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COASTAL DEFORMATION AND SEA-LEVEL CHANGES IN THE NORTHERN CHILE SUBDUCTION AREA (23°S) DURING THE LAST 330 KY

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Abstract — The Nazca–South American plate boundary is a subduction zone where a relatively complex pattern of vertical deformation can be inferred from the study of emerged marine terraces. Along the coasts of southern Peru and northern Chile, the vertical distribution of remnants of Pleistocene terraces suggests that a crustal, large scale uplift motion is combined with more regional/local tectonic processes. In northern Chile, the area of Hornitos (23°S) offers a remarkable sequence of well-defined marine terraces that may be dated through U-series and amino-stratigraphic studies on mollusc shells. The unusual preservation of the landforms and of the shell material, which enabled the age determination of the deposits, is largely due to the lengthy history of extreme aridity in this area. The exceptional record of late Middle Pleistocene to Late Pleistocene high seastands is also favoured by the slight warping of two distinct fault blocks that have enhanced the morphostratigraphic relationships between the distinct coastal units.

Detailed geomorphological, sedimentological and chronostratigraphic studies of the Hornitos area led to the identification, with reasonable confidence, of the depositional remnants of sea-level maxima coeval with the Oxygen Isotope Substages 5c, 5e, 7 (probably two episodes) and the isotope stage 9 (series of beach ridges) The coastal plain, at the foot of the major Coastal Escarpment of northern Chile, appears to have been uplifted at a mean rate of 240 mm/ky in the course of the last 330 ky. From the elevation of the older terraces and late Pliocene shorelines, it can be inferred that these steady vertical motions were much more rapid than during the Early Pleistocene. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Over the last 150 years, several famous studies on coastal deformations and neotectonic uplift have been reported in Chile. After D'Orbigny (1842) and Darwin (1846), other naturalists (e.g. Domeyko, 1848, 1860; Pissis, 1856; Vidal Gormaz, 1901; Courty, 1907) have discussed, at length, the significance of the Quaternary marine terraces preserved along the coast of northern Chile, particularly in the areas of La Serena-Coquimbo (30°S) and also between Antofagasta and Iquique (24–22°S). For more than a century, the evidence of coastal uplift in Chile was tentatively related with the Andean Cordillera orogenesis and/or with the historically active seismicity of the country. It was only in the 1970s that the plate tectonic model offered a geodynamic framework that integrated the marine terraces, the seismic activity, the plate boundary and the subduction of the Nazca plate below the South-American plate (Barazangi and Isacks, 1976). However, until recently, much uncertainty has remained concerning the age of the Quaternary terraces, and thus the rate of uplift recorded along the Chilean coast. The age of the conspicuous terraces at La Serena and Coquimbo, on which had been based the chronostratigraphy of the Quaternary marine units in Chile (Herm and Paskoff, 1967; Herm, 1969; Paskoff, 1970, 1977) could not be established precisely. Furthermore, it was commonly assumed that the terraces had been formed during episodes of significantly higher sea level stands than the present datum.

Subduction Plate-Boundaries and Quaternary Uplift Motions

At subduction plate boundaries the margin of the overlying plate generally registers strong uplift motions during Quaternary times (Ota, 1986). In the western Pacific, the identification of Late Pleistocene and late Middle Pleistocene emerged reef tracts at elevations of hundreds of metres above present sea level indicates uplift rates in the order of several millimetres per year over timescales of several hundred thousand years (Chappell, 1974; Bloom *et al.*, 1974; Ota, 1986). Therefore, it has been commonly considered that such high values of uplift rate were representative of any subduction zones. Actually, uplift values of over 0.5 mm/year, in the long range, may prove to be quite exceptional. In Peru and Chile, for instance, the vertical deformation of the coastal area appears to be much weaker: uplift rates are about an order of magnitude lower than those calculated across the Pacific Ocean. Along the coast of southern Peru, Pleistocene marine terraces are seldom observed at more than +200 m above present sea level, and regional uplift rates are of the order of 150–100 mm/ky for the entire Quaternary (Ortlieb *et al.*, 1995a). In some localities affected by local tectonic activity, though, uplift rates of up to 300 to 460 mm/ky were determined (Goy *et al.*, 1992; Ortlieb *et al.*, 1994a, *in press*). Besides, a several hundred kilometre long coastal segment in north-central Peru (7–14°S) does not show any evidence of Quaternary uplift (Macharé, 1987; Ortlieb and Macharé, 1990a). In contrast, the area in front of the termination of the aseismic Nazca Ridge (14–15°S) was uplifted, during the last million years, at a maximum rate of 740 mm/ky (Macharé and Ortlieb, 1992). Thus, it is clear that the deep-seated processes directly associated with the subduction of the Nazca plate, which should present some regional homogeneity, do account for only a part of the vertical deformation registered along the Peru plate boundary. Before a general pattern of regional deformation can be determined along this subduction plate boundary, we still need to decipher the detailed history of local uplift motions in distinct coastal sectors.

Geochronological Problems

Quantifying positive vertical motions along coastal regions requires that the emerged Pleistocene marine terraces be dated and correlated with interglacial high seastands. But dating marine terraces is a difficult task. The lack of corals along the Pacific coast of South America, south of 4°S, implies that radiometric measurements need to be done on mollusc shells, although U-series dating of molluscan material is often considered as unreliable (Kaufman *et al.*, 1971). Other geochronological methods were used, but did not always yield clear-cut and definitive results. The electron spin resonance (ESR) method was attempted in a series of localities from southern Peru and northern Chile (Radtke, 1985, 1989; Ratusny and Radtke, 1988; Hsu *et al.*, 1989), and amino acid epimerisation (allo/isoleucine) and racemisation measurements were performed on shells from numerous marine terraces of the same area (Hsu, 1988; Hsu *et al.*, 1989; Ortlieb *et al.*, 1992, *in press*; Leonard and Wehmiller, 1992). These geochronological methods all have their inherent limitations, and none are straightforward for the dating of fossiliferous deposits associated with former high seastands. The radiometric methods (U-series and ESR) are limited by the migrations of radionuclides within mollusc shell carbonate during diagenesis. Amino acid racemisation (or epimerisation) in contrast is primarily a relative dating method, which needs to be calibrated by an independent geochronological method in every region. One of the chronological problems that arose in the last decade was a regional aminostratigraphic framework, 'calibrated' on ESR data and largely based on a kinetic model of epimerisation developed in California and adapted to Chile (Hsu, 1988; Hsu *et al.*, 1989) that yielded dates for deposits at variance with some morphostratigraphic evidence (cf. Ortlieb and Macharé, 1990b; Ortlieb *et al.*, *in press*). The discrepancy is not resolved yet, although some new data from central Chile may lead to the elaboration of a revised aminostratigraphic scale (Leonard and Wehmiller, 1992; Leonard, *pers. commun.*, 1995). While one can count only on the geochronological tools presently available, no age determination of marine terraces in Peru and Chile should be proposed without, at least strong supporting morphostratigraphical criteria.

The major purpose of the present work is to provide new morphostratigraphic and geochronological data from an area considered representative of a several hundred kilometre long sector of the coast of northern Chile. The chronostratigraphic interpretation of the sequence of terraces and neotectonic observations strongly suggest that, beside some local warping and faulting activity, the study area has experienced neotectonic uplift of regional significance. The apparent steadiness of the vertical deformation during at least the last 330 ka is taken as an indication of the crustal nature of the involved motions. We interpret that they constitute a passive response of the edge of the continental margin to the process of subduction of the Nazca plate. It will also be shown, from the distribution of the older marine terraces, that some modification occurred, during the early Middle Pleistocene, in the regional uplift rate and, possibly, in the subduction regime. Vertical deformation was much slower in the Early Pleistocene along the studied sector of the plate boundary.

THE NORTHERN CHILE COAST: GEOLOGICAL SETTING

Pleistocene Marine Terraces at the Foot of the Coastal Escarpment

The landscape of northern Chile is dominated by the Coastal Cordillera, a narrow range that reaches 2000 m in elevation and is limited to the west by a major escarpment. The Coastal Escarpment runs along the coast for more than 1000 km and suddenly vanishes at Arica, at the international boundary with Peru, where the coastline changes its general trend from N–S to NW–SE. Between Arica (18°S) and Iquique (20°S), the Coastal Escarpment is very steep, measures more than 1000 m (and locally up to 2000 m) and plunges directly into the sea; no marine terraces are preserved along this coastal sector (Paskoff, 1978). But, from Iquique southwards, a narrow coastal plain develops at the foot of the escarpment; this coastal fringe cut into the basement of the Coastal Cordillera (mainly thick Jurassic volcanics) exhibits remnants of Pleistocene marine deposits. In some places, several marine abrasion surfaces are preserved in staircase disposition, between the coastline and up to +200 m (all elevations hereby are given above present mean sea level). In many cases, a thin sheet of coastal and marine sediments blankets the wave-cut abraded platforms (Ratusny and Radtke, 1988; Radtke, 1989).

In the coastal stretch between Iquique and Antofagasta (23°30′S), the width of the coastal plain is uneven (typically between 1 and 3 km). Immediately north of Antofagasta the coastal plain broadens towards the west to constitute the core of Mejillones Peninsula (see inset of Fig. 1). This peninsula is a large, anomalous, structural block cut by some large crustal faults, which disrupts the N–S trending coastline of northern Chile. In Mejillones Peninsula, numerous emerged coastal and marine features of Plio-Pleistocene age, like staircased marine platforms and wide strand plains covered with long sequences of beach-ridges, indicate that, during the late Cenozoic, strong vertical motions have been occurring (Okada, 1971; Ferraris and Di Biase, 1978; Armijo and Thiele, 1990). The highest-lying Early Pleistocene marine sediments are found at an elevation of +440 m, on the edge of a faulted block (Ortlieb *et al.*, 1995b). However, in the major part of the peninsula and along the adjacent coastal plain, the latest Pliocene and earliest Pleistocene marine deposits are commonly lying at elevations of the order of +200 to +220 m (Ortlieb, 1993). Thus, the peninsula may be viewed as a large, composite, crustal block which was uplifted by a mean amount of about 200 m in approximately the last 2 My, and some faulted compartments were differentially uplifted by an additional amount of up to 240 m. More rapid uplift motions had been previously suggested by authors who actually did not study the chronology or stratigraphy of the emerged terraces and associated deposits (Okada, 1971; Armijo and Thiele, 1990). Some of the highest (above +400 m) wide marine platforms visible in the peninsula that were interpreted as Pleistocene landforms, were actually cut by Pliocene seas, as revealed by the faunal content of the associated deposits.

At Antofagasta, where the coastal plain is narrow again, the Quaternary marine terraces are largely eroded and degraded. The highest-lying shore-platform (the 'Antofagasta Terrace'), at the foot of the Coastal Escarpment, is located at a mean +100 m elevation, and was assigned to the Pliocene on palaeontological grounds (Martínez de los Ríos and Niemeyer, 1982). Recent re-examination of the sedimentary cover of this conspicuous terrace revealed that coastal deposits bearing Pleistocene faunal elements locally overlie the Pliocene beds associated with the platform (Ortlieb *et al.*, 1995b). 15 km south of Antofagasta, at Coloso, the coastal plain narrows and disappears, so that the Coastal Escarpment reaches the coastline. At Coloso, the Antofagasta Terrace is +80 m high, while the last interglacial shoreline is preserved at about +6 m (Ortlieb *et al.*, 1993, 1995b). Thus, at the southern extremity of the 400 km-long Iquique-Antofagasta coastal plain, it is inferred that the net vertical motions were limited. For the whole Quaternary period (=last 1.8 My), a mean uplift rate of the order of 50 mm/ky is calculated. But, assuming that the last interglacial sea level was a few metres above the present datum, it is also interpreted that the vertical deformation was almost nil during the late Quaternary (Ortlieb *et al.*, 1993).

Study Area

At 100 km north of Antofagasta, one sector of the coastal plain exhibits a particularly well preserved sequence of three marine terraces, with fossiliferous deposits protected by a thin layer of alluvial cover. It is located at Hornitos, immediately to the NE of the Mejillones peninsula, where the width of the coastal plain is less than 4 km. The study area extends from Punta Yayes (22°48′S) to Punta Chacaya (22°59′S; Fig. 1). The narrow coastal sector can be subdivided from north to south into two embayments (Caleta Hornitos and Caleta Chacaya) that are limited by three rocky promontories (Punta Yayes, Punta Hornos and Punta Chacaya; Fig. 1). The most conspicuous sequence of marine terraces is located in the southern half of the Hornitos embayment. A more complete series of terrace remnants (numbered I to IV in Fig. 1) is preserved in the Chacaya embayment, but these are partially covered with eolian sand sheets and alluvial fan deposits (Ortlieb *et al.*, 1995c). On the rocky headlands of Punta Hornos and Punta Chacaya the remnants of Pleistocene marine transgressions consist of shore-platforms that are generally devoid of marine sediments. At least six platforms are recognised in the three morphological ridges of Punta Yayes, Punta Hornos and Punta Chacaya (and identified by correlative numbers 1–6 in Fig. 1). To the east of Punta Chacaya, the terrace identified by number "4" is preserved at +130 to +140 m elevation; morphostratigraphically it seems to predate terrace IV of the Chacaya embayment.

In the embayments the substrate of the terraces is formed by Pliocene marine sandstones (Herm, 1969; Ferraris and Di Biase, 1978) that were easily eroded by the succeeding transgressions. The sediment covering the marine platforms are typically coarse-grained sands and gravels, with a varying amount of marine pebbles and larger blocks. The faunal content of the marine terrace deposits do not vary significantly from the present day nearshore fauna (Ortlieb *et al.*, 1994c; Ortlieb and Guzmán, 1994). The major difference lies in a somewhat greater diversity of the fossil assemblages with respect to the modern fauna. No particular change in the nearshore oceanographic conditions seems to have occurred from one interglacial stage to the other, at least in the last three interglaciations. This means also, that no paleontological

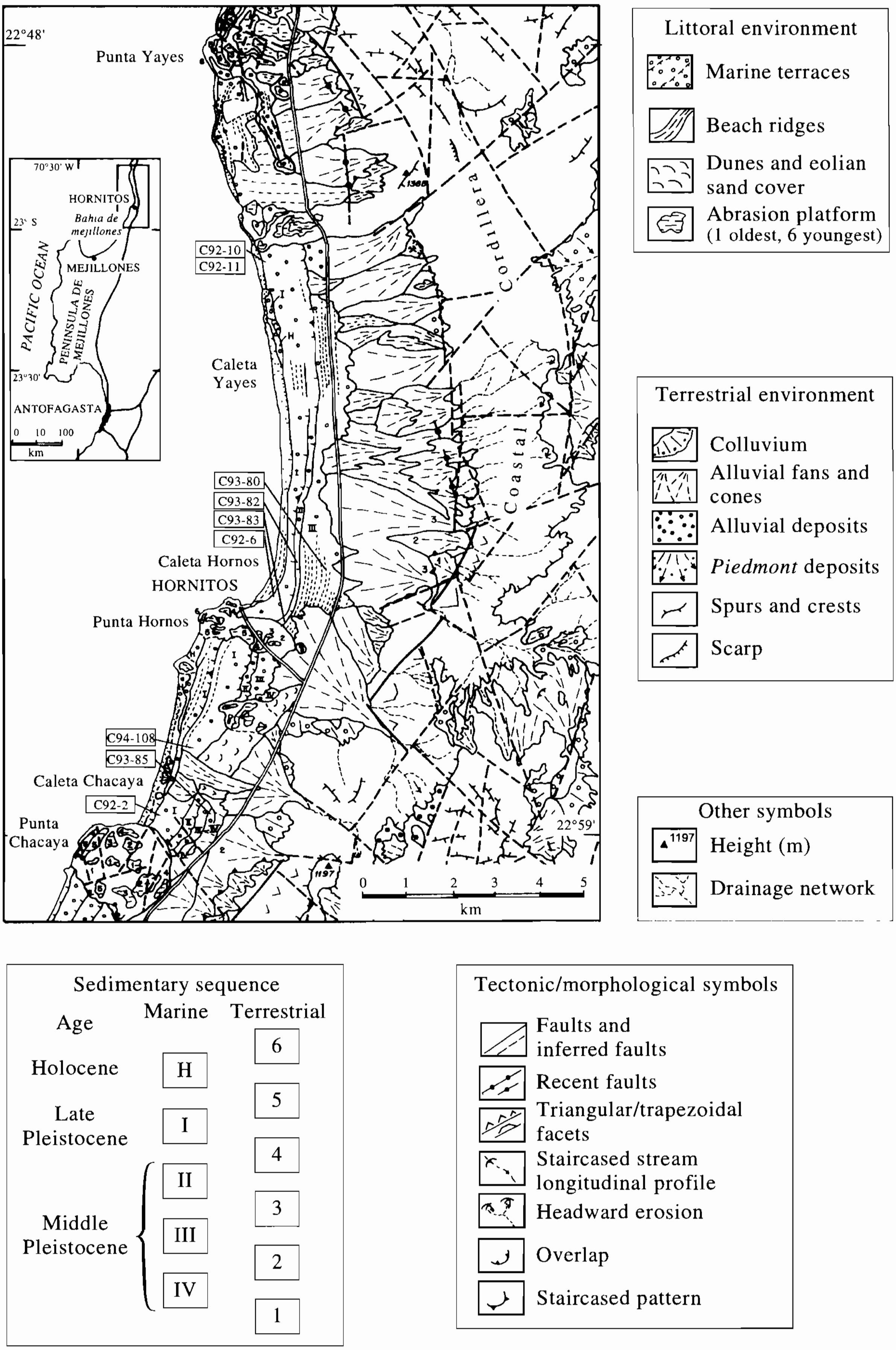

FIG. 1. Geomorphological sketch map of the study area between Punta Yayes and Punta Chacaya, to the northwest of Mejillones Peninsula, northern Chile, showing the geological and morphotectonic context in which are preserved the three major marine terraces I, II and III. These staircased terraces are correlated with the isotopic stages 5, 7 and 9.

argument may be used to identify any particular marine terrace at Hornitos.

The Coastal Escarpment is almost 1000 m high in the eastern part of the study area. The alluvial fans that piled up at the foot of the escarpment obscure any evidence for marine terraces higher than those cropping out at +80 to +100 m. Nevertheless, in the northernmost part of the study area, due east of Punta Yayes, is preserved a small remnant of Early Pleistocene deposits, at an elevation of ca. +170 m (Ortlieb *et al.*, 1995b). This isolated outcrop is tentatively correlated with other occurrences of a similar unit (identified by an overlying ash layer) to the north (Michilla, at +160 m) and south (Antofagasta, at +100 m) of the study area. Its faunal content indicates a Pleistocene age, and its morphostratigraphic position (as highest-lying terrace) lead to consider it as the oldest Pleistocene marine remnant of the area.

Holocene Coastal Evolution

The major Holocene coastal feature in the Hornitos embayment is a several hundred metre wide eroded platform covered by littoral drift sand. The elevation of the inner edge of the modern terrace at the base of the sea cliff locally reaches about +5 m. The coastal cliff was abandoned several thousand years ago, after sea level fell by some 2 m (?). Radiocarbon and U-series (TIMS) dating of a recent emerged shore deposit at Michilla (20 km north of Hornitos) suggests that the highest sea level stand during the Holocene occurred at 7000 BP (Leonard and Wehmiller, 1991; Ortlieb *et al.*, 1995b). A few metre high small morphological terrace (that includes an alluvial component) is preserved at the foot of the coastal cliff in the middle of the Hornitos embayment. The lack of emerged Holocene coastal sediments in the south of the Hornitos embayment is attributed to the effect of recurrent tsunami events. The last strong seismic events that struck the northern Chile coast (in 1868 and 1877) were accompanied by tsunami waves whose runup reached a height of, respectively, 6 and 9 m in the Cobija-Hornitos area (Lockridge, 1985). In the Chacaya embayment, as in the north-easternmost Bay of Mejillones, the backshore is formed by a 3 to 4 m high, sandy terrace which was probably formed during one (or several) late Holocene former tsunami event(s). A feature characteristic of the back shore of the southern Chacaya embayment is the accumulation of recent mud flow deposits atop the marine sandy sediment.

The Holocene strand plain is particularly wide at Hornitos. This coastal landform is more developed than along other sectors of the northern Chile coast, and constitutes a modern equivalent of the Pleistocene emerged terraces that were preserved in the study area. The exceptional development of the modern and older terraces is attributed to geological (favourable Pliocene substrate), geographical (embayment morphology and semi-protected topography) and oceanographic (long-shore transport) conditions, and also to a slightly more rapid uplift regime than in nearby localities.

THE HORNITOS SEQUENCE OF MARINE TERRACES

Morphostratigraphy of the Terraces

In the Hornitos embayment, three marine terraces can be distinguished between the Holocene seacliff and the foot of the Coastal Escarpment (Figs 1 and 2). These terraces present various morphological differences.

The lowest (youngest) Pleistocene terrace, numbered 'I' in Figs 1 and 2, is well preserved all along the Hornitos embayment. Its distal edge, atop the 12 km long coastal cliff that was formed in the mid-Holocene, lies at +18 to +25 m (a.s.l.). Its inner margin, at the foot of the palaeo-seacliff formed during the maximum of the transgression, is found at about +30 m, with a maximum elevation of +36 m east of the village of Hornitos. This terrace is morphologically well defined and was considered up to now as having been cut during a single episode of high sea-level (Herm, 1969; Radtke, 1985, 1989; Ortlieb *et al.*, 1994b). However, the flat morphology of that terrace

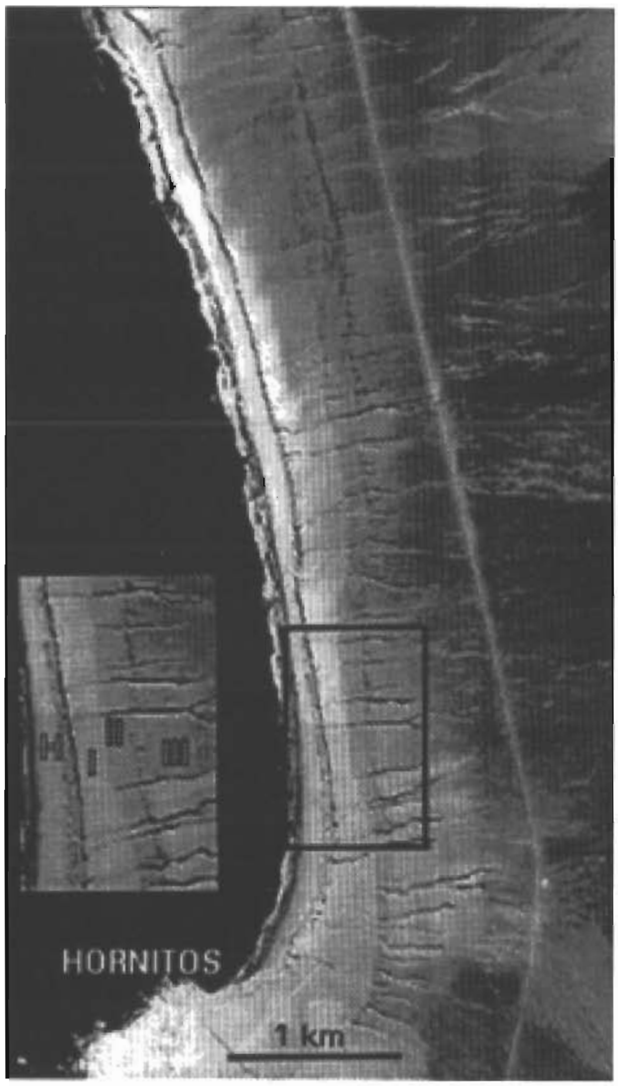

FIG. 2. Aerial photograph of the Hornitos embayment, with enlargement of a sector where the three Pleistocene terraces and the Holocene terrace are well preserved, and in staircased disposition. (Document Servicio Aerofotogramétrico SAF- 81, CH60-S.5-3, 018962, Fuerza Aerea de Chile).

FIG. 3. Photograph taken from the first Pleistocene marine terrace (I) showing that below the alluvial component of the coastal terrace, there is a two-step marine abraded platform with two separate nearshore units. Each step was formed during distinct episodes of high sea level: isotopic substages 5c and 5e.

surface mainly reflects the attitude of a sheet of alluvium, which actually hides a composite marine terrace; below the alluvial cover the coastal sediments of the terrace form two distinct stratigraphic units (Ortlieb *et al.*, 1995b, 1995c). Each unit is associated with a distinct wave-cut platform, and a vertical offset of up to 2 m was measured between the inner edge of the lower platform and the outer edge of the higher one (Fig. 3). The limit between the two platforms is located at about +25 m, and can only be observed in some of the 'quebrada' (arroyo) entrenchments that cut the terrace I and its Pliocene substratum. This morphostratigraphic disposition suggests that the two wave-cut platforms were formed one after the other, probably during two interstadial high seastands, within the same interglacial episode. As this is the lowest lying Pleistocene marine terrace, it is inferred that both platforms were cut during two substages of the isotopic stage 5 (probably substages, 5e and 5c).

The second higher marine terrace at Hornitos is the least developed of the three. It is narrower than the other two and disappears in the northern half of the embayment (Figs 1 and 2). The maximum elevation of its inner edge varies between +50 m and +55 m to the east of Hornitos; however, at the southern extremity of the Hornitos embayment, a slight upwarp of the terrace brings it up to a maximum elevation of +63 m. On the structural ridge formed by Punta Hornos, to the south of Hornitos village, remnants of this terrace were found at up to +75 m. Locally, two distinct platforms with their associated marine sediments were distinguished; they are interpreted as the remnants of two episodes of high seastand, probably during a single interglaciation. As the terrace was formed prior to the lower terrace, it is confidently assigned to the penultimate interglacial period (i.e. isotopic stage 7). Both subunits might correspond to Oxygen Isotope Substages 7a and 7c.

The third higher terrace is very wide, particularly east of Hornitos. Its inner edge, hidden by the large alluvial fans formed at the foot of the Coastal Cordillera, is located at an elevation slightly higher than +80 m. Numerous 'quebrada' cut perpendicular to the coast show that the thin sedimentary cover (typically less than 2 m) of this remarkably flat terrace consists of a series of prograding units of coarse beach deposits set in off-lap disposition. Four sedimentary units were clearly recognised in the field, but up to eight parallel lineaments are visible in aerial photographs (see Figs 1 and 2). These lineaments are remnants of beach ridges that were probably formed coevally with some of the much wider and larger beach-ridges of the northern Mejillones peninsula (Ortlieb *et al.*, 1995b).

In Chacaya embayment, the equivalent of Terrace I is represented by two terraces, one well-developed with an abundant sedimentary cover and an abrasion platform on which no sediments are preserved. The best developed marine terrace (with sediments) is cut by N–S trending small normal faults which produced small vertical scarps (a metre, or two, high). As mentioned above, the three lower terraces equivalent to those of Hornitos are extensively covered by sand dunes and alluvium (Fig. 1). In spite of the thick alluvial fans accumulated at the foot of the major escarpment, several remnants of a fourth terrace (IV), are observed at a +90 m elevation (Fig. 1). This terrace predates Terrace III but as the latter is much narrower than in Hornitos embayment, it is not clear whether Terrace IV should be assigned to a previous interstadial within the same interglaciation or to a previous isotopic stage.

Previous Chronostratigraphic Interpretations

Herm (1969) was the first author to describe the three conspicuous terraces at Hornitos and to study their faunal content. He proposed to correlate them with the Serena I, Serena II, and Herradura I terraces identified in the Coquimbo-La Serena region (30°S), but the lateral correlation was essentially based on altimetric criteria. According to the chronostratigraphic scale elaborated at that time by Herm and Paskoff (1967), the Herradura I terrace would correspond to the penultimate interglaciation while the Serena I and II units were tentatively assigned to the Early Pleistocene. Later, Radtke (1985, 1989) obtained the first geochronological results through ESR and U-series dating from mollusc shells of the three Hornitos terraces. He determined that the most recent Pleistocene terrace at Hornitos was of last interglacial age (i.e. younger than previously considered), while the two older terraces, which did not yield quite reliable radiometric results, were assigned to some previous transgressions of the Middle and/or the Early Pleistocene (Radtke, 1989). Amino acid epimerisation and racemisation studies were also performed in the area by Leonard *et al.* (1987) and Hsu *et al.* (1989) who, however, did not give any detail on the sampling localities. Later, Leonard and Wehmiller (1991) described the most recent Pleistocene marine terrace (equivalent to Terrace I at Hornitos) at Michilla. These authors also suggested that the low terrace should be assigned an isotopic stage 5 age, but without more refinement regarding substages of the last interglaciation.

New Geochronological Analyses

In this investigation, more than 70 amino acid epimerisation analyses and 10 U-series measurements were performed. The internal consistency of the chronometric results, together with the general coherency between these results and the morphostratigraphic and sedimentological interpretations provide a strong basis for establishing a chronostratigraphic scale for the northern Chile coast (Table 1). The shell species used for the geochronological analyses are all pelecypods, mostly veneridae (*Protothaca thaca*, *Eurhomalea rufa* and *Venus antiqua*) but also *Mulinia* cf. *edulis* and *Mesodesma donacium*. They are nearshore molluscs, commonly found in the marine terrace deposits and sometimes in growing position (paired valves). Material for amino acid analyses was sytematically collected at a depth of several decimetres, whenever possible at 1 m depth, below the surface, to limit the effect of thermal variations within the

TABLE 1. U-series and aminostratigraphic results from shells of the four marine terraces in the embayments of Hornitos and Chacaya, northern Chile. The four staircased terraces (I, II, III, IV) are assigned to the isotopic stages 5, 7, 9 and 9 or 11 (?). Allo/isoleucine and U-series data support the morphostratigraphical observation of a double sea stand record in the more recent terrace (I): substages 5c and 5e

Samplelocality	Elevation (m a.s.l.)	Shell species	Allo/Isoleucine value	*n*	std	mean	U/Th apparent age TIMS	alpha count	Assumed age (I.S.)
HORNITOS									
C92-6	+25	*Protothaca thaca*	0.36	3	0.02	0.39	105.3±1.0		
"		*Mulinia edulis*	0.42	2	0.01		108.3±0.8		5c
"		*Eurhomalea rufa*	0.38	1			108.8±1.0		
C92-10	+18	*Protothaca thaca*	0.49	2	0.07	0.50	106.1±0.8	124±7.0	
"		*Eurhomalea rufa*	0.51	2	0.02		109.2±0.9	116±6.0	
"		*Eurhomalea rufa*						106±5.0	5e
"		*Eurhomalea rufa*						119±5.0	
C92-11	+18	*Mulinia edulis*	0.51	4	0.07				
C93-83	+60	*Mulinia edulis*	0.63	3	0.04	0.62			
"		*Mesodesma donacium*	0.61	3	0.04				7
C93-82	+55	*Eurhomalea rufa*	0.62	3	0.08	0.62			
C93-80	+75	*Mulinia edulis*	0.71	3	0.06				
"		*Protothaca thaca*	0.73	3	0.05	0.71			9
"		*Mesodesma donacium*	0.69	3	0.05				
"		*Venus antiqua*	0.70	1					
CHACAYA									
C92-2	+23	*Mulinia edulis*	0.47	3	0.05	0.47			
"		*Mesodesma donacium*	0.46	3	0.03				
C94-108	+30	*Mulinia edulis*	0.45	3	0.05				5e
"		*Mesodesma donacium*	0.47	3	0.05	0.48			
"		*Venus antiqua*	0.53	3	0.02				
C93-85	+90	*Protothaca thaca*	0.79	2	0.10	?	(217.2±9.4)		9 or 11?
"		*Eurhomalea rufa*	1.10	3	0.02				

soil. In most cases a set of valves from three distinct individuals were analysed. All the mentioned species epimerise at an identical rate (Hsu *et al.*, 1989; Leonard and Wehmiller, 1992; Ortlieb *et al*, 1990b, 1996). The species *Eurhomalea lenticularis* undergoes epimerisation at faster rates, and did not yield consistent results when compared with the other species, so that results obtained on this material were not taken into consideration. Besides, two localities at Chacaya provided anomalously spread results, with high allo/isoleucine ratios: these data were attributed to a local overheating of the samples (within the soil) and were discarded. All the allo/isoleucine and U-series analyses were performed at GEOTOP, Université du Québec à Montréal. Details about analytical procedures can be found in Hillaire-Marcel *et al.* (1995).

U-series data

U-series data ($^{230}Th/^{234}U$, $^{234}U/^{238}U$) include alpha-spectrometry and TIMS (thermal ionisation mass spectrometry) measurements. The first method was used for samples from a single locality in the northern extremity of the study area (C92-10/11, Table 1). There, three out of four measurements yielded apparent ages of ca. 120 ka and a fourth sample gave a result of 106 ka ($\pm$5 ky). In the same locality, two additional samples analysed through TIMS yielded results of 106 ka ($\pm$0.8 ky) and 109 ky ($\pm$0.9 ky). At the present stage, two interpretations may be forwarded. Either, this unit was deposited during Oxygen Isotope Substage 5c and incorporated some fossil shells reworked from substage 5e deposits, or it correlates to substage 5e. Then, the somewhat younger apparent U-series ages would indicate late diagenetic incorporation of uranium into the shells (during Oxygen Isotope Substage 5c?), resulting in lower $^{230}Th/^{234}U$ ratios (i.e. lower ages). As will be seen below, allo/isoleucine (A/I $\sim$ 0.5; Table 1) data from this site would support an assignment of the unit to the highest sea-level episode of the last interglacial (isotopic substage 5e).

In another locality (C92-6), which also corresponds to the edge of the coastal cliff but in the southern extremity of the Hornitos embayment, three TIMS results were obtained; they range from 105 to 109 ka ($\pm$1 ky; Table 1). In this case, we surmise that the shells are coeval with the substage 5c because their allo/isoleucine ratios (A/I $\sim$ 0.4; Table 1) are significantly lower than in the former case.

Finally, an articulated sample of bivalve *Eurhomalea rufa* from the +90 m terrace (IV) at Chacaya yielded a 'finite' age of $\sim$217$\pm$9 ka (C93-85, Table 1). The embedding unit can be assigned to either an early isotopic substage 9, or to stage 11 (see below). We thus conclude that some discrete late diagenetic U-uptake occurred in the corresponding sample, resulting in a 'young' apparent age.

Aminostratigraphy

The results of the amino acid epimerisation analyses are generally coherent within the study area. Five aminozones could be distinguished among the four Pleistocene morphostratigraphic units (Table 1). Within the youngest terrace deposits, two aminozones with mean values around 0.4 and 0.5, respectively, were defined. The most recent samples (C92-6), according to the aminostratigraphic analyses (Table 1), come from the same locality which provided apparent U-series ages in the range 105–108 ka; they are thought to represent substage 5c. In the locality at the south of Hornitos embayment (C92-10), samples from the same three species of pelecypods yielded higher allo/isoleucine ratios, and thus are assigned to an older high sea stand, most probably substage 5e. In Chacaya embayment, two localities of the lowest marine terrace (C92-2 and C94-108) yielded A/I ratios of 0.47 and 0.48 (means of several species), that correlate with the 0.5 aminozone of Hornitos. We interpret that the A/I ratios of 0.47 to 0.50 correspond to the isotopic substage 5e.

The deposits of the second higher terrace (II) were sampled in two localities one to the east of the village of Hornitos (C93-82) and another one close to the Punta Hornos ridge where the fossils were better preserved in a finer, sandy sediment (C93-83), and at a slightly more elevated (+60 m) altitude than the typical +50 m elevation of the inner edge of terrace II. The third terrace was sampled in the middle part of the wide platform, to the east of Hornitos village (C93-80); the shelly bed is located between a coarse basal conglomerate and a finer grained unit which was capped by alluvial silt. Finally, the shells from the fourth terrace were sampled, in the Chacaya embayment, in a nearshore *in situ* deposit (C93-85) that had been covered by a thick mudflow unit; all the analyses were made on paired shells in the last locality.

The mean A/I ratios obtained on shells from the three older terraces (II, III and IV) were 0.62, 0.71 and either 0.79 (*Protothaca* mean) or 0.95 (*Protothaca* and *Eurhomalea* interspecific mean), respectively (Table 1). The difference in the ratios is of the same order of magnitude as the range between the two distinct aminozones of the younger terrace. Nevertheless, as the samples were collected in staircased terraces, it is inferred that these aminozones correspond to two, or three, interglacial high seastands prior to the last interglacial (Oxygen Isotope Stages 7, 9 and possibly 11). The difference observed in the A/I ratios provided by *Protothaca thaca* and *Eurhomalea rufa* samples of the +100 m terrace precludes any age determination for now.

The reliability of the aminostratigraphic results for the three younger terraces is assessed by the cluster of values obtained from every locality, among, as well as within, the species of pelecypods that were analysed. The correlation observed between the increasing values of A/I ratios and the morphostratigraphic position of the samples (i.e. elevation of terrace/relative age of the deposits) strongly suggests that in the Hornitos area, the thermal history of the buried samples was rather homogeneous from one locality to the other, except for a few localities at Chacaya already mentioned. The consistency of the morphostratigraphy and the aminostratigraphy does not validate the latter by itself, but at least provides some confidence into the proposed interpretation.

An additional element of chronostratigraphic correlation, and of calibration of the regional aminostratigraphy, is provided by geochronological results from a locality some 90 km south of Hornitos, in the northern part of the bay of Antofagasta. At that locality (called La Portada), U-series dating and aminostratigraphic analyses were performed on *Mulinia* cf. *M. edulis* and *Mesodesma donacium* (Ortlieb *et al.*, 1996). Three concordant U-series apparent ages of ca. 282 ka (275±11 ky, 282±9 ky and 288±12 ky) were obtained, while a double series of 14 shells of *Mulinia* cf. *edulis* and 14 shells of *Mesodesma donacium* yielded mean A/I ratios of 0.66 and 0.67, respectively (unpublished results obtained at GEOTOP, Montréal). We assume that this marine terrace was formed during the isotopic stage 9 (at 300–330 ka). The mean A/I ratio of 0.67 that was obtained from the analysis of 28 shells would be representative of the isotopic stage 9 in the Antofagasta Bay area (Ortlieb *et al.*, 1996). A chronological correlation between this value of A/I ratio of 0.67 and the 0.71 aminozone at Hornitos is quite acceptable, and supports the chronostratigraphy elaborated at Hornitos.

From previous ESR and U-series dating (Radtke, 1985, 1989) as well as from the amino acid racemisation and epimerisation studies performed in this sector of the northern Chile coast (Hsu *et al.*, 1989: Leonard and Wehmiller, 1991), it had been concluded that the most recent Pleistocene terrace could be assigned to the last interglacial episode. The new set of results provides more specific interpretations for the youngest terrace and proposes a more precise chronostratigraphical framework for the older ones. We conclude that, in the Hornitos-Chacaya area, the lower terrace was formed during two successive transgressions within the last interglaciation, most probably the substages 5e and 5c. The second terrace also shows morphostratigraphic evidence that it was formed in a two-step process. The second and third older terraces were not properly dated by the radiometric method, but amino acid epimerisation data is sound enough to enable a chronological correlation between terraces II and III with the Oxygen Isotope Stages 7 and 9.

TECTONIC DEFORMATION

Faulting and Warping Activity

Field observation and aerial photograph analysis of the study area indicate that some tectonic deformation did occur since the end of the Middle Pleistocene in the coastal region. Relatively recent fault scarps are visible along the Coastal Escarpment, across the alluvial fans and in the coastal plain itself. The most recent faults are observed near the head of some alluvial fans, close to the front of the escarpment (Fig. 1). Two fault systems oriented N120–140° and N20–30° and a few N–S trending faults are identified. These fault systems were mildly activated, or reactivated, both north and south of Hornitos (Punta Yayes and Punta Chacaya).

The marine terraces are seldom cut by fault traces, but they show warping and deformations that could be related to the reactivation of previous fractures. Besides, the attitude of the marine terraces and their geometrical disposition clearly point to a block deformation (Ortlieb *et al.*, 1995c). Two tectonic blocks can be distinguished: one in the Yayes-Hornitos embayment, and another one in Chacaya embayment. The variation of altitude of the Pleistocene shorelines, at the inner edge of the terraces, indicates that a small-amplitude tilt occurred in both blocks (Fig. 4). As every terrace reaches a higher elevation in the north of the embayments, it is inferred that the southward tilt of each block has been active (but not necessarily continuous) for a relatively long time span. The spatial disposition of the terraces suggests that the registered motions concern the whole blocks, and not small compartments within the blocks. The tilt motions of the two faulted blocks are interpreted as minor, and repeated, readjustments linked to the active deformation occurring in the half-graben of northern Mejillones Peninsula for the last several hundred thousand years (Ortlieb, 1993).

Regional Uplift Rates

In neotectonic studies dealing with vertical deformation of the coastal zone, two problems must be addressed; the age determination of emerged shorelines and the original position of the sea level (with respect to present sea level, for instance) at the time the terraces were formed. For the first problem, morphostratigraphical arguments and available geochronologic data were presented. For the second problem, some discussion is needed as there is no general consensus regarding the reconstruction of the palaeo-sea level coeval with every high seastand (e.g. Bloom *et al.*, 1974; Shackleton, 1987; Radtke, 1989).

The late Quaternary uplift motions

From the study of a large number of localities worldwide of the last interglacial shoreline, it could be inferred that the 'eustatic' sea level corresponding to the maximum of the last major transgression (at ca. 124 ka) was a few (about 6?) metres above its present-day position. These data which have a global value, and do not necessarily apply in every region (e.g. Murray-Wallace and Belperio, 1991), are classically used to evaluate the amplitude of the uplift motions in coastal areas where the trace of the 124 ka sea level is well identified. In the study area, the trace of the shoreline coeval with the peak of the last interglaciation is best identified to the east of the village of Hornitos, at the foot of the palaeo-seacliff that cuts the second higher terrace. The inner edge of Terrace I, east of Hornitos, is located at a +36 m maximum elevation. This altitude of the substage 5e highest stand of sea level thus suggests a net amount of uplift of 30 m during the last 120 ky or so, and provides a mean uplift rate estimate of 240 mm/ky.

As the shoreline remnants assigned to the isotopic

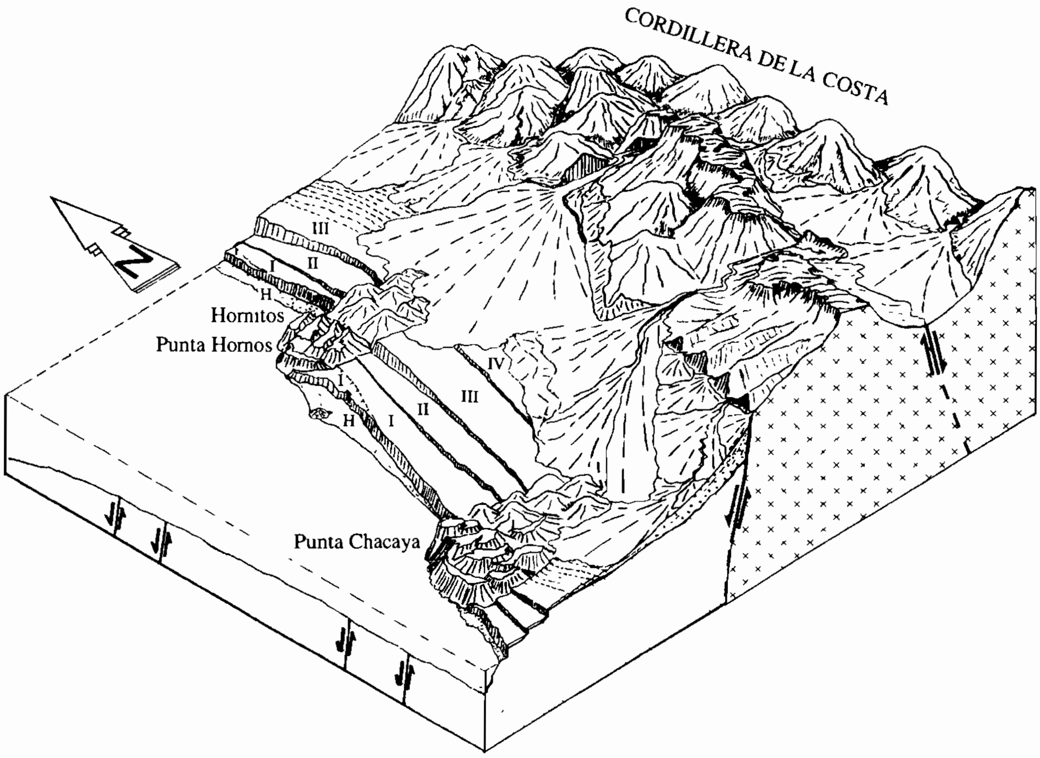

FIG. 4. Block diagram of the southern half of the Hornitos embayment and of Chacaya embayment showing the major active faults during the late Middle and Late Pleistocene and the southward tilt of the two faulted blocks separated by the Punta Hornos ridge. Numbers I to IV correspond to the four staircased terraces correlated with the isotopic stages 5, 7, 9 and possibly 11 (?).

substage 5c are found at an elevation of ca. +25 m on the same transect to the east of the village of Hornitos, some inferences can be made regarding the palaeo-sea level position during this interstadial episode. If it is assumed that a regional uplift rate of 240 mm/ky remained constant since the substage 5e, a former shoreline preserved at +25 m, and dated at 105 ka, would imply that, at that time, the palaeo-sea level was very close to the present datum. The hypothesis that the substage 5c sea level was not lower than the present sea level was previously proposed in a detailed study on the Ilo region (18°S) in southern Peru (Ortlieb *et al.*, *in press*). This palaeo-sea level reconstruction does not agree with the traditional 'eustatic' model of sea level fluctuations during the last interglacial period which was proposed by Bloom *et al.* (1974) and Chappell and Shackleton (1987), but is supported by reports and studies from distinct regions of the world (Bloom and Yonekura, 1985; Li *et al.*, 1989; Toscano and York, 1992).

The late Middle Pleistocene uplift motions.

A reconstruction of palaeo-sea level during the previous interglacial periods cannot be attempted in the same way as for the substage 5c, unless it can be established that the uplift rate has been constant through time. On the reverse, if it could be assessed that the reconstructed sea level coeval with the isotopic stages 7 and 9, respectively, are in a vertical position compatible with a given uplift rate, this would bring some support to the hypothesis that the uplift rate was constant through time. Following this reasoning, and considering that the stage 9 interglaciation was almost as warm as stage 5 (Shackleton, 1987), we suppose that at the transgression maximum the sea level was very close to its present-day position. With this assumption, the +80 m elevation of the inner age of Terrace III at Hornitos, which is assigned to the stage 9 (peak at ca. 330 ka), would indicate a net uplift rate of 240 mm/ky. This coincidence is significant. We consider it as a strong argument in favour of the permanency, for at least 330 ka, of an uninterrupted uplift motion of the southern half of the Hornitos embayment.

With an assumed continuous uplift rate of 240 mm/ky, the highest shoreline corresponding to Terrace II, found at +50 to +55 m, would be about 220 ky old. The younger of the two abrasion platforms of this terrace, with its shore platform cut some 5 m below the transgressive maximum, might well have been formed at ca. 200 ka (Oxygen Isotope Substage 7a). From this calculation, based on the assumption of a continuous uplift rate, we conclude that the sea level coeval with the substages 7a and 7c was probably also close to the present datum. The reconstruction of the sea level position during isotopic stage 7 has been controversial; several field indications from various parts of the world (e.g. Radtke, 1987; Murray-Wallace *et al.*, 1987) are not consistent with the estimate of a low high stand proposed by Shackleton (1987) through an interpretation of deep sea core data.

The geometrical disposition and the absolute altitude of the inner edge of the terraces I, II and III suggest a continuous uplift motion of the area to the east of Hornitos. The calculated net rate of 240 mm/ky is compatible with sea level reconstructions during the Oxygen Isotope Stages 5, 7 and 9.

The whole Pleistocene uplift motions.

Remnants of early Middle Pleistocene and of Early Pleistocene are scarce and difficult to identify. Several abrasion platforms, with scanty associated deposits, are preserved on the ridges of Punta Chacaya and Punta Hornitos. The most elevated ones may be of early Middle Pleistocene age. The highest elevated deposit in the area, which was assigned a tentative Early Pleistocene age, was observed at a +170 m elevation east of Punta Yayes. Considering that the isotopic stage 25, at ca. 950 ka, might have been as warm as the Holocene, according to Shackleton (1987), and might have been characterised by the highest sea level position during the early Pleistocene, it may be envisaged that the +170 m terrace corresponds to that interglacial. Anyway, if the age of this deposit is comprised in the range 1.6 to 0.8 Ma (i.e. the assumed range of the Early Pleistocene) and if an assumption of palaeo-sea level close to the present datum is made, an approximate estimate of net uplift rate of 100 to 200 mm/ky can be calculated. These values might represent underestimates if the palaeo-sea level was eustatically lower than the present one. In any case, these approximate estimates calculated for the whole Quaternary period, suggest that prior to the last 330 ky the regional uplift rates were significantly lower than subsequent uplift rates. We thus conclude that the evolution of the vertical deformation would be twofold: a slow, or very slow, uplift regime during the Early Pleistocene and, later on, a more rapid uplift in the last 400 ky or so. Such increase in the uplift rate is observed at a regional scale and may imply that some acceleration of the subduction motion occurred in the second half of the Quaternary.

CONCLUSION

Precise chronostratigraphy of emerged marine terraces is essential for neotectonic studies that aim to determine vertical deformation of coastal regions, and the variation in uplift rates throughout the Quaternary. In the areas of the world where no coral reefs are present, the dating of Pleistocene shorelines has been a problem. In general, it is recommended to confront two, or more, geochronological methods. Nowadays the U-series measurement through the TIMS technique allows to put constraints on the behaviour of the U-Th system and therefore to better assess age differences between Late and Middle Pleistocene age deposits. In any case, the geochronological attempts should be accompanied by careful morphostratigraphic analyses which involve field studies, aerial photograph interpretation and neotectonic mapping. Until recently, this combination of approaches could not be performed in northern Chile. This largely explains that the evaluation of vertical motions recorded along the northern Chilean sector of the south-eastern Pacific plate boundary remained a matter of vivid discussions (Armijo and Thiele, 1990; Flint *et al.*, 1991; Leonard and Wehmiller, 1991, 1992; Ortlieb, 1993; Hartley and Jolley, 1995; Ortlieb *et al.*, 1995a, b).

In this paper, we selected the coastal sector of the northern coast of Chile where the three more recent Pleistocene terraces are well developed, with a wide extension, and where they are neatly separated by clearly exposed palaeo-seacliffs. The morphological evidence of the chronology of the successive encroachments of the sea is particularly clear. It is no coincidence that this was also the first area where marine terraces were studied in northern Chile (Herm, 1969). Through our morphostratigraphic study and with the support of some U-series measurements and a relatively large number of amino acid epimerisation analyses, we propose a new interpretation of the record of late Middle Pleistocene and Late Pleistocene sea level fluctuations in the region, and an evaluation of the regional uplift rate during the last three interglacial cycles.

The chronostratigraphic study of the remnants of marine terraces in the Hornitos area suggests a relatively continuous uplift motion during the last 330,000 years, with a mean value of 240 mm/ky. This uplift rate was calculated on the basis of the elevation of the inner edge of the last three terraces along an E–W transect that cuts the village of Hornitos. A transect in Chacaya embayment, or in the northern end of the Hornitos embayment, would have yielded slightly distinct values (by a few cm/ky) because local tilting did occur in both embayments. But the important point is that the tilt motions were sufficiently regular through time, and of such an amplitude, that the geometrical relationships between the last three terraces and the present coastal zone were maintained. In fact, it should be added that these tilting motions played a role in the preservation of the distinct marine sedimentary units and coastal landforms, and made possible the recognition of the substages within the two lower terraces.

The particular development of the lower marine terrace (Terrace I) at Hornitos in a context of regular uplift motion of the coastal area enabled the record of two sea level fluctuations within the Oxygen Isotope Stage 5. Thus, contrary to what had been interpreted up to now (Herm, 1969; Radtke, 1989; and ourselves in a preliminary report (Ortlieb *et al.*, 1993)), it is established that the substages 5e and 5c are registered in this coastal sector. The altimetric position of the 5c deposit and its geometric disposition with respect to the 5e deposit imply that the 5c sea level was very close to the present datum. This conclusion confirms a similar interpretation made elsewhere and in southernmost Peru, close to the Chilean border (Ortlieb *et al.*, *in press*). It also explains many problems of interpretation of aminostratigraphic analyses recently performed on material from the last interglacial terrace in southern Peru and northern Chile.

The uplift rate determined for the Hornitos area, for the period 330 ky–Present, is higher than those calculated in the Mejillones Peninsula or in the Antofagasta area. But, considering the altitude of the last interglacial terrace, it should be representative of the coastal sector extending to the north for more than 100 km, and probably 300 km

(Iquique). The regional character of this vertical deformation, that is prevalent upon the small amplitude faulting activity and/or small tilt or warping that affected the coastal region from Chacaya northward, and its steadiness during hundreds of thousand years strongly suggest that relatively deep, crustal, phenomena are involved. We surmise that the processes that have been driving the calculated 240 mm/ky uplift rate are directly linked to the subduction of the oceanic Nazca plate below the South American continental plate.

A precise evaluation of the uplift motions in a longer span of time is hindered by the scarcity of remnants of older marine terraces, and by the difficulty to establish any chronostratigraphy of the deposits. However, available data on the position of a late Pliocene marine platform and of a supposedly Early Pleistocene terrace suggest that the region has not been uplifted at a rate of the order of 240 mm/ky during the whole Quaternary. They would rather indicate a much slower uplift during the Early Pleistocene, and possibly, during the first half of the Middle Pleistocene. Some (deep-seated?) phenomena may have occurred during the early Middle Pleistocene and might be responsible for a sudden acceleration of the vertical motions along this sector of the plate boundary.

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