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QUATERNARY SHORELINES IN SOUTHERN PERU: A RECORD OF GLOBAL SEA-LEVEL FLUCTUATIONS AND TECTONIC UPLIFT IN CHALA BAY

José Luis Goy,* José Macharé,† Luc Ortlieb‡[1] and Cari Zazo§
**Departmento de Geología, Universidad de Salamanca/37008, Salamanca, Spain*
†Instituto Geofísico del Perú, Apartado 3747, Lima 100, Peru
‡Mission ORSTOM au Pérou, Apartado 18-1209, Lima 18, Peru
§Museo Nacional de Ciencias Naturales, CSIC, José Gutierrez Abascal 2, 28006 Madrid, Spain

The coastal area bordering the bay of Chala (14°50′S., 74°15′W.), southern Peru, contains one of the most complete sequences of Quaternary shorelines in South America. Remnants of about 27 high seastands have been preserved between present mean sea-level and +275 m. Most remnants consist of staircased marine terraces and associated deposits which are partly covered by alluvial fan and colluvial units deposited during intervening periods of lower sea-levels.

No geochronological data are yet available; a tentative chronostratigraphy of the terrace sequence is based on the geometric and stratigraphic relationships between successive landforms, and deposits. We group most marine terraces into 15 'major morphostratigraphic units' (MMUs). Some of these major units seem to correlate with interglaciations, for example Isotopic Stage 5, or with interstadials (Stage 3). Higher in the Chala sequence, major morphostratigraphic units mapped during field and air-photo studies may represent only parts of Middle Pleistocene interglaciations. We infer that shorelines located at +68, +121, +168, and +184 (or +200) m correlate with the highest seastands of Isotopic Stages 5, 7, 9, and 11, respectively.

The proposed chronostratigraphy suggests an average uplift rate of ca. 460 mm/kyr for the Chala Bay area during the last 500 ka. This rate is slightly higher than in the surrounding coastal areas (ca. 270–350 mm/kyr), but significantly lower than rates in the area where the Nazca Ridge is being subducted below the South American Plate (maximum rate ca. 740 mm/kyr). Deformed shorelines evidence several fault displacements within the Chala basin, but such deformation does not seriously distort the record of former sea-levels in the basin. The Chala terrace sequence is the first reliable record of Middle and Late Quaternary sea-level fluctuations described from Peru.

INTRODUCTION

Study of emerged marine terraces provides one of the best ways to assess vertical motions experienced by coastal regions during the Quaternary. This approach requires (1) assumptions about the vertical position of the geoid during each high seastand throughout the Quaternary, and (2) ages for marine terraces along the uplifted coasts. These conditions are commonly met with reasonable accuracy for Late Quaternary time (last 125 ka). The identification of remnants of high sea-level during the last interglacial, and the elaboration of models of sea-level variations in the last climatic cycle (Chappell, 1974a, b; Bloom *et al.*, 1974; Chappell and Shackleton, 1986; Shackleton, 1987) were largely based upon radiometric methods (U-series) used on fossil nearshore carbonates (mainly corals) from tropical areas. But for the Middle Pleistocene (740–125 ka) and Early Pleistocene (1600–740 ka) periods, there are many uncertainties about the position reached by global sea-level during the warmest interstadials and interglacials and about the age of these episodes. A framework for Quaternary chronostratigraphy, as well as the best proxy for sea-level variations, are provided by deep-sea core isotopic data (Shackleton and Opdyke, 1973, 1976; Williams *et al.*, 1981, 1988; Shackleton, 1987). However, isotopic data is insufficient to assess paleo-positions of global sea-level. Reconstructions of relative sea-level variations need to be based on direct measurement of former shorelines, and the best areas to study shorelines are in coastal areas with constant and relatively low rates of uplift. Such coasts should have been uplifted at a high enough velocity to permit paleo-shorelines to be distinguished along vertical profiles, but low enough so that the shoreline record goes as far back in time as possible (Ortlieb, 1987, 1988).

Coastal areas raised by constant uplift during the Quaternary are not numerous. In South America, a likely area of long-term constant uplift is along the Peruvian coast, where the Nazca Plate has been subducting beneath the South American Plate at a constant rate for the last few million years (80 km/myr, Pilger, 1983; Pardo and Molnar, 1987), and where Plio–Quaternary uplift is documented (Broggi, 1946; Sébrier *et al.*, 1982; Macharé, 1987; Hsu, 1988; Ortlieb and Macharé, 1990b). Thus, long sequences of staircased Quaternary shorelines should be preserved along this part of the Peruvian coast.

Marine Terraces on the Peruvian Coast

North and south of a relatively stable, 1,000 km-long, segment of the central coast of Peru (6°30′–14°S.), the coast shows much evidence of Quaternary uplift (Sébrier *et al.*, 1982; CERESIS, 1985; Ortlieb and Macharé, 1990a). In northern Peru, Pleistocene marine terraces, known as 'tablazos', are rare and only locally extensive (Bosworth, 1922; Devries, 1984, 1986, 1988).

[1]Presently at: ORSTOM-University de Antofagasta, Facultad de Recursos del Mar, Casilla 170, Antofagasta, Chile.

In southern Peru, relatively narrow but numerous marine terraces commonly rise up to +100–200 m, as shown on regional maps south of 14°S. (e.g. Bellido and Narváez, 1960; Mendívil and Castillo, 1960; Jaen and Ortiz, 1963; Narváez, 1964; García, 1968; Caldas, 1978; Olchausky, 1980). These emerged terraces demonstrate uplift (Steinmann, 1929; Broggi, 1946; Sébrier *et al.*, 1982; Teves, 1977; Macharé, 1987), but only recently have they begun to be dated (Hsu, 1988; Ortlieb and Macharé, 1990b; Ortlieb *et al.*, 1990, 1991).

The most studied region of Pleistocene shorelines in Peru is located near San Juan-Marcona (15°20′S.) (Broggi, 1946; Hsu, 1988; Hsu *et al.*, 1989; Macharé, 1987; Ortlieb and Macharé, 1990b; Macharé and Ortlieb, *in press*). There, staircased Quaternary marine platforms are particularly extensive and numerous; the oldest (earliest Pleistocene) terrace, the highest known Quaternary marine unit in South America, reaches a maximum elevation of +780 m. Because the aseismic Nazca Ridge is being subducted below the South American continent in the San Juan-Marcona region, it was assumed that this tectonic feature was responsible for the rapid uplift of the area (Macharé, 1987; Hsu, 1988; Macharé and Ortlieb, 1990, *in press*).

Farther south, Pleistocene marine terraces are common, but are seldom found in long, continuous, sequences that would permit a reconstruction of sea-level variations. Some tens of kilometers south of San Juan-Marcona, for instance, several sets of Quaternary beach ridges range in elevation from sea level to ca. +200 m. But beach-ridges are lithologically similar and are poor indicators of paleo-sea levels because they formed during regressions (instead of transgressive maxima). In many sectors of the southern Peru coast where marine terraces are preserved, they are often partly hidden by sand dunes or alluvial deposits. However, one sequence of marine terraces at Chala (14°50′S.; Fig. 1), first described by Laharie (1970), offers a long record of well-preserved shoreline features and deserves closer study.

The Chala Sequence of Marine Terraces

The area bordering the bay of Chala (15°45′–15°55′S., 74°10′–74°20′W.) displays a staircase-like sequence of 27 marine terraces that climbs to +275 m. More terraces are found here than in any other sector of the southern Peruvian coast, except for the San Juan-Marcona area. The marine terraces are separated from one another by steep erosional escarpments (risers). The resistant igneous bedrock of the Chala area has helped preserve a record of successive marine encroachments. The scarcity of beach sands along the embayment and the unusual WNW–ESE orientation of the coastline in this sector (at angle with the dominant wind direction) explain the lack of covering eolian sands, like those in coastal regions north and south of Chala (Gay, 1962).

But the Chala area is unique in its preservation of colluvial and alluvial units deposited during or soon after each episode of marine terrace formation. Thin alluvial deposits partly overlie most of the terraces, or may locally be interstratified with marine beds formed during transgressions. Small fans were deposited above shoreline remnants at the foot of ancient sea cliffs. These continental sediments have been little eroded because of the low rainfall that affects the Peruvian coast, and because continuous uplift quickly raises them above the level of wave erosion.

As a result of these favorable conditions, the Chala area recorded successive marine transgressions and intervening pulses of alluvial deposition. It thus offers a unique opportunity for a detailed morphostratigraphic study of a particularly long series of marine and continental Quaternary sediments.

Methodological Approach

Our reconnaissance study of Quaternary coastal deposits and landforms in the Chala area aimed to use a local morphostratigraphy based on geomorphological mapping to support a chronologic interpretation. The maps of Quaternary marine and continental deposits and major recent landforms are based on an interpretation of air photos at two different scales (approximately 1/70,000: Fig. 1, and 1/6,000: Fig. 2), as well as on sedimentological, paleontological and altimeter surveys. Figure 1 shows the major morphostratigraphic units distinguished in Chala Bay and the main faults active in Plio–Pleistocene time in the area. The second map (Fig. 2) focuses on the central zone of the bay, along Chala River, and depicts with more detail the geometrical relationships between successive coastal cliffs, marine deposits, alluvial fans and other continental sediments. A common legend is attached to the two maps.

Combined geomorphological, sedimentological and paleontological studies helped to identify the depositional environment of each sedimentary unit, to establish lateral correlation of ancient coastal features, and to reconstruct for each marine terrace the position of the highest paleo-shoreline. The fossil content of the marine emerged sediments (Ortlieb and Diaz, 1991; Ortlieb, *unpublished data*) proved to be of limited chronostratigraphic utility since no significant variation was observed among the distinct terrace deposits.

Mapped continental sediments include alluvial terraces, alluvial fans and cones, colluvium units and slope deposits (Fig. 1). Most alluvium is carried by several rivers that have progressively entrenched the volcanic bedrock of Chala basin. The back-edge of some marine terraces is covered by a relatively large amount of alluvium that forms coalescent fans and cones while the back-edges of others are practically devoid of alluvial cover. In the former case, the thick alluvial units suggest relatively long periods of deposition.

The morphostratigraphic study focused on the record of high seastands and on the reconstruction of the history of sea-level variations. The altimeter measurements were performed with a high-precision aneroid altimeter (readings with a 1 m accuracy) and involved repeated calibrations at sea level to take into account

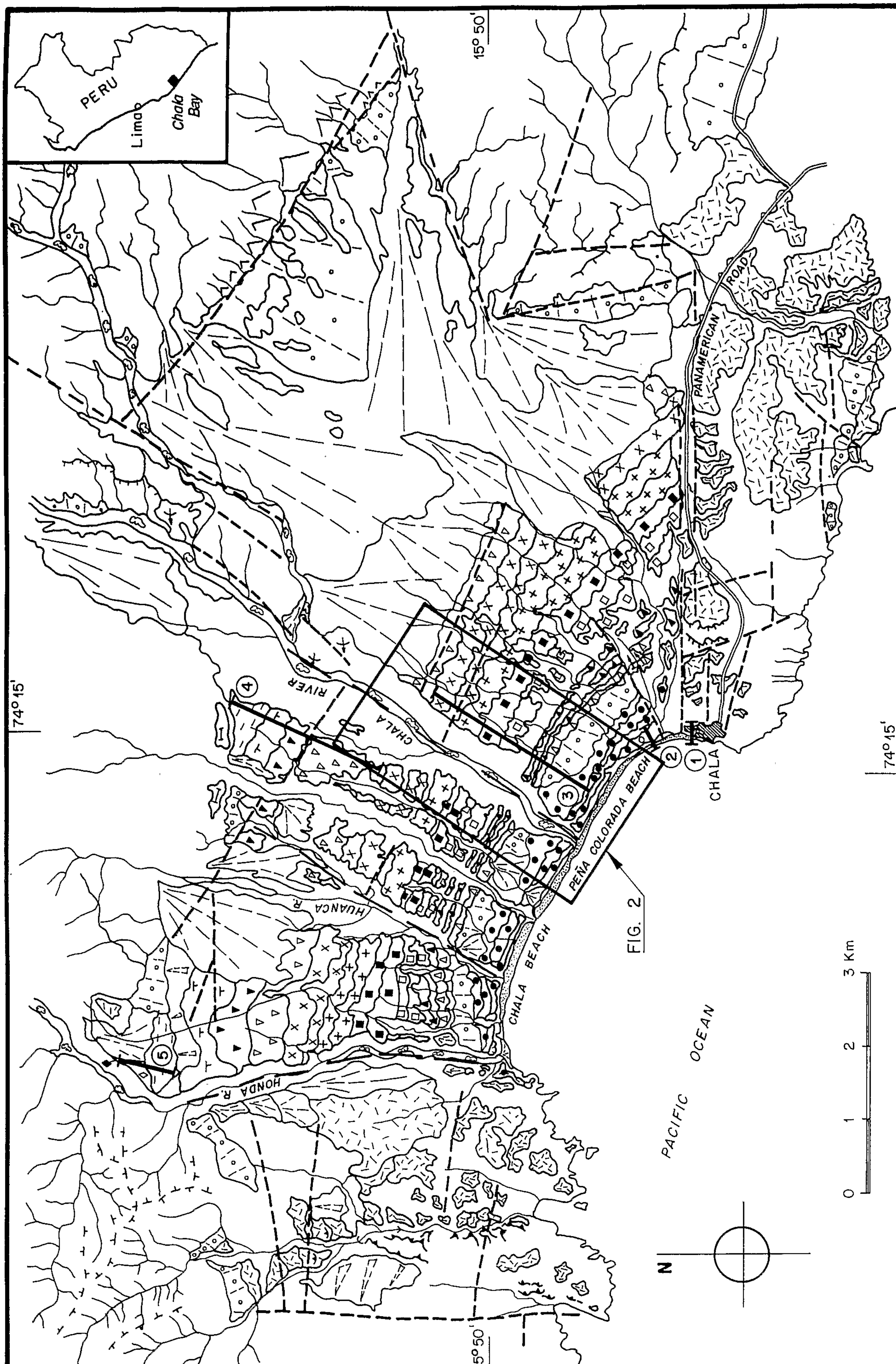

FIG. 1. *continued overleaf.*

LEGEND -- Part 1

AGE	HEIGHT (m)	MARINE LANDFORMS AND DEPOSITS	CONTINENTAL LANDFORMS AND DEPOSITS	SECTION in Fig.1	MMU
HOLOCENE	+3	Beaches and littoral ridges	Alluvial cones	1	I
	+5	Erosional surface	Fluvial terrace; Fluvial terrace		
?					
LATE PLEISTOCENE	+11	Erosional surface at +11m		2	II
	+18	Terrace at +18m			
			Scarp		
	+31	Terrace at +25 - 31m	Alluvial cones	3	III
	+45	Terrace at +42 - +45m	Alluvial cones		
	+54	Terrace at +50 - +54m	Alluvial cones		
	+68	Terrace at +68m	Alluvial cones		
			Scarp		
MIDDLE PLEISTOCENE	+90	Terrace at +90m	Alluvial cones, colluvium		IV
	+99	Terrace at +99m			
			Scarp		
	+111	Terrace at +111m	Colluvium		V
	+121	Terrace at +118 - +121m			
			Scarp		
	+145	Terrace at +145m	Alluvial cones, colluvium		VI
	+154	Terrace at +151 - +154m			
			Scarp		
	+162	Terrace at +162m	Alluvial cones, colluvium		VII
	+168	Terrace at +168m			
			Scarp		
	+177	Terrace at +177m	Alluvial cones, colluvium		VIII
	+184	Terrace at +184m			
		+184 (W) / +170 (E) Terrace at +184 = +170m	Scarp	(hatched)	
	+180	Terrace at +180m			IX
	+190	Terrace at +190m			
	+195	Terrace at +195m			
?			Scarp		
EARLY PLEISTOCENE	+205	Terrace at +202 - +205m	Colluvium	4	UNDIFFERENTIATED
			Scarp		
	+218	Terrace at +216 - +218m	Alluvial fan		
			Scarp		
	+228	Terrace at +228m	Alluvial fan		
			Scarp		
	+235	Terrace at +235m	Alluvial fan, colluvium		
		+254 (W) / +235 (E) Terrace at +235 = +254m		(hatched)	
			Scarp		
	~266	Terrace at +266m	Alluvial fan	5	
			Scarp		
	+274	Terrace at +274m	Alluvial fan		
			Erosion or scarp		
		Marine Pliocene			
		Pre-Pliocene substratum			

FIG. 1. *continued.*

LEGEND -- Part 2

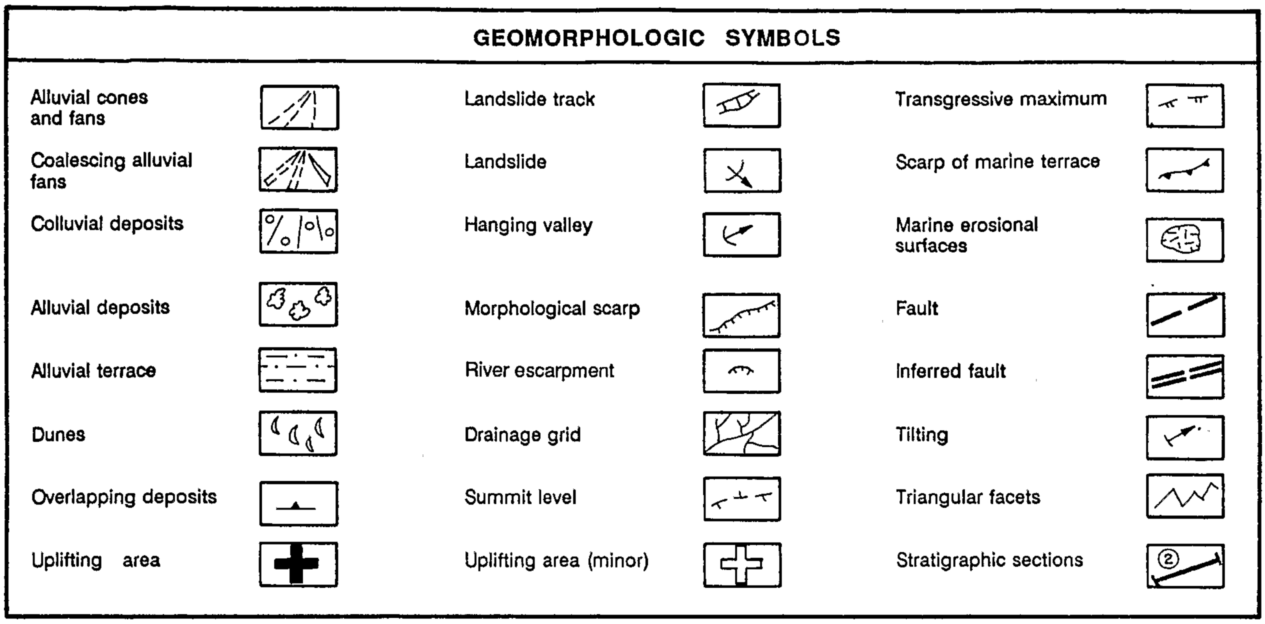

FIG. 1. Geomorphological map of the Chala Bay area, Peru, showing major faults and the distribution of the major morphostratigraphic units (MMUs) and Quaternary deposits described in the text. Symbols are explained in the Legend (in two parts), which is common to both maps of Figs 1 and 2. First part of Legend: The first column indicates our chronologic interpretation. The second column lists marine terraces and their elevations surveyed in the Chala basin, along cross-sections 1–5 (column 4) located in Fig. 1. Column 3 shows the types of continental landforms and deposits closely associated with each episode of marine terrace formation. The last column lists the major morphostratigraphic units (MMU), that were identified in the Chala sequence (numbered with roman numerals, see text). In the second column, numbers to the left indicate the highest measured elevation of the corresponding shoreline (this elevation is used to refer to the terraces in the text and in Fig. 3), while numbers to the right indicate one or two measured elevation(s) of the shorelines. Breaks in the horizontal lines in this column show differences in elevations resulting from faulting. The second part of the Legend explains geomorphologic symbols used on the two maps.

pressure and temperature variations. Uncertainty in the determination of the shoreline positions combined with the instrumental accuracy resulted in an estimated overall precision of the measurements of ±3 m. In most cases, the shoreline elevations (relative to mean sea level, MSL; Fig. 1) refer to the highest position reached by sea level during each highstand, as carefully estimated from well-preserved marine deposits and erosional features (paleo-seacliffs, shoreline angles, terrace back-edges). We use measured shoreline elevations to refer to each marine (highstand) episode and to the corresponding marine terrace deposits and landforms (Figs 1–3).

The staircased arrangement of the marine terraces and the favorable conditions for terrace preservation in the area made lateral correlation of the landforms and depositional units relatively easy. The few river valleys cutting across the Chala terrace sequence also exposed the inner edges of the terraces. Two easily recognizable sand units that have a high reflectance on air-photos and crop out throughout the Chala basin were also helpful in the lateral correlation of the terraces.

We grouped successive marine terraces in what we term 'major morphostratigraphic units' (Figs 1–3). Major morphostratigraphic units (MMUs) are assemblages of sedimentary deposits and landforms that formed in relatively short spans of time during high seastands (interglacials). These units are separated by features which suggest periods of low seastands (glacials), for example, thick alluvium overlying a marine terrace or high sea-cliffs, which indicate relatively long time periods between high seastands (assuming constant uplift). Our air-photo interpretation suggests that the Chala sequence may be divided into about fifteen major units. We discuss below the relationships between the individual marine terraces and major morphostratigraphic units of the Chala sequence (Figs 1–3), and the high seastands and interglacials of the Pleistocene.

Geochronological Limitations

Studies of vertical motions in coastal regions rely on accurate ages for marine terraces. Late Pleistocene (and latest Middle Pleistocene) shorelines may often be dated by radiometric (U-series, electron spin resonance) or bio-geochemical (amino-acid racemization) methods. Commonly, the identification of the shoreline of the last interglacial maximum (Isotopic Substage 5e) by one of these dating methods then leads to extrapolated age estimates for earlier shorelines.

At Chala, a few preliminary U-series analyses were conducted (at GEOTOP Laboratory, Montréal) on mollusk shells from the lowest-lying terraces. These analyses did not produce reliable ages because the shells behaved as open geochemical systems. Other authors have encountered the same problem in the San

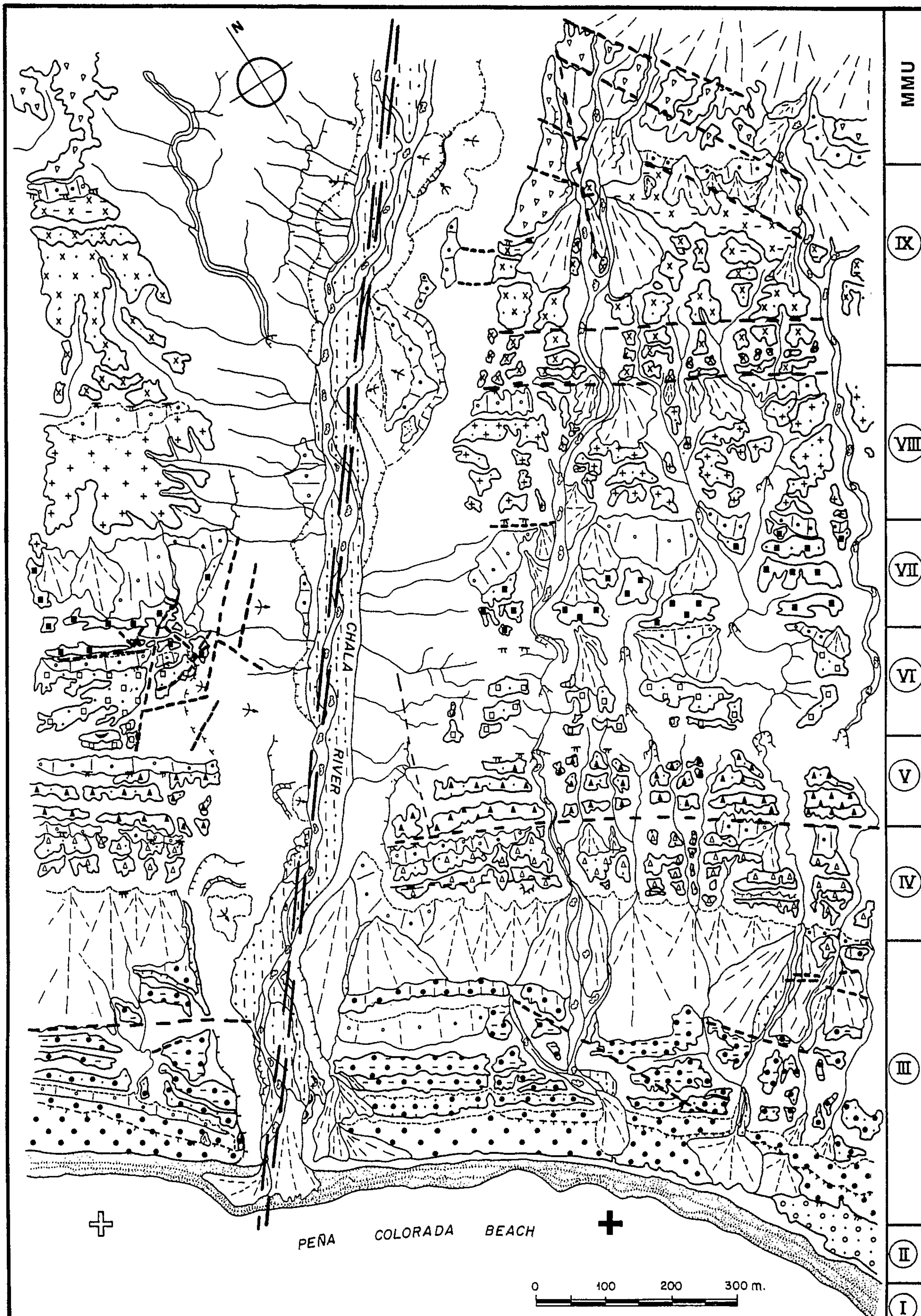

FIG. 2. Detailed geomorphological map of a central sector of the Chala Bay area, along the Chala River valley (see location in Fig. 1). Explanation of symbols in Legend for both Figs 1 and 2 (see Fig. 1).

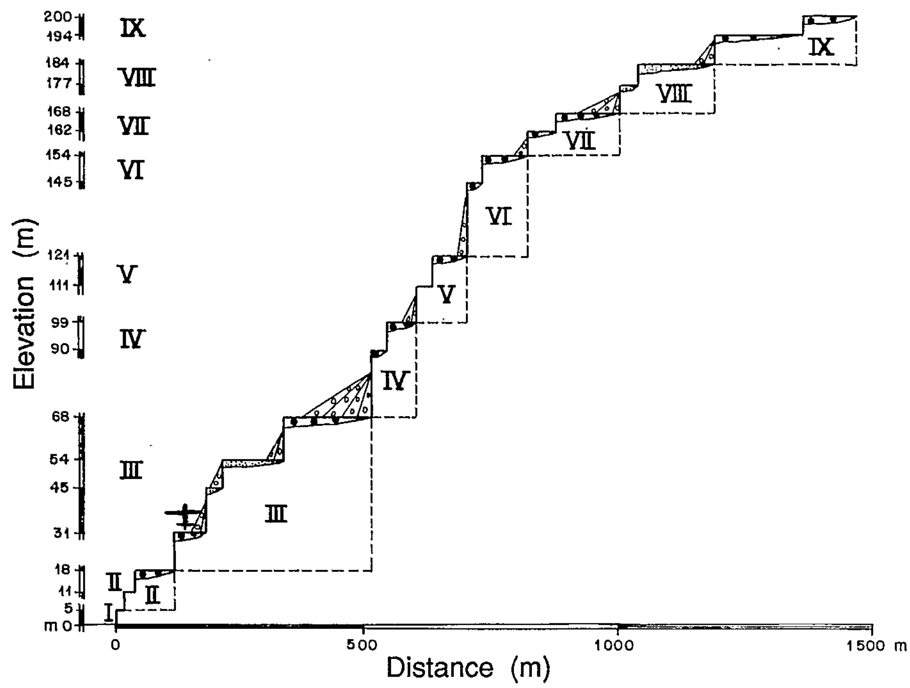

FIG. 3. Schematic composite cross-section of the lower part of the Chala sequence of marine terraces, based on the 5 cross-sections located in Fig. 1 (circled numbers). Maximum elevation (in meters above present MSL) reached by sea level during the formation of each marine terrace is indicated on the vertical axis. Horizontal distances give an idea of the width of each marine terrace. The roman numerals refer to major morphostratigraphic units (MMUs of Figs 1 and 2) defined in text. Black dots indicate coarse marine terrace sediments; small points correspond to relatively thick marine sand units; open circles represent the largest alluvial fans and cones which generally mark the boundary between successive MMUs (except for MMUs III and VIII).

Juan-Marcona area (Osmond, 1987; Hsu, 1988; Hsu *et al.*, 1989). Amino-acid racemization analyses on mollusks and barnacles from several terrace deposits are in progress (at GEOTOP). Interpretation of initial analyses is a problem because of uncertainties in calibrating amino-acid age estimates using regional data from previous studies (Hsu, 1988; Hsu *et al.*, 1989). The basis for calibration of the regional aminostratigraphy proposed by Hsu (1988) and Hsu *et al.* (1989) in the San Juan-Marcona area is debatable both on morphostratigraphic (identification of the last interglacial shoreline) and geochronological (questionable ESR age estimates) grounds (Ortlieb and Macharé, 1990b; Ortlieb *et al.*, 1991). A thorough discussion of the amino-acid racemization data from the Chala area will be presented elsewhere.

Calibration of relative dating methods, including ESR and amino-acid racemization methods requires sound numerical ages. In the regions where U-series ages are unavailable (for lack of fossil corals for instance), detailed morphostratigraphic studies of marine terrace sequences, may sometimes provide a valid basis for amino-acid and ESR data calibration (Ortlieb, 1987; Ortlieb and Macharé, 1990b).

GEOLOGICAL AND STRUCTURAL SETTING

The Chala area is located in the emerged part of a forearc massif called the 'Cordillera de la Costa', which was a structural ridge during most of the Tertiary (Macharé *et al.*, 1986). Near Chala the Cordillera de la Costa basement is composed of a Jurassic volcanic sedimentary sequence (Chocolate Formation) that was intruded by Cretaceous monzonites and monzo-diorites correlated with the Coastal Batholite (Olchauski, 1980). The Tertiary is represented by marine siltstones, sandstones, and conglomerates that crop out in fault-bounded blocks in the northern and central parts of Chala Bay, and by subaerial pyroclastic rocks in the northeastern corner of Fig. 1. Although not radiometrically dated, these volcanoclastic and sedimentary rocks have been correlated with the Pliocene La Planchada Formation of the Camaná basin, 100 km south of Chala (Beaudet *et al.*, 1976; Huamán, 1985). Remnants of a (Late ?) Pliocene marine transgression are preserved in river valleys west and east of the study area, but were not observed near Chala. During the Late Cenozoic, the paleogeographic evolution of the Chala basin was partly controlled by tectonic activity, notably by displacements on several major faults (Huamán, 1985).

Three major fault systems bound the Chala basin: the first trends roughly N.–S. along the Honda River, the second is oriented N120°E., almost parallel with the coastline about 4 km inland, and the third has an E.–W. strike and extends east of Chala (Fig. 1). Within the zone delimited by these major faults, several secondary faults can be detected, especially along the course of the Chala and Huanca Rivers (N30°E., Fig. 1). Previous studies (Sébrier *et al.*, 1984; Huamán, 1985;

Macharé *et al.*, 1986) indicate that this part of the southern Peruvian forearc has been recurrently subjected to episodes of stretching and shortening during the Late Cenozoic. Since the last compressional phase of Andean tectonics, which probably occurred in the Early Pleistocene, the region has experienced a predominant N.–S. trending extensional state of stress.

MORPHOSTRATIGRAPHY OF THE CHALA SEQUENCE

Our morphostratigraphic study of the Chala sequence is based on a detailed analysis of the distribution of the landforms and major marine and continental deposits associated with each of the successive emerged shorelines.

Marine Terraces and 'Major Morphostratigraphic Units'

At Chala, 27 distinct marine terrace remnants of Quaternary high seastands were distinguished: the younger two are Holocene and all older terraces are Pleistocene. The typical uplifted marine terrace is several tens of meters wide (rarely several hundreds of meters) and slopes slightly (1–5°) toward the sea. The abrasion platforms of the terraces are eroded into volcanic bedrock (or, locally, into Tertiary sedimentary units) and are covered by marine sediments (0.5–2 m thick), which in turn are often overlain by a thin bed of alluvium. The marine deposits consist of unsorted sand and gravel containing pebbles and boulders, and are generally poorly cemented. The well-rounded, larger clasts, reworked from older marine and/or fluvial deposits, are locally abundant and may form conglomerates several meters thick. In a few localities, sublittoral sequences of sand are preserved with an *in situ* fauna (paired valves of pelecypods), but most often shells in the marine deposits are fragmented and beachworn.

The back (inland) edges of marine terraces are generally marked by the topographic scarp of a paleoseacliff; their external (seaward) edge is normally formed by the top of the cliff that was eroded during the subsequent highstand. The cliffs that separate the marine terraces may be divided into two categories (at least in the lower part of the sequence): larger cliffs about 20–25 m high, and smaller scarps only a few meters high. This difference in scarp heights is one of the criteria that we use to distinguish major morphostratigraphic units in the Chala sequence.

'Major morphostratigraphic units' (MMUs) are assemblages of landforms (one or more marine terraces) and associated deposits (both continental and marine sediments) that seem to have formed in a relatively brief episode. These large scale groups of morphologic features can be observed in the Chala sequence, either in the field (from elevated viewpoints along the Pan-American road) or on air-photos. The group of marine terraces that lies between +25 and +70 m (MMU III), in particular, appears from some distance as a wide, multi-phased feature (Fig. 1).

Fifteen MMUs were recognized and numbered from the youngest to the oldest, I to XV (Figs 1 and 2). The nine youngest MMUs include between one and four individual marine platforms, while the oldest (MMUs X to XV) are represented by single marine terraces. Identification of the oldest MMUs is provisional because erosion of the earliest marine landforms and deposits, or burial by alluvial deposits in some sectors, obscures their chronologic relationships.

The legend of Figs 1 and 2 presents a composite sequence of the main features identified in the Chala basin, as well as a tentative reconstruction of the main processes that produced the Quaternary sequence. Most detailed information used for this reconstruction, including shoreline elevations, was collected along the 5 transects shown on Fig. 1.

The Nine Youngest MMUs

The youngest major morphostratigraphic unit (MMU I) is represented by landforms and sediment of Holocene age: the present beach, an isolated remnant of an emerged shore platform, a high seacliff cut in lithologically varied bedrock, and alluvial sediment along river valleys. The beach is mostly sandy in the eastern part of the Chala embayment (near a source of Tertiary sedimentary strata) and gravelly (rounded clasts up to boulder size transported by the rivers) in the rest of the bay. The clasts accumulate in temporary storm berms as much as 3 meters high (Fig. 2). A small, emerged, abraded platform is observed at a maximum +5 m elevation, near the former 'Hotel de Turistas' of Chala. The limited width of the platform and its location between two faults (Fig. 1) suggest it is an uplifted remnant of a Mid-Holocene terrace (Ortlieb and Macharé, 1989).

Terrace remnants corresponding to MMU II were mapped only along the eastern part of Chala Bay (Fig. 1). They mainly consist of a small abraded platform at +11 m (on which the 'Hotel de Turistas' was built) and a marine terrace deposit with a maximum observed elevation of +18 m (Fig. 2). Because these features have no lateral equivalents in the rest of the embayment we hesitated to recognize them as a separate MMU. But since they are cut into the youngest units of MMU III, and because the marine deposit is altered enough to be pre-Holocene, we have grouped them into a morphostratigraphic unit distinct from MMUs I and III. The present elevation of the platform and terrace deposit is probably due to recent uplift on a nearby N45°E. trending fault (Fig. 1).

MMU III is the most widely exposed unit of the Chala sequence. It is the only major unit that includes four marine terraces. The highest shorelines of each of the terraces are found at +31, +45, +54, and +68–64 m respectively (Fig. 3). The youngest marine terrace of MMU III (+31 m) is almost continuous along the Chala embayment (Fig. 1). Roadcuts along the Pan-American road, NW of Chala, show that the sedimentary sequence overlying the abrasion surface includes poorly sorted and fossiliferous sediment, conglomeratic marine beds, and lenses of lagoonal fine sand and silt. Locally, this sequence is partly cut into similar sediments deposited during the previous transgression (terrace at +45 m), or onlaps a 3 m thick alluvial conglomerate, which overlies deposits of the earlier +45 m terrace. The span of time between the two periods of terrace formation was brief (a single alluvial phase) and apparently corresponds with an episode of sea-level lowering between two interstadial highstands. The small variations observed in the elevation of the shoreline (+31–25 m) of the +31 m terrace document small, recent, vertical displacements on faults during tilting of tectonic blocks.

The second youngest marine deposit (+45 m) of MMU III is well preserved in the central part of the embayment (Fig. 1). North and south of the Chala River valley, this deposit cuts deeply into the sediments of the previously deposited marine unit (+54 m).

The third youngest marine terrace of MMU III (+54 m) is laterally very extensive (Figs 1 and 2). It mainly consists of a thick sequence of coarse regressive marine sand several meters thick and more than a hundred meters wide. The chronologic relationships between this terrace deposit and the next older terrace (+68–64 m) are uncertain. The +54 m terrace undoubtedly post-dates the +68 m shoreline, but it is unclear if it is much younger than the shoreline (distinct interstadial), or if it constitutes a regressive feature of the +68 m highstand episode. The +54 m terrace does not seem to cut into the +68 m terrace, although alluvial units were deposited between the marine sediments of the two terraces.

The earliest shoreline of MMU III is found at the foot (+68–64 m) of a 25 m-high paleo-seacliff. The morphological similarity between the paleo-seacliff and the modern one eroded by the sea during the Holocene argues for a correlation between the +68 m shoreline and the earliest highstand of the last interglacial (Oxygen Isotopic Substage 5e). Extensive alluvial fans and colluvium (Figs 2 and 3) cover the foot of the seacliff and most of the marine sediment coeval with the transgressive 5e maximum. In spite of the lack of outcrops of marine sediment, this paleo-shoreline is one of the most conspicuous in the Chala sequence.

MMU IV is comprised of two narrow marine terraces (+90 and +100 m) around most of the bay. In the southeastern part of the embayment, surface faulting contemporaneous with terrace formation has split these two features into 3 or 4 distinct terraces (Figs 2 and 3).

Landforms of MMU V are similar morphologically with those of MMU IV, and include two narrow terraces (+111 and +121 m) (Figs 2 and 3). The 20 m high paleo-seacliff backing this MMU is steeper and more conspicuous around the bay than the cliff separating the landforms of MMUs IV and V. It is similar to the Holocene seacliff and the cliff backing the terraces of MMU III (Fig. 3).

The main landforms of MMU VI are a narrow, well-formed, marine abrasion platform (shoreline at +135 m, locally at +145 m) and a much wider terrace (+154 m) characterized by an irregular surface. The sea-cliff that marks the inner edge of this MMU is particularly low; near the southeastern bank of Chala River it is replaced by a swale-like depression (due to runoff erosion or possibly to displacement on a small fault).

In MMU VII we grouped two marine terraces (+162 and +168 m) that are often difficult to distinguish on air-photos. The scarp that divides these two terraces is small (3 m), but the paleo-seacliff bounding the inner edge of this MMU is steep and high (10 m). Abundant alluvial fans overlie the marine deposits of this unit.

The landforms and deposits in MMU VIII are laterally extensive and somewhat similar to those of MMU III. This MMU includes two marine terraces (+177 and +184 m). High reflectance from the surface of these terraces on air-photos is due to an extensive, light-colored, gypsiferous sand, locally called 'yapato'. The sand is the result of a pedogenetic alteration of the marine terrace deposits. Below the 'yapato' surface, the sequence of sediment underlying the lower of the two terraces on the western bank of Chala River consists of, from top to bottom:

— a fluvial (?) conglomerate (1.5 m thick) with reworked marine shingle-like cobbles and a gypsiferous matrix (secondary gypsum migrates from underlying beds and/or evaporates from marine overflow water behind beach-ridges);

— two superposed lagoonal beds (each ca. 0.5 m thick), the uppermost with fine marine sand and gypsum, and the lower one with coarse, greyish sand and gravel;

— an alluvial gravelly conglomerate (1 m) with abundant sandy matrix;

— alternating beds (ca. 2.5 m) of marine sand and gravel with small boulders that overlie a marine abrasion platform. The fauna of this unit includes the pelecypods (predominantly *Mesodesma donacium* and *Eurhomalea lenticularis*), gastropods and barnacles commonly found in the nearshore zone in the area.

The whole sequence described, which is probably thicker than in most terrace deposits of the Chala area, indicates that the sediments underlying the marine terraces are not restricted to a single transgressive marine deposit. The 'yapato' soil on the MMU VIII terrace documents surface faulting in the center of Chala Bay. The highest outcrops of 'yapato' surface are at different elevations on both sides of Chala River: +184 m on the southeastern bank and +170 m on the northwestern bank. Thus, displacement of the Chala River fault (Figs 1 and 2) may have occurred between the deposition of MMU VIII and the formation of MMU VII landforms, which do not show a 14 m vertical displacement across the river.

Three prominent marine terraces of MMU IX on the northwestern bank of Chala River were identified at ca. +180, +185 and +190 m. In the eastern part of the embayment, the landforms related to this MMU (and older ones) are extensively covered by the distal edges of alluvial fans that head in the foothills of the Andes (Figs 1 and 2).

The Oldest MMUs

The deposits and landforms of the oldest MMUs (i.e. X, XI, XII, XIII, XIV) are found mostly in the northwestern part of the embayment, particularly along the eastern side of the Honda River (Fig. 1). These MMUs include the highest marine terraces of the Chala embayment at +205, +218, +228, +235, +266 and +274 (?) m, respectively (Figs 1 and 2). Elevations were measured at only a few localities, so the listed elevations may not be accurate paleo-sea-levels for the oldest high sea-stands in the Chala area.

The two oldest MMUs reported in the Chala area above an elevation of +240 m may be of Late Pliocene age. Outside the study area, on the western bank of the Honda River, a Quaternary marine limit is mapped at +240/+260 m; there, the highest Pleistocene marine sediments in the area onlap Pliocene sandstones at +220–230 m. Thus, unless recent movement on the Honda River fault (Fig. 1) has raised the marine limit, the oldest MMUs may be Pliocene.

CHRONOSTRATIGRAPHIC INTERPRETATION

Global Sea-level Variations

Since the work of Shackleton and Opdyke (1973, 1976) on the deep-sea cores V28-238 and V28-239, the chronostratigraphy of the Pleistocene has been closely linked to the oxygen-isotope stratigraphy (Bowen, 1978; Imbrie and Imbrie, 1980; Pisias *et al.*, 1984; Ruddiman *et al.*, 1986; Williams *et al.*, 1988). This isotopic chronostratigraphy provides only approximate ages for the interglacials and glacials of the Pleistocene, although several time scales based on different mathematical treatments of deep-sea core data have been proposed (Shackleton and Opdyke, 1976; Imbrie *et al.*, 1984; Williams *et al.*, 1988; Ruddiman *et al.*, 1989). For the Early Pleistocene, there is not even a consensus on the identification and numbering of the isotopic stages. Therefore, the 'absolute' chronology of Middle and Early Pleistocene high seastands remains largely approximate. Isotopic data, however, do provide a rough chronology, and indicate the magnitude of global sea-level variations, both of which are of great help in interpreting sequences of marine terraces.

Radiometric dating of Late Pleistocene coral reefs allowed calibration of the youngest part of the deep sea-core isotopic chronology (Shackleton and Opdyke, 1973, 1976) and provided estimates of paleo-sea-level height for each high seastand of the last interglacial: Isotopic Substage 5e (125 ka), 5c (105 ka) and 5a (80 ka) (e.g. Chappell, 1974a, b; Bloom *et al.*, 1974). Most researchers agree that sea level reached a maximum elevation of about +6 m above present MSL at the beginning of the last interglacial (Substage 5e), and that during the ensuing Substages 5c and 5a sea level probably was close to present MSL, or at most a few meters below MSL (Chappell and Shackleton, 1986).

During the interglacial maxima of the Middle Pleistocene, sea level was also probably close to MSL. The deep-sea core isotopic data suggests that the Isotopic Stage 7 lasted some 70 kyr (Imbrie *et al.*, 1984; Martinson *et al.*, 1987; Williams *et al.*, 1988) and that it included at least two major and one minor highstand. During the Stage 7 highstands, sea level was probably below the present datum (Shackleton, 1987). For Isotopic Stages 9 and 11, some core data show single major peaks that are high enough to suggest that sea level attained a position similar to present MSL. The last four interglacials (Stages 5, 7, 9, and 11) were probably longer and warmer than earlier Pleistocene interglaciations because the older isotopic stages are characterized by lower peaks that suggest high seastands lower than present. Stages 13, 17, 19 and 21, in particular, were apparently characterized by relatively low seastand maxima (Shackleton, 1987).

Early Pleistocene sea-level fluctuations also had smaller amplitudes and frequencies than later Pleistocene fluctuations (Shackleton and Opdyke, 1976; Williams *et al.*, 1981, 1988; Ruddiman *et al.*, 1986). Records of Early Pleistocene highstands are extremely scarce, possibly because the shorelines of this period were almost entirely eroded during the subsequent transgressions of the Middle Pleistocene.

Tentative Chronostratigraphy of the Chala Sequence

Following our description of the major morphostratigraphic units found in Chala Bay, and the brief overview of the present knowledge about global Quaternary sea-level variations, let us examine how the Chala sequence may be interpreted chronostratigraphically.

MMUs I and II

MMU I consists of Holocene coastal features and is, therefore, correlated with the Isotopic Stage 1.

The MMU II terrace remnants, preserved in the town of Chala only, are latest Pleistocene. These terraces formed after the youngest terrace of MMU III (80 ka ?) and before the Mid-Holocene sea-level maximum (5–7 ka), probably during Isotopic Stage 3. These terraces may correlate with either (or both ?) of the Stage 3 high seastands observed elsewhere at about 60 or 40 ka (Bloom *et al.*, 1974; Chappell, 1974a, b). Their maximum elevation (+18 m) may indicate relatively rapid uplift of a small fault-bounded block, because paleo-sea level at 60 and 40 ka rose only to ca. −30 m (Bloom *et al.*, 1974; Chappell and Shackleton, 1986).

MMU III

The well-developed features of MMU III include four marine terraces (+31, +45, +54, +68 m) and intervening continental deposits. The stratigraphy of MMU III shows that alluvial episodes, coeval with low seastands, alternated with episodes of marine terrace formation (highstands). The thickness and sedimentology of the continental deposits suggest that the alluvial phases were brief and did not correspond to entire glacial periods. So, we group the landforms and deposits preserved between about +25 m and +68 m into a single MMU, which we infer encompasses a limited period of time, most probably a full interglacial stage.

The physical boundaries of MMU III are two major seacliffs of comparable shape and height: the Holocene sea-cliff and the scarp between +70 and +90 m. The morphological and geometrical similarity of the two scarps may indicate that the duration of cliff formation was equivalent for both features. Because the seacliff backing the modern shore was eroded during the present interglacial (Holocene), the +70–90 m seacliff may have been eroded during an early phase of the last interglacial (Substage 5e, 125 ka). In both cases, the seacliff height may reflect the amount of uplift experienced by the coastline during entire glacial periods (ca. 80–10 ka and ca. 180–130 ka).

Thus, if the +68 m shoreline corresponds to the sea-level maximum of Substage 5e (125 ka), the high seastands responsible for two of the younger marine terraces (+54, +45 and +31 m) may have occurred during Substages 5c (105 ka) and 5a (80 ka). Because the landforms and associated deposits related to the paleo-shorelines at +31 and +45 m are typical of marine terraces formed during such highstands, these terraces may be coeval with Substages 5a and 5c. An alluvial unit between the deposits associated with the +45 and +31 m terraces confirms that a sea-level lowering of interstadial magnitude occurred between the two high seastands marked by the terraces. The wide and thick sand at +54 m may have been deposited during a second highstand within Substage 5e or during a late Substage 5e regression.

Older MMUs

MMUs IV to IX in the Chala sequence are found between ca. +90 and +200 m. All these older units include a pair of marine terraces (except for the oldest one which has 3 marine terraces). Our definition of 'major morphostratigraphic units' implies that a series of depositional/erosional events occurred in a limited span of time during interglacial periods of high sea-level. If so, most MMUs probably include groups of landforms and deposits related to the successive interglacials recorded by the isotopic stages of Pleistocene deep-sea cores. On this basis, MMUs IV, V, VI, VII, VIII, and IX, might be coeval with Stages 7, 9, 11, 13, 15 and 17, respectively. However, there is another interpretation supported by several lines of evidence. It should be noted that we correlated MMU II with Isotopic Stage 3, which is an interstadial, not an interglacial period. Furthermore, the oxygen isotope curves from many deep-sea cores strongly suggest that during Stages 15 and 17, sea level did not reach a position similar to the present one (Shackleton and Opdyke, 1973, 1976; Shackleton, 1987); consequently, it is unlikely that these minor interglacial highstands correlate with the extensive morphologic features and deposits of MMUs VIII and IX (Figs 1–3). In fact, a closer examination of morphostratigraphic features and some assumptions about Middle Pleistocene sea-level fluctuations suggest alternative chronologic interpretations.

Beginning with Isotopic Stage 7, this interglacial (the penultimate) may be represented by landforms of both MMU IV and V. As Isotopic Stage 7 lasted at least as long as Stage 5 and included (at least ?) 3 high seastands, it should be represented by more than the two small terraces (at +90 and +99 m) of MMU IV. MMU IV features are preserved between +90 and +100 m (10 m elevational spread), whereas those of MMU III are vertically spread between +25 and +70 m (45 m); if the landforms and deposits of MMUs IV and V are combined, their total vertical spacing is ca. 30 m (+90–121 m). Another argument in favor of a correlation of both MMU IV and V with Stage 7 is the steep, 20 m-high scarp between +120 and +140 m, which is similar to the scarps at +4–20 m and +70–90 m. Thus, we favor a tentative correlation between both MMU IV and V and the Stage 7 interglacial.

For the same reasons (similar time span for Stages 5, 7 and 9 and the small height of the scarp between MMU VI and VII landforms), Isotopic Stage 9 may be represented by the landforms and deposits of both MMU VI and VII (however, the paleo-seacliff backing the landforms of MMU VII is less than 10 m high).

Following this chronologic interpretation, the thick sequence of deposits in MMU VIII at ca. +180 m and capped by the 'yapato' soil, would correlate with Isotopic Stage 11. MMU IX features may also be related to Stage 11. Oxygen-isotope data from many deep-sea cores (Shackleton, 1987) suggest that Stage 11 was a long-lasting interglacial that was as warm as Stage 5 and during which sea level reached higher than present MSL. In northwestern Mexico, marine terraces correlated with this stage appear to be more extensive than any other terraces of Middle Pleistocene age (Ortlieb, 1987, 1991). So, it is plausible that all the terraces observed between +170 and +200 m in Chala area (MMUs VIII and IX), which have a similar width and extent to those correlated with Stage 5, were formed during Stage 11.

Obviously, our tentative chronology needs to be confirmed by independent dating control. Such control may be provided by future amino-acid analyses (once the regional aminostratigraphy is well-defined), or possibly by paleo-magnetic studies. Meanwhile, this tentative chronostratigraphy is a working hypothesis that is consistent with the morphostratigraphic subdivision of the Chala sequence.

UPLIFT AND FAULTING

Regional Uplift Rates

In Chala Bay, the mean uplift rate calculated from the elevation of the +64–68 m shoreline that we assume to be of Substage 5e age (last interglacial maximum) is ca. 460 mm/kyr. Both north and south of Chala, remnants of the shoreline that seem to correlate with the +68 m feature are generally found at +40–50 m, an elevation indicating lower regional uplift rates of ca.

270–350 mm/kyr. Thus, the faulted block of the Chala basin has been uplifted slightly more rapidly than adjacent parts of the coast during the Late Quaternary.

Our chronostratigraphic interpretation of the late Middle Pleistocene units suggests that the highest seastands of the Isotopic Stages 7, 9 and 11 are recorded at +121, +168, and +184 (or +200) m, respectively. Accordingly, the mean uplift rate during the period 430–200 ka was about the same order of magnitude (500–430 mm/kyr) as the rate in the Late Quaternary (460 mm/kyr). The relative vertical spacing of the marine terraces above +200 m suggests that earlier in the Pleistocene (490–1600 ka), the mean uplift rate may have been significantly lower (ca. 250 mm/kyr ?). But, of course, we still know very little about the paleo-sea level heights, and ages of the Early Pleistocene highstands.

Surface Faulting

The three major faults bounding the Chala basin (Fig. 1) and the secondary faults that partly control the drainage system of the area, vertically deformed the terraces during the Quaternary. Slip on the N120°E. trending fault system that limits the Chala basin to the northeast, for instance, is indicated by the thick alluvial sequences deposited along the mountain fronts during most of the Quaternary. In our mapping of marine terraces, we found several vertically offset shorelines, which provide estimates of the amount of displacement and the age of deformation. For example, a 14 m vertical offset of the MMU VIII terraces was produced by displacement on the Chala River fault. This displacement occurred shortly after the formation of the +180 m marine terrace, probably during Isotopic Stage 10 (approximately 360–390 ka), and before the formation of the MMU VII terraces (Stage 9). We also found some displacements of a few meters on faults bounding small blocks within the Chala basin.

Other displacements between major fault blocks found during our general survey of shorelines include: Late Quaternary westward tilting of a block limited by the (N35°E. trending) Chala River fault and a fault along the unnamed river that ends north of Chala town (Fig. 1); Late Quaternary westward tilting of the block bounded by the (N35°E. trending) Huanca and Chala River faults; and eastward tilting of the block limited by the Honda River (N.–S. trending fault ?) and Huanca River (N35°E. trending fault). As a consequence of these displacements, the Pleistocene shorelines are slightly more elevated on the western and eastern basin margins than in the central part of the Chala basin.

CONCLUSIONS

Studies of the vertical tectonic deformation of marine terraces and of Pleistocene sea-level variations are closely interdependent. One cannot reconstruct paleo-sea-level heights during Pleistocene highstands without assumptions about uplift rates. Conversely, neotectonic studies of coastal areas need ages for emerged shorelines as well as estimates of former sea-level positions (relative to present MSL) when marine terraces were formed. But where ages for terraces are lacking, studies must rely on morphostratigraphic mapping and chronostratigraphic interpretation.

Morphostratigraphic analysis is most likely to be successful on extensive sequences of emerged shorelines. In Peru, where there is an urgent need to establish a chronostratigraphic framework for the marine Pleistocene, the small basin of Chala, with its long, well-preserved, sequence of terraces, was selected as the most promising area for a reconnaissance study of the Quaternary landforms and deposits, even though no radiometrical ages were available.

Field observations and air-photo interpretation of the Chala marine terrace sequence led us to group marine and continental landforms and deposits into major morphostratigraphic units (MMUs). These units were initially interpreted as groups of features related to single interglacial episodes. But interpretation of the deep-sea core isotopic record, as well as the morphology and heights of marine terrace scarps and the thickness of associated alluvial deposits suggest that the record of high seastands in the Chala area is more complex than suggested by our initial interpretation: successive interglacial episodes may be represented by pairs of MMUs. The two MMUs that probably are correlative with single interglacial episodes are those of MMU I (Holocene) and MMU III (last interglacial, Stage 5). However, neither of these MMUs is typical; the Holocene MMU is not yet completed, and the assemblage of features included in MMU III is equivalent to assemblages in groups of at least two MMUs higher in the sequence.

Our chronology for pre-last interglacial of the Chala sequence is based on correlation of MMU III with the last interglacial and then on extrapolation of older MMUs back in time (upwards in the sequence); the last four interglacials (Stages 5, 7, 9 and 11) are represented by the groups of marine terraces between +20 and +200 m. The earliest part of the Pleistocene is less well represented by terrace remnants between +200 and +240–274 m.

According to our chronostratigraphic interpretation, long-term uplift of the Chala basin may have been constant in the last half million years, and more rapid (460 mm/kyr) than the regional rate of uplift inferred for the southern Peru coast. Due to this higher rate of uplift, the Chala marine terrace sequence registers Late and Middle Pleistocene sea-level fluctuations with greater detail than areas to the north and south.

Surface displacements on faults within the Chala basin appear of limited magnitude, and can generally be measured accurately. This is not the case in the San Juan-Marcona area where surface faulting has significantly displaced many marine terraces (Ortlieb and Macharé, 1990b; Macharé and Ortlieb, *in press*). For this reason, in spite of excellent preservation of many Pleistocene shore platforms at San Juan-Marcona, it is difficult to determine the age and amplitude of the fault displacements and to correlate marine shorelines (Hsu, 1988). Because the rates of surface faulting near Chala are much lower, the sequence of Chala yields a more detailed record of Pleistocene sea-level variations than the only previously studied area on the Peruvian coast.

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