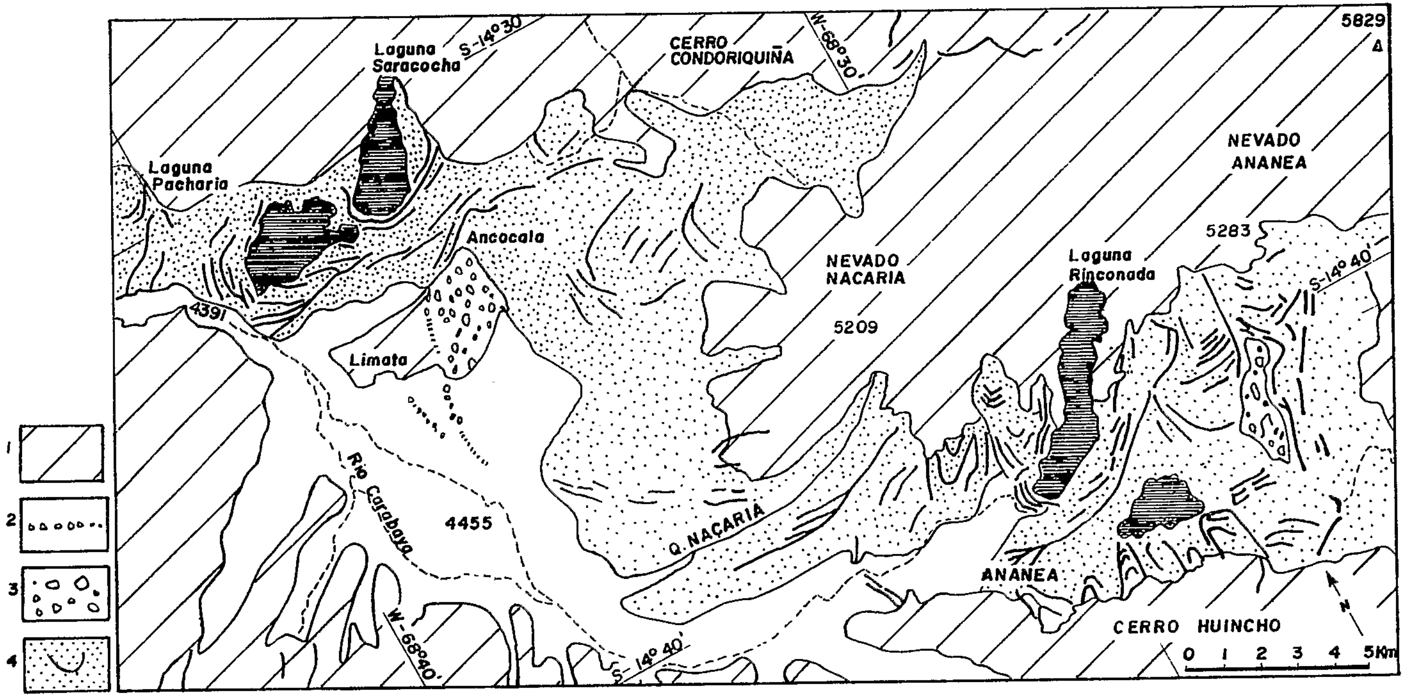

Figure 2.- Quaternary units of the Ananea-Ancocala basin, eastern Cordillera of southern Peru.
1. Paleozoic basement. 2. Arcs of erratic blocks of the Limata Glaciation. 3. Glacial and outwash deposits of the Ancocala Glaciation. 4. Glacial drift and morainic crests of the Chaquiminas Glaciation.
(Simplified after Fornari **et al.**, 1988).

localities (Fig. 4). In the Quelccaya Ice Cap, south of the Cordillera de Vilcanota, such tardiglacial events were dated respectively at 12,500 and 11,000 BP (Mercer, 1984). The latter, considered as an equivalent of the northern hemisphere "Younger Dryas", is dated rather at 10,000 BP in the Junín Plain, and nearly 9,700 BP in the Manachaqui valley (Wright, 1984; Birkeland **et al.**, 1989).

Small "neoglacial" readvances occurred in the Peruvian Andes during the Holocene. Birkeland **et al.** (1989) described an advance (or a break in the recession) in the Manachaqui valley before 6,450 BP. In the Cordillera de Huaytapallana, Seltzer & Wright (1989) reported two episodes of glacial growth with similar magnitudes, one prior to 1,300 BP and another after 650 BP. The latter seems to extend from 600 to 300 BP in the Quelccaya Ice Cap, where it has been correlated with the "Little Ice Age" (LIA) of Europe and North America (Mercer, 1984; Thompson **et al.**, 1985, 1986), although Wright (1984) had previously considered that in the Andes, the LIA-like moraines would correspond to an earlier event represented in the Junín Plain by moraines older than 1,100 BP (calibrated age: A.D. 900-980).

PAST RAINFALL PERIODS ALONG THE COAST

No significant progress have been achieved in the reconstruction of the Pleistocene climatic changes along the coastal region. Previous studies had considered that the present-day arid climate has prevailed during most of Quaternary times, even if repeated episodes of heavy rainfall were assessed by some thick alluvial deposits (Dollfus, 1965; Laharie, 1970; Teves, 1976; Sébrier & Macharé, 1980, Macharé, 1981).

Morphostratigraphical correlations of these alluviation phases with the Pleistocene glacial chronology were elaborated but remain hypothetical (Sébrier & Macharé, 1980). Some of the alluvial deposits may in fact be related to local rains fallen in the coastal regions (Fig. 5), while the major part of the alluvium comes from the middle and upper slope of the Andes and thus calls for climatic changes outside the coastal domain.

In northwestern Peru, the coastal landscape is dominated by marine features like wide Holocene flats and extended Pleistocene marine abrasion platforms, which offer limited information on Quaternary climatic changes. The fact that the "tablazos" (marine terraces) have been largely preserved for hundreds of thousand years and are cut by only a small number of "quebradas" (i.e. gullies) suggests that rainfall might have been generally reduced during the Pleistocene in the northwestern extremity of the country. Nevertheless, Bosworth (1922) reported the occurrence of three periods of alluvial deposition preceding the present-day conditions in the nearby foothill valleys.

Recently, important data have been gathered on the latest Pleistocene and Holocene climates along the northern and central coastal zones. They are provided by several paleontologic, paleoceanographic and archaeological studies, some of them being supported by radiocarbon dating. During the seventies, a debate

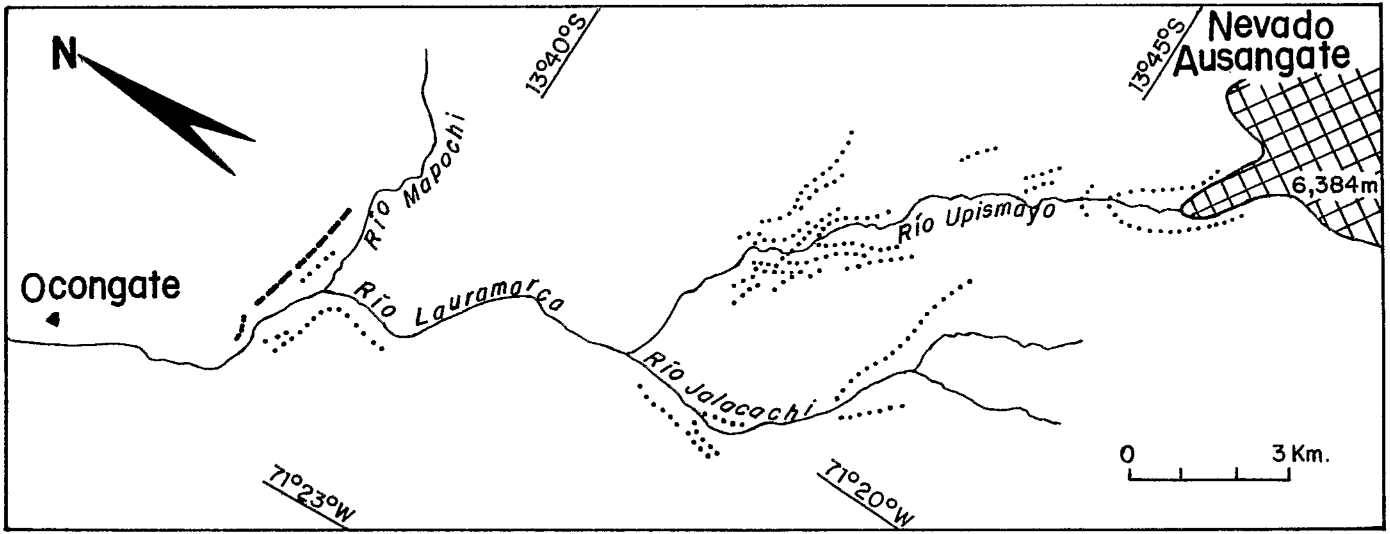

Figure 3.- Nested morainic arcs in the Cordillera de Vilcabamba. The lower ones near Ocongate reach 3,600 m, whereas those from the middle Rio Upismayo lie near 4,200 m a.s.l. (From Mercer, 1984).

opposed authors in favour or against the hypothesis that rather drastic climatic changes had occurred during the last 10,000 years. A review of the different interpretations (Ortlieb & Macharé, 1989) pointed out that they were often relying on one kind of paleoecologic or paleoclimatic indicator regardless of the other available data. As a result, the respective authors had been led to propose contradictory hypotheses about the paleoclimatic evolution of the late Quaternary. Actually, it seems that most of the purported evidence for past wetter climatic episodes may be related to former El Niño events. Occurrences of such a phenomenon in the recent past may be registered in different local proxy records (Ortlieb **et al.**, 1989). Among the recently studied indicators of El Niño anomalous conditions one may cite: the build-up of beach ridges (Richardson, 1983; Sandweiss, 1986; Ortlieb **et al.**, 1989; Fournier **et al.**, 1990), sequences of flooding deposits (Craig & Shimada, 1986, Wells, 1987, 1988, 1990), paleobiological records (Rollins **et al.**, 1986; Devries, 1987; Perrier **et al.**, 1990; Devries & Wells, 1990), and ice core data (Thompson **et al.**, 1984, 1985) (Fig. 6 and 7).

CLIMATIC CHANGES RECORDED IN THE AMAZONIAN FOREST

The Peruvian Amazonia is a large domain where well diversified physiographic zones (Dumont **et al.**, 1990) seem proper to record paleoclimatic data. Unfortunately, studies on the paleoclimatic evolution of this part of Amazonia began only recently. Quaternary alluvial deposits crop out in stepped terraces bordering the present day rivers in zones submitted to Plio-Quaternary tectonic movements, but the most suitable terrains for paleoclimatic records are fine-grained sediments deposited far away from the cordilleran reliefs. For instance, it was observed that in the Iquitos zone, more than 200 km away from the easternmost subandean reliefs, a major sedimentary change took place near the Pliocene/Pleistocene transition: lacustrine clays and peat-bearing sediments (Pebas Formation) underlie fluvial sandy sediments of the Iquitos Formation, which contain quartz clasts up to 5 cm in diameter (Dumont & García, 1989). Indeed, the drastic lithological change seems to be associated with the end of a subsident episode in the basin and the onset of a fluvial drainage, likely to be related to the early Pleistocene Andean tectonic pulse (Sébrier **et al.**, 1985). Nevertheless, these deposits imply a stronger and more contrasted fluvial regime than today, since the clasts are 10 times larger than those deposited presently on the banks of the area.

South of Iquitos, two sets of successive terraces post-date the Iquitos Formation (Dumont **et al.**, 1988). The upper terrace (Pumacahua) is composed of white sand, clay and numerous trunk remains for which radiocarbon dates of 32.000 and >40.000 BP were obtained. These deposits are widespread in western Amazonia: in the Pucallpa area (Dumont, unpubl.data), in northern Madre de Dios (Campbell & Frailey, 1984) and in the Acre region (Frailey et al., 1988). In the latter locality, lateral equivalents show lacustrine and evaporitic facies; radiocarbon dating indicates that these arid conditions

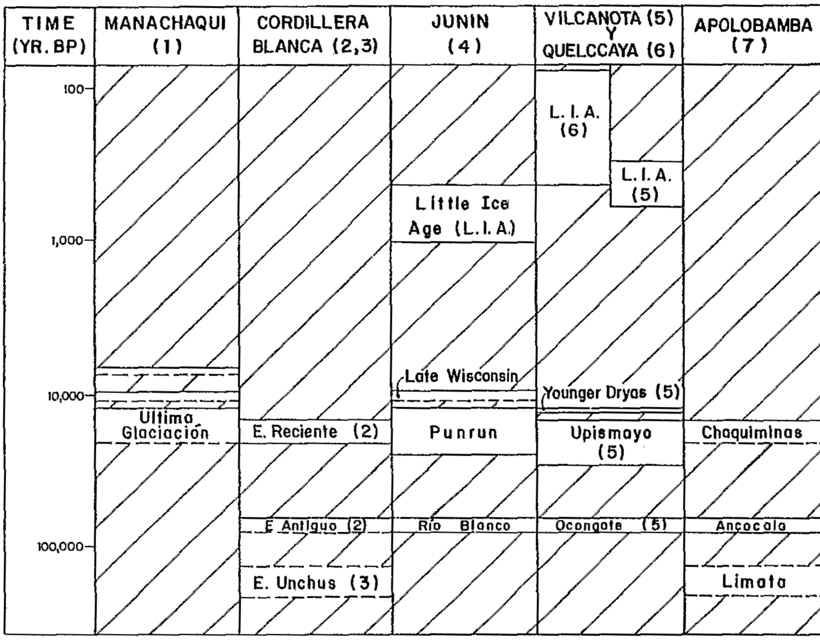

Figure 4. Tentative chronostratigraphic correlation chart of Late Pleistocene and Holocene glacial deposits of Peru. Data from 1. Birkeland et al.,(1989), 2. Bonnot (1984), 3. Heim (1947), 4. Wright (1983, 1984), 5. Mercer (1984), 6. Thompson (1986), 7. Fornari et al., 1988

predominated ca. 50,000 BP (Kronberg, et al., 1990); this result agrees with the conclusions of Colinvaux's (1989) review. The lower terrace (Chupiari) contains fine-grained sand, silt and leave accumulations and yields radiocarbon ages around 13,000 BP (Dumont et al., 1990). By the similarity of its facies and sedimentary structures, this Chupiari level closely resembles the present-day deposits of the area. The distribution, age and lithology of the Amazonian terraces suggest a possible relationship with Andean interglacial or interstadial periods.

REGIONAL PALEOCLIMATIC INTERPRETATIONS

Paleoclimatic data from Peru is unevenly distributed, and therefore is hardly useful to reconstruct the evolution of climate in the coastal, cordilleran and Amazonian regions. Nevertheless, several authors attempted paleoclimatic interpretations. Some of them put emphasis on the cyclicity of the climatic fluctuations (i.e. the Andean glaciations, the "pluvials", or the Holocene El Niño events), while others intended to reconstruct the atmospheric dynamics prevailing during glacial, interglacial, or Holocene times.

1. Chronology of Pleistocene cold periods

During several decades, the onset of cool climates associated with the first "Quaternary" glaciation was considered to be expressed by the remnants of a poorly dated but widespread increase in fluvial dynamics, observed in distinct areas of the country. Consequently, the first major phase of alluviation in the central coast (Cañete Formation), the upper part of the Jauja Group in the Huancayo basin, and the coarse-grained sediments of Amazonia (Iquitos Formation) were tentatively correlated with the early Pleistocene. However, the evidence for the occurrence of a cordilleran glaciation during the Pliocene (Bonnot et al., 1988) shed a new light on the chronostratigraphy and paleoclimatic interpretation of some of the key late Cenozoic sedimentary strata in the country. The climatic change which occurred in Peru close to the mid-Pliocene (ca. 4 or 3.5 Ma) seems to have been more important and better preserved in the geological record, than the Plio-Pleistocene boundary.

The "global" climatic fluctuations recognized for the last million years, with ten glaciations or so recorded by deep-sea cores (Shackleton & Opdyke, 1976; Imbrie **et al.**, 1984), are represented in the Peruvian continental record only by three or four glacial (cordilleran) and alluvial (coastal) morphostratigraphic units. Only the major last full glacial event (I.S. 2, ca. 20 ka), supported by radiocarbon dating and, with much less confidence, the I.S.4 (ca. 70 ka) and I.S.6 (150 ka), are evidenced by glacial landforms in the Peruvian Andes. We ignore how much geological evidence of previous events was eroded and to what extent older glacial drift remains correspond to distinct glacial episodes.

Dollfus (1965) correlated the coastal alluvial terraces with glacial epochs, while Teves (1982) placed them both in glacial and interglacial periods, and Macharé (1981) considered that they were most probably emplaced at the transition from glacial to interglacial conditions. The suggestion that the aridity has been predominant in western Peru since the formation of the Andean physiographic barrier (Garner, 1959) has been accepted by most of the following workers.

2. Modelling of the climatic characteristics of cold periods

Several authors have widely discussed the weather conditions prevailing during the last (and previous) glacial periods in different areas. Herein, we shall briefly recall the general conclusions about the atmospheric circulation controlling the regional climate and the behavior of the main climatic elements (temperature and precipitation).

During a glacial period, the intensity of the southeast Pacific anticyclone seems to have been strong, and would account for an intense atmospheric circulation with reinforced easterly trade winds (Lamb & Woodrofe, 1970; Simpson, 1975; Campbell, 1982) associated with a very active Walker circulation (Quinn, 1971), all which should have favoured the development of coastal fog and of "lomas" vegetation (Campbell, 1982). Conversely, the position of the Intertropical Convergence Zone (ITCZ) during ice ages is not known, despite the hypotheses that, the ITCZ remained throughout the year north (Colinvaux, 1972), or south (Newell, 1973) of the equator have

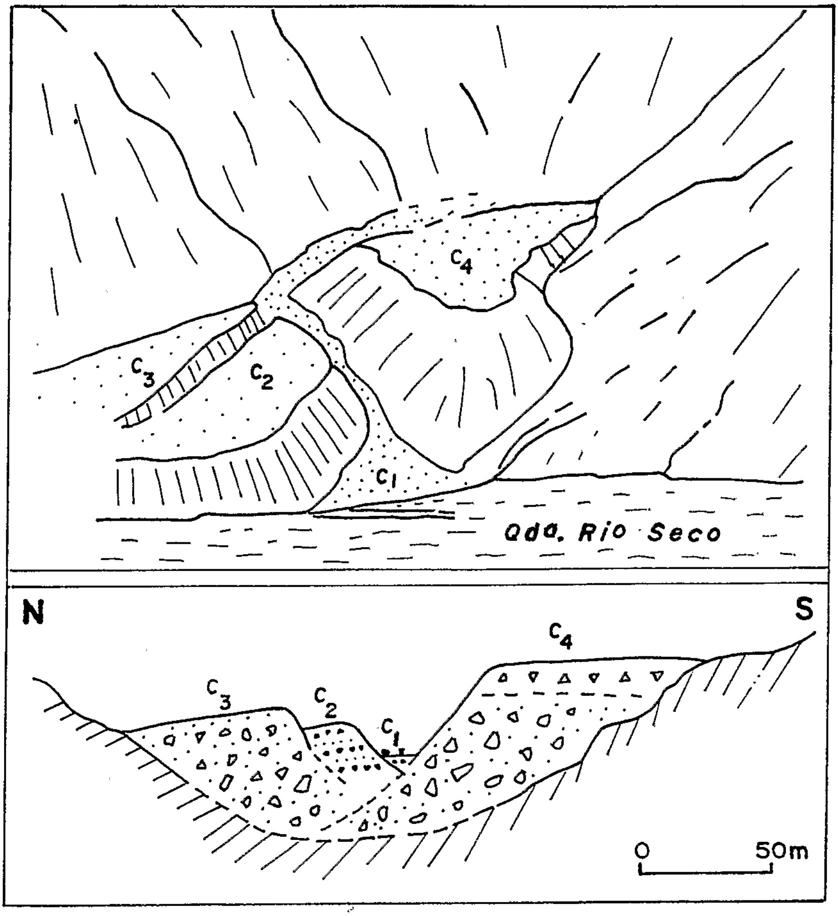

Figure 5.- Morphological sketch and cross section of the alluvial fan sequence fed by the 6 km-long quebrada Río Seco de Lurín, 40 km south of Lima. Note the four events of incision-infill of the valley. (From Macharé, 1981).

been already discussed (Houvenhagel, 1974; Simpson, 1975; Hastenrath, 1985).

Temperature distributions during ice ages have chiefly been modelled for the oceanic areas. Early sea surface temperature (SST) estimations of 5° to 6°C less than present-day mean temperatures were based on isotopic composition of foraminifera $CaCO_3$ (Luz, 1973; Fairbridge, 1972), recent modelling displays 4°C and 3°C below present conditions off Peru for February and August respectively (CLIMAP Proj. members, 1981). Estimates of low latitude, low elevation land surface temperature depression is usually less than 3°C

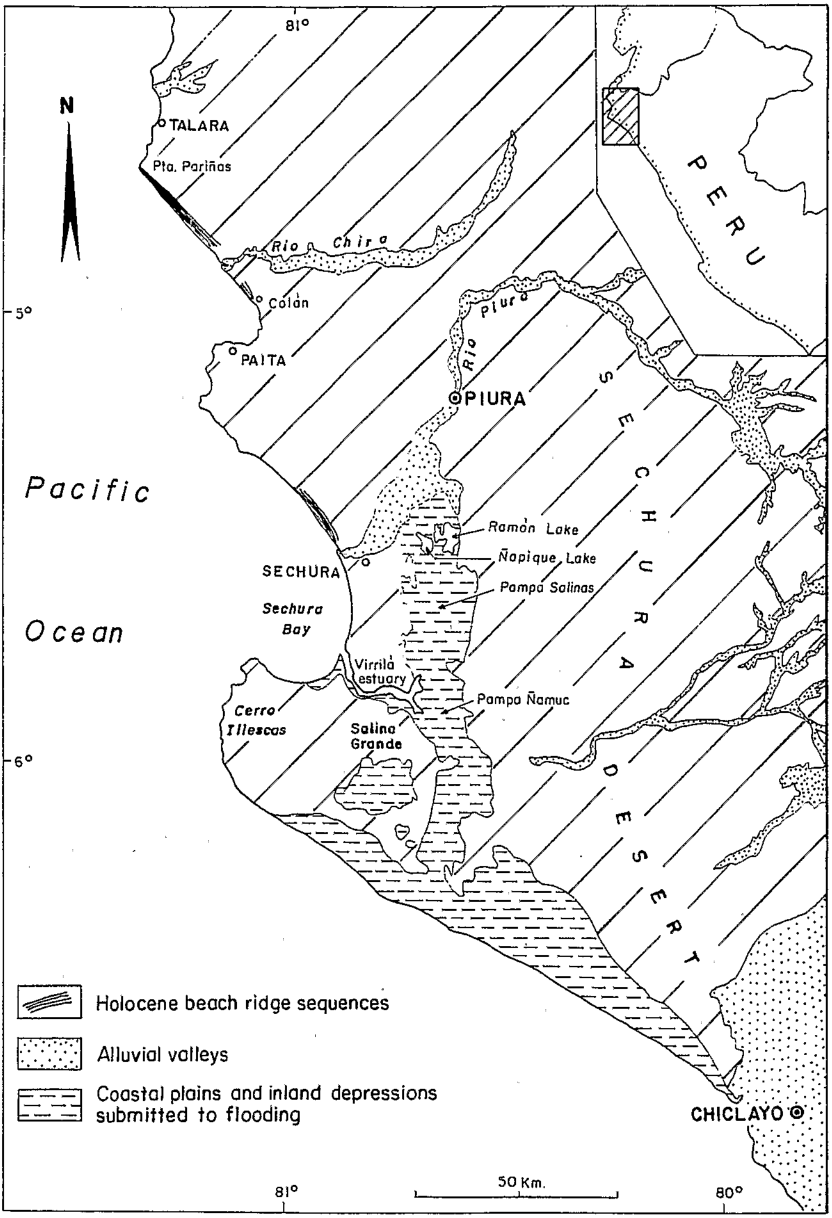

Figure 6.- Morphological sketch map of northwestern Peru showing the main environments where paleo-El Niño events have been recorded. (From Macharé **et al.**, 1990).

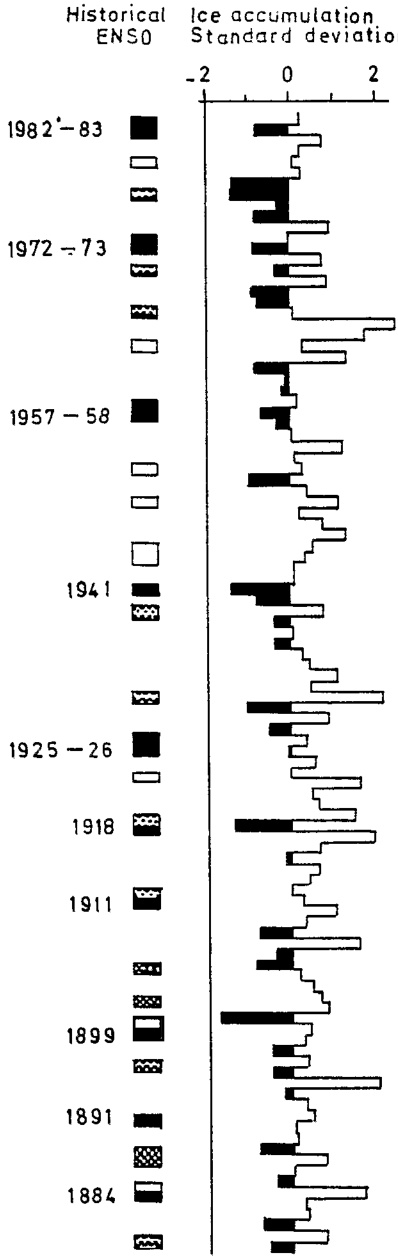

Figure 7.- Variation curve of ice accumulation rates recorded in the Quelccaya ice cap versus strong (black), moderate (dotted) and minor (blank) occurrences of El Niño events in the recent past. (From Thompson, 1988).

(Bjerknes, 1961), but no data are available for mountain regions, even though this factor seems to be most important for the triggering of a glaciation in the central Peruvian Andes (Seltzer, 1990).

Enhanced aridity accompanied the glacial conditions in Peru as well as in most of the tropical regions (Hastenrath, 1985). In the coastal zone, the prevalence of arid climate has been reported since long time (Fenner, 1948; Garner, 1959), and would be associated to a reduction of the effective evaporation rate and to subsidence of the westerly humid winds. In the cordilleran zone, aridity is evidenced by pollen analyses indicating a lowering of the Andean forest altitude (Hansen **et al.**, 1984). Several geological and biological (botanical) arguments support Pleistocene arid conditions in most of the Amazonian basin (Colinvaux, 1989; Kronberg **et al.**, 1990). In this context, there exist two main sources of moisture: a southward shift of the ITCZ which would affect the northern regions, and the advancements of polar cold fronts which would account for rainfall on the southern Peruvian Amazonia and snowfall on the eastern cordillera of southern Peru (Servant & Villarroel, 1980).

Eustatism is another factor that may play an important role in the understanding of paleoclimate along the coastal zone. Quinn (1971) considers that the low sea-level during the last glacial maximum was a determinant element for the reinforcement of the Walker cell. Chauchat (1987) underlined the implications of sea-level position in the altitude-controlled climatic boundaries in the northwestern coastal zone, and the greater extension of the "lomas".

3. Major features of Holocene climates

The transition from late Pleistocene to Holocene climates was apparently very sharp in the cordilleran zone, and had an important influence on the development of early Andean civilizations (Patterson & Lanning, 1967; Cardich, 1985). The first half of the Holocene is rather poorly kwown, but in extra-Andean areas probably correspond to the progressive emplacement of the climatic characteristics that have prevailed up to nowadays. The idea of a climatic optimum has not fully been adressed. The best evidence for such optimum found along the coast corresponds to paleobays for which a few set of radiocarbon dates indicate ages between ca. 5,000 and ca. 7000 BP (Wells, 1988; Perrier et al., 1990). The identification of rainy events (El Niño) during the second half of the Holocene both in coastal records and in the Quelccaya Ice Cap record show that direct relationships exist between the climatic events of the coast with those within the Andean region.

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