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Pampa del Palo: an anomalous composite marine terrace on the uprising coast of southern Peru

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Abstract — Quaternary sediments along the southern Peruvian coast occur as staircase terraces of coastal and shallow-marine deposits in response to continuous uplift related to the active boundary between the Nazca and South-American plates. However, near Ilo (in the same coastal stretch) the emergent Pampa del Palo terrace consists of a relatively-thick, vertical stack of shallow-marine, coastal and lagoonal deposits that indicate a rather different geodynamic behaviour. Coastal deposits are correlatable with the successive marine highstands of isotopic stages 7 (?) and 5 (substages 5e and 5c).

Combining aerial photo-interpretation, geomorphological mapping, sedimentological analysis, chronostratigraphical data, and structural observations, the Pampa del Palo feature is interpreted as a faulted block that moved independently of the remaining southern Peruvian coast and, for some time between the end of Middle Pleistocene (before ca. 220 ka) and the early Late Pleistocene (ca. 120 ka), it rose more slowly or was even down-faulted relative to the rest of the southern Peruvian margin. The independent block movements ceased after substage 5e, when the Pampa del Palo "terrace" was incorporated into the regional uplift of the area. Since ca. 100 ka, measured uplift rates in the Ilo area amounted up to 160 mm/10^3y when the area has been affected by a few active, NE-SE trending faults only. Copyright © 1996 Elsevier Science Ltd & Earth Sciences & Resources Institute

Resumen — Los sedimentos cuaternarios aparecen a lo largo de la costa sur del Perú como terrazas escalonadas y encajadas, con sedimentos sublitorales y costeros, en respuesta al continuo levantamiento de la zona de contacto activo entre las placas de Nazca y Sudamérica. Sin embargo, cerca de Ilo (en ese mismo sector costero) la terraza emergida de la Pampa del Palo contiene un registro relativamente potente de sedimentos marinos someros, costeros y lagoonales, apilados verticalmente, lo cual pone de manifiesto un comportamiento geodinámico bastante diferente. Estos depósitos marinos son correlacionables con los sucesivos niveles altos del mar correspondientes a los estadios isotópicos 7 (?) y 5 (subestadios 5e y 5c).

Combinando la interpretación fotogeológica, la cartografía geomorfológica, el análisis sedimentológico, los datos cronoestratigráficos y las observaciones estructurales, la terraza de la Pampa del Palo se interpreta como un bloque de falla que se movió independientemente de la restante costa del Perú durante cierto tiempo entre finales del Pleistoceno Medio (antes de unos 220 ka) y comienzos del Pleistoceno Superior (unos 120 ka), ascendiendo más lentamente o incluso descendiendo. El movimiento como bloque independiente cesó tras el subestadio 5e, cuando el bloque quedó de nuevo incorporado al ascenso general. Desde hace unos 100 ka, las tasas medidas de ascenso en la región de Ilo (incluyendo el bloque de la Pampa del Palo) llegan a 160 mm/10^3y. Desde entonces sólo han actuado en el área unas pocas fracturas de dirección NE-SE.

INTRODUCTION

Quaternary Vertical Motions along the Peruvian Margin

The western margin of South America is subject to vertical motions which are commonly related to the subduction of the Nazca plate. Recent studies on uplifted Quaternary marine terraces have documented the vertical deformation along the Peruvian and Chilean coasts (DeVries, 1986, 1988; Macharé *et al.*, 1986; Macharé, 1987, Radtke, 1987; Hsu, 1988, 1992; Hsu *et al.*, 1989; Flint *et al.*, 1991; Macharé and Ortlieb, 1991, 1992; Hartley and Jolley, 1995). These studies have established that most of these coastal regions have been emergent with varying uplift rates, except for a 900 km-long segment in north-central Peru (6–14°S) which appears to have remained stable, or slightly subsiding, since Pliocene time. The highest uplift rates (740 mm/10^3y) have been calculated from the San Juan Marcona area (15°S) where the aseismic Nazca Ridge is currently being subducted beneath the South American Plate (Macharé, 1987; Macharé and Ortlieb, 1992; Hsu, 1992). South of 17°S, mean uplift rates for the last million years are typically of the order of 100–150 mm/10^3y (Goy *et al.*, 1990; Ortlieb and Macharé, 1990a; Macharé and Ortlieb, 1991, 1992, 1993). In the Ilo area (17° 32'–17° 48'), Zazo *et al.* (1994) measured values of regional uplift of about 220 mm/10^3y, at least during the last 300 ka.

Determination of the magnitude and rate of recent vertical motions in coastal regions heavily depends on the identification and geochronology of Quaternary shorelines and associated coastal features. The earliest Pleistocene marine deposits in Peru have been identified and distinguished from Pliocene units by paleontological means but cannot be confidently correlated with specific episodes of interglacial sea-level highstands. The chronostratigraphical interpretation of younger terraces (late Middle Pleistocene and Late Pleistocene) requires geochronological analyses and/or morphostratigraphic studies which take into account the sea-level fluctuations during the latest interglacials (e.g. Ortlieb & Macharé, 1990b; Goy *et al.*, 1991).

Geochronology of Peruvian Marine Terraces

In western South America where corals are absent, age determination of marine layers (coastal terraces) must rely on mollusc shells. Radtke (1987), Osmond (1987), Hsu (1988), Hsu *et al.* (1989) and Ortlieb *et al.* (1990, 1991, 1992) used and compared several dating methods including U-series, electron spin resonance (ESR) and aminoacid racemization. U-series and ESR proved to be useful only in the unusual cases where the migration of radionuclides was minimal. The ESR and aminoacids techniques require careful calibration which is not easy unless sound and unequivocal radiometric (U-series) data are available.

Hsu (1988), Hsu *et al.* (1989, 1990), Ortlieb *et al.* (1991, 1992) independently conducted extensive aminostratigraphic studies based on allo/isoleucine epimerization ratios on several geni of pelecypod shells in southern Peru, particularly in the San Juan Marcona (15°S) and Ilo (17°S) areas. These studies involved 220 analyses by Hsu and collab. and about 450 analyses by Ortlieb and collab., but they led to partially divergent chronological interpretations. The two aminostratigraphic scales are offset by at least an interstadial and as much as an interglacial episode (Ortlieb *et al.*, 1991). The establishment of an aminostratigraphic chronology in Peru is complicated furthermore by methodological problems regarding the statistical representativity of the samples, the overlap of the aminozones and the interspecific correspondence of allo/isoleucine ratios (Ortlieb *et al.*, in prep.). Until these problems are resolved, one may consider that, although allo/isoleucine ratios are most useful as a relative chronological tool used in a restricted area, they cannot yet *per se* provide a chronological scale of Pleistocene marine deposits in terms of numerical age or isotopic stage correlation. This is especially true when the aminostratigraphic age is at odds with the morphostratigraphic evidence.

Abundant geochronological data, and particularly aminoacid analyses, are now available from the Ilo area in southern Peru (Hsu, 1988; Hsu *et al.*, 1989; Ortlieb *et al.*, 1991, Ortlieb *et al.*, 1992) but are difficult to interpret, for the reasons outlined above. A major additional problem is that the regional morpho- and chronostratigraphy of the Ilo area were obscured by uncommon tectonic features.

Interrelated Chronostratigraphic and Neotectonic Problems at Ilo

In the Ilo region (Fig. 1), three major, conspicuous, marine terraces have been reported at about +25 m (the so-called "Pampa del Palo"), +120 m (the so-called "Pampa Inalámbrica") and +350 m (Narváez, 1964). The author of the geological map (Narváez, 1964) suggested that the two topographically-lower terraces were of Pleistocene age. Tosdal *et al.* (1984) interpreted the two lower terraces to be of latest Pliocene-Early Pleistocene age, on the basis of questionable paleontological data. More recently, Hsu (1988) and Hsu *et al.* (1989, 1990) confirmed the Late Pleistocene age of the Pampa del Palo terrace, and furthermore showed that the last-interglacial deposits were underlain by older Pleistocene marine sediments. Through an aminostratigraphic analysis, Hsu and collaborators interpreted two discrete units below the superficial sediment of Pampa del Palo which could be assigned to isotopic stages 7 and 9, and inferred that some subsidence probably occurred at the end of the Middle Pleistocene.

Goy *et al.* (1990), Ortlieb *et al.* (1991) and Zazo *et al.* (1994) confirmed the superposition in the Pampa del Palo terrace of marine and lagoonal units deposited during successive highstand episodes. These authors also stressed that several marine terraces were preserved close to the anomalous Pampa del Palo feature, but at higher topographic elevations. They reported the existence of a series of terrace-remnants at +40, +50, +60–70, +120 and +160 m, and inferred that the region had experienced a rather-continuous uplift during the Quaternary.

In a previous report, Ortlieb *et al.* (1992) reassessed the last interglacial age of the Pampa del Palo terrace using combined U-series analyses ($^{230}Th/^{234}U$ and $^{234}U/^{238}U$), allo/isoleucine data, and measurements of the ^{18}O composition on a series of marine shells from Pampa del Palo area (including nearby marine terraces). Although they could not determine the precise age of the topographically-higher terraces, they suggested that the surface of the Pampa del Palo terrace postdates the isotopic-stage 7 deposits found at +25 m, and that the age of the +60–70 m terrace might be of isotopic stage 9. This chronostratigraphic interpretation clearly led to infer a continuous uplift motion of the area, at least inland from the Pampa del Palo feature. Nevertheless, Ortlieb *et al.* (1992) did not discuss the problem of the genesis of the Pampa del Palo feature.

Lastly, Zazo *et al.* (1994) carried out a morphotectonic study of the Pampa del Palo terrace within the geodynamic framework of the Ilo region which included sedimentological and aminostratigraphical work. The study produced a morphostructural map (Fig. 1) illustrating the main tectonic features which are considered to be responsible for the geometry and stratigraphic architecture of marine, lagoonal, and terrestrial deposits. The study revealed that the Pampa del Palo terrace is located on a downthrown block bounded by fault systems trending N120 and N20–40 E. These faults are considered to have probably been reactivated during isotopic stage 5 (Fig. 1) resulting in the development of a sedimentary regime which is viewed as exceptional within the context of this uprising coastal region.

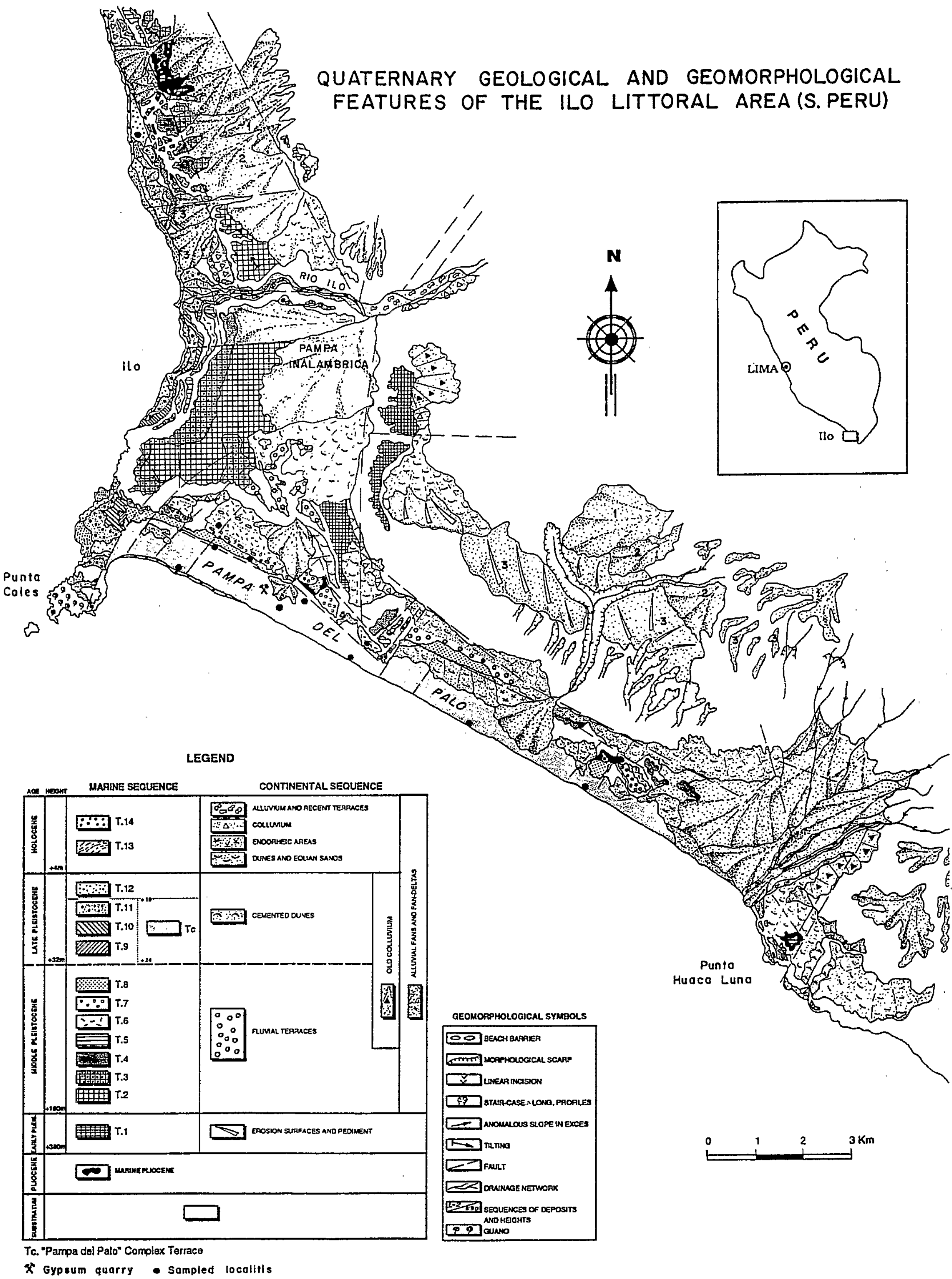

Fig. 1. Morphostructural sketch map of Quaternary coastal features in Ilo area (after Zazo *et al.*, 1994).

This paper presents detailed geomorphical, sedimentological and structural data from the Pampa del Palo terrace and the surrounding Ilo area. The aim of the paper is to clarify the regional tectonic setting and to explain the anomalous character of the Pampa del Palo depositional marine terrace. Unravelling the genesis of the Pampa del Palo feature has obvious implications for the reconstruction of recent vertical motions of the southern Peruvian coast, and, hence, for the establishment of a consistent aminostratigraphy for Peruvian Quaternary marine terraces. From a methodological point of view, it may also be useful for future studies of composite depositional terraces.

THE PAMPA DEL PALO AND SURROUNDING MARINE TERRACES IN THE ILO AREA

Geologic and Morphological Setting

The extreme aridity of the Peruvian coast during most of Quaternary times has generally resulted in good preservation of landforms and deposits, including Pleistocene marine terraces and the intervening continental deposits (Goy *et al.*, 1991). In this particular environment, the interpretation of aerial photographs reveals many geological and geomorphical features which can be used to reconstruct the recent evolution of coastal regions. The coastal landscape of the Ilo region is dominated by marine terraces carved into the western slopes of the Peruvian Coastal Cordillera (Fig. 1) in a staircase-like pattern. Usually terraces include a basal erosional surface related to a marine abrasion platform, overlain by a thin layer of nearshore sediments (typically a few decimetres to 2 m thick). Locally, the terrace may be covered by alluvial-fan deposits and eolian-sand sheets.

Detailed geomorphological mapping of Quaternary deposits and features in the study area (Figs. 1 and 2) shows that the alluvial and marine-coastal deposits prevailed in space and time. Eolian activity also plays a role, particularly southwards of Punta Coles, where the coastal area faces the prevailing winds. Sand dunes and eolianites are most abundant southwards of Punta Huaca Luna.

The alluvial system consists mainly of fans and cones of various sizes, associated with either small creeks draining the Peruvian Coastal Cordillera or bigger streams, such as the Ilo River and Quebrada Huaca Luna (Fig. 2). We assume that small fans are generally associated with recent local drainage, while much larger fans (e.g. those which cover the NE part of Pampa Inalámbrica, or the Huaca Luna fan) have accumulated over a longer time-span encompassing several glacial/interglacial climatic cycles. A few remnants of fluvial terraces and the Pampa Inalámbrica fan suggest that the Rio Ilo mouth was located southeast of Punta Coles at some time in the early Middle Pleistocene. There are at least three sequences of fans in the area (Fig. 2).

Coeval sequences of alluvial fans (1, 2, 3 in Fig. 2) from different localities show distinct geometric relationships (staircase, onlap, offlap, Fig. 1). This suggests that, besides the climatic control, there was a superimposed tectonic factor that perhaps did not influence the genesis of the fans, but was responsible for the diversity of relative disposition of the fans.

The marine-coastal system includes all the wave-abraded platforms and the associated marine and lagoonal deposits preserved in the area. North of Punta Coles, a sequence of up to 11 marine terraces (T_2 to T_{13}, Fig. 2) extends along a 15 km-long, 3 km-wide coastal strip, with the highest-elevated, well-defined terrace located about +160 m above present mean sea-level (inner edge of Pampa Inalámbrica). Remnants of an older encased terrace found at an elevation exceeding +380 m (T_1, Fig. 2) may be included in the sequence, and are tentatively assigned an early Quaternary (or Pliocene?) age. South of Punta Coles, remnants of marine platforms correlated with terraces T_2 to T_8 (+40 m), were also identified (in spite of a relatively abundant eolian sand cover). We interpret terraces T_9, T_{10} and T_{11} to have no staircase equivalent south of Punta Coles: they seem to be replaced by the anomalous Pampa del Palo terrace. The large surface known as the Pampa del Palo terrace extends at elevations below T_8 (+40 m). The sea has cut a live cliff in this surface exposing a 20 m-thick accumulation of vertically-stacked shallow-marine, coastal, lagoonal, and alluvial sediments. Thus, the generation of this depositional terrace might be at least coeval with the platforms (staircase terraces) T_9 to T_{11}.

Faulting Pattern and Tectonic Activity

There are several fault structures in the study area (Figs. 1 and 2). Some of these are inferred to be pre-Quaternary features which controlled the relief of this coastal area, while others appear to have been active, or to have been reactivated, in more-recent times (Fig. 1). Quaternary faults can be traced over distances ranging from hundreds of meters to 20 kilometres, bounding tectonic blocks that have experienced noticeable relative vertical motions.

Some of these fractures have been active during Quaternary times controlling the geometry and spatial relationships of sedimentary units (Zazo *et al.*, 1994). This is shown in the geomorphological map of marine and terrestrial deposits by the faults that, directly or indirectly, affect them, the varying elevation of some marine layers at distinct localities, the changes in the direction of the drainage pattern, the morphology of some cliffs, etc.

North of Punta Coles, the staircase pattern of Pleistocene marine-abraded platforms depicts a continuous uplift motion during the last million years. The Middle and Late Pleistocene activity of the N160°E-trending fault system, which delineates the coastal range, favoured the development of a belt of polyphase alluvial fans with the same orientation. These faults control

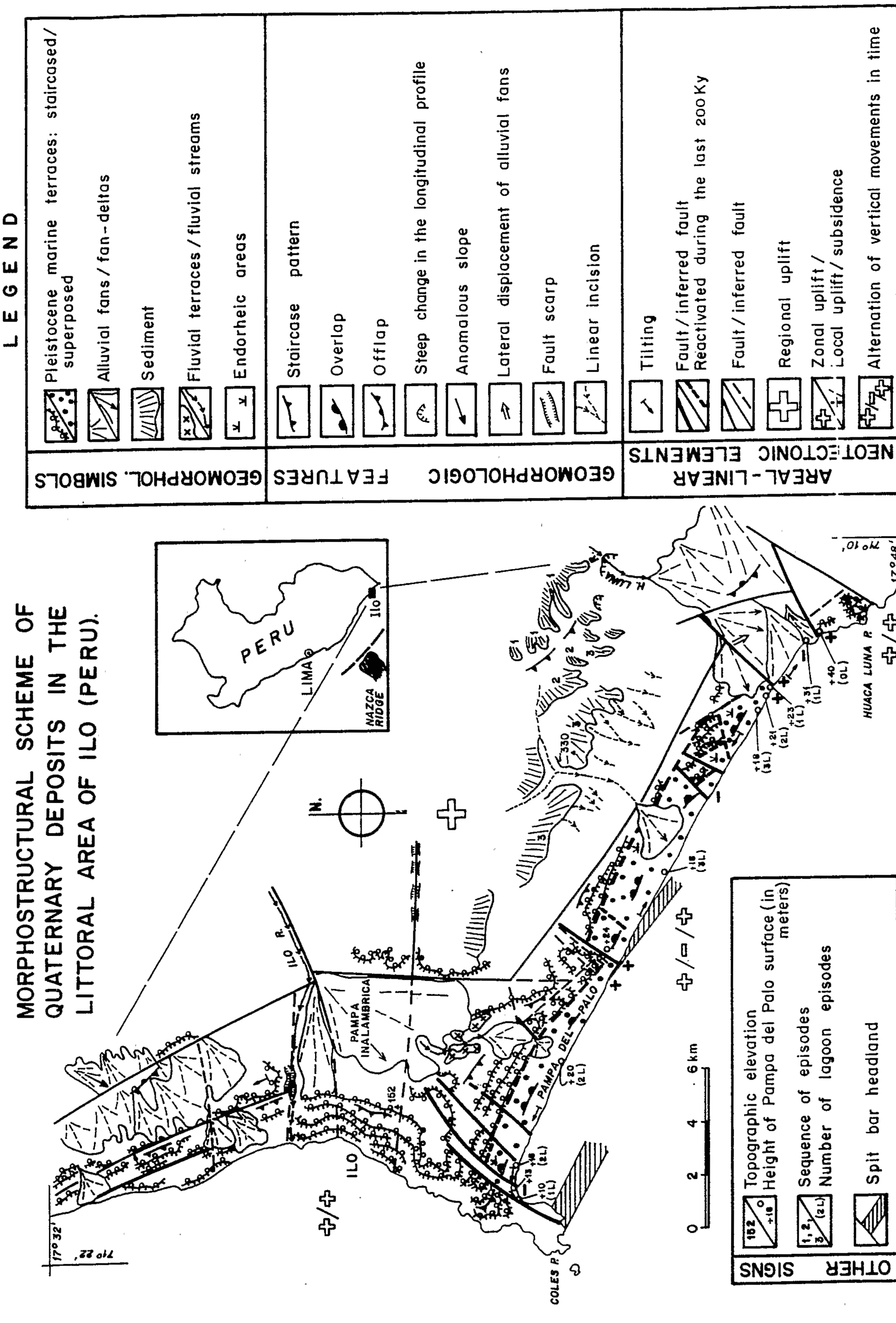

Fig. 2. Quaternary geology and geomorphological map of Ilo coastal region (southern Peru).

the apexes of younger alluvial fans located close to the present coastline, and also the trace of the sea-cliff related to the +15 m and +10 m marine terraces (T_4 and T_{12}, Fig. 2). Another fault system, roughly oriented E-W, resulted in block tilting and affected drainage patterns (Fig. 2).

South of Punta Coles two major trends are recognised: N120°E and N20°E to N40°E. A most striking feature is the geometric disposition of the marine terraces (Figs. 1 and 2). The older marine layers (T_2 to T_8) occur in staircase disposition but their lateral extension is smaller than north of Punta Coles. These terraces are interrupted by a fault line oriented N120 E. From this line to the south-southeast, the only observed feature is the 20 km long, 2 km wide Pampa del Palo surface (T_c in Fig. 2) located at +20 m elevation between Punta Coles and Quebrada Huaca Luna. The southwestern margin of this tectonic block is formed by the present sea-cliff which also trends N120°E. Towards its northwestern extremity, the tectonic block is affected by N20°–40°E faults that form small grabens oriented NE-SW, and which downthrow the surface of the Pampa del Palo by about 10 m. The combined action of the N120°E and N20°N40°E faults favour the development of small endorheic areas and allow the Pliocene substratum to crop out (Fig. 2).

THE SEDIMENTARY SEQUENCE OF THE PAMPA DEL PALO TERRACE

General Stratigraphy

The structure and sedimentary composition of the Pampa del Palo terrace can be studied through detailed observation along the 20 km-long vertical sea cliff, and in several open pits dug in the upper part of the terrace. As mentioned previously, this depositional terrace consists of up to 20 m of alternating marine, lagoonal and alluvial deposits (Fig. 3). The only section which deeply cuts the upper part of the Pampa del Palo terrace, perpendicular to the coastline, is a gypsum quarry (Fig. 2) located SE of the airstrip.

A complex sequence of alluvial sediments, three lagoonal units and five marine units were identified in the area, between Punta Coles and Punta Huaca Luna.

Alluvial Sediments

The alluvial deposits of the Pampa del Palo sequence consist of redsish mudstones and sandstones, locally pebbly, with horizontal bedding. Some layers are burrowed with individual burrows similar to those found in paleosol horizons of fluvial deposits. Some carbonate nodules, associated to these layers, are interpreted as generated by edaphic processes in (semi) arid climate.

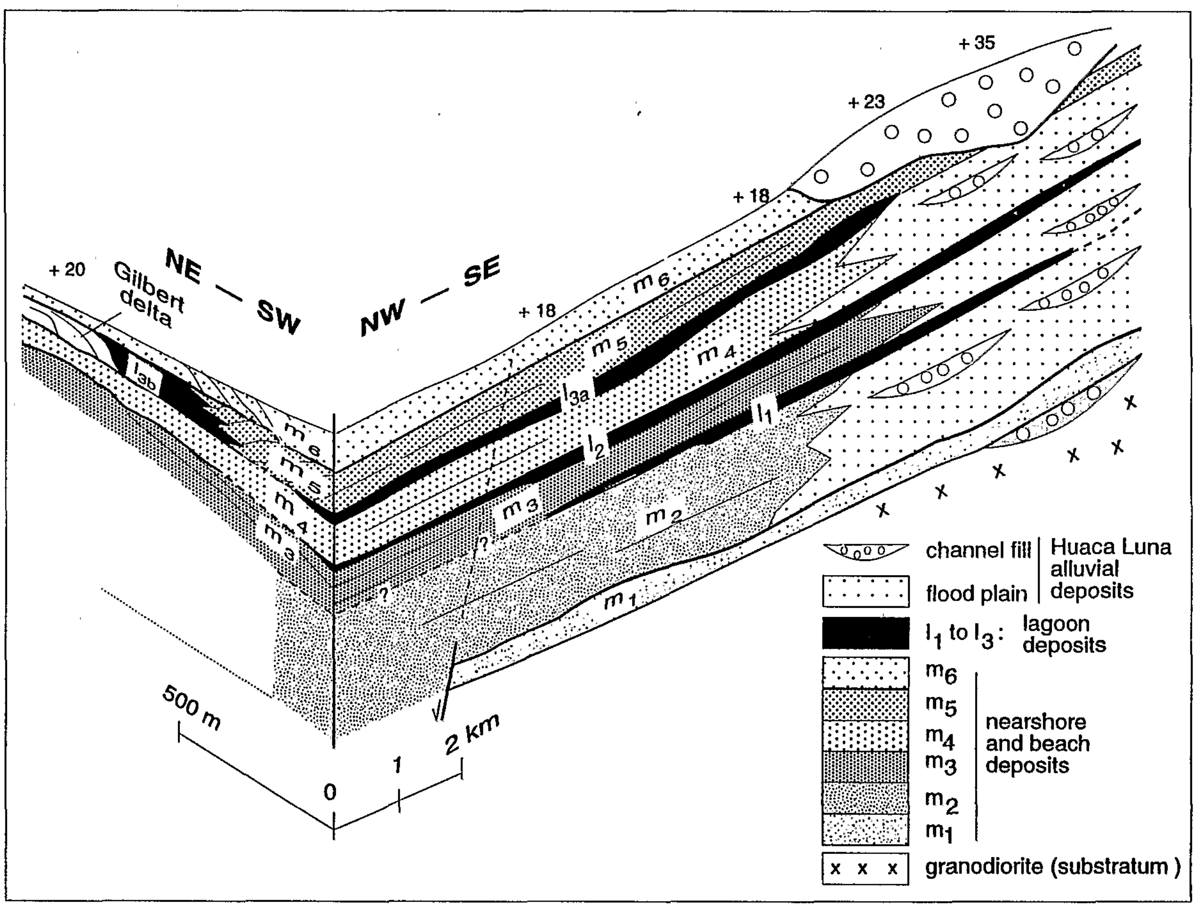

Fig. 3. Schematic cross sections along (NW-SE) and across (NE-SW) Pampa del Palo depositional terrace. For better visualisation, the fault does not produce displacement in units m_2 to m_5 and there is lateral continuity of units in both faulted blocks.

Coarser-grained layer occur interbedded in the previously-cited materials. They typically occur as:

(1) Clast-supported conglomerate layers with erosional bases of the channel type. More regular top strata are observed when they are not incised by the erosional surface forming the base of the overlying coarse-grained layer. Clast sizes vary greatly from cobbles to boulders of variable roundness. Local imbrication of flatter pebbles indicates paleoflows toward the south-west, roughly normal to the present coastline. Clast petrology evidences their origin in the adjacent mountain ranges (sierras) sited to the east. No other sedimentary structures were observed in our survey of these materials. These layers are interpreted as channel-fill deposits.

(2) Tabular beds of heterometric, clast-supported, conglomerates, sometimes reduced to almost single clast layers. They are placed upon erosional surfaces with gentle relief cutting the mudstone/sandstone facies. No internal structures or imbrications were observed in our survey. According to these data they are interpreted as sheet flood deposits covering the subaerial parts of an alluvial system.

In general, the alluvial deposits are interpreted as deposited by alluvial fans with high transport efficacy (*sensu* Colombo, 1992), characterised by large extension, dominance of terrigenous sediments transported and deposited by traction currents, and well developed fan body and toe.

The largest part of these facies were deposited by the alluvial fans emerging from the Huaca Luna mountain stream (Figs. 1 and 2), forming a vertical stack of alluvial-fan units that laterally grade into the sediments interpreted as deposited in nearshore, coastal and lagoonal realms (Fig. 3). As demonstrated later, these units were deposited during several oscillations of sea level, this means that there must be several stacked alluvial fan units, but no precise study of the erosional surfaces separating them was carried out.

Alluvial deposits related to the Huaca Luna fan form most of the sea cliff sequence at the southern extremity of the Pampa del Palo terrace. Near Punta Huaca Luna, the alluvial sequence overlies the oldest marine unit and is partly overlain by another marine layer (Fig. 3).

Lagoon Sediments

Sediments interpreted as lagoonal units consist of fine-grained sandy to muddy sediments with gypsiferous and carbonate crusts. Stromatolite structures are preserved in some of these crusts. They locally include fossiliferous beds with mollusc species (*Anomia peruviana, Ostrea* sp., *Trachycardium procerum, Tagelus dombeii*) indicators of shallow, restricted, sandy environments. These layers rarely exceed one metre in thickness. We assume that such lagoon deposits were related to sandy barrier islands located more to the south-east.

We distinguished several of these intercalations, here informally termed (in ascending stratigraphic order) l_1, l_{3a} and l_{3b} (Fig. 3). In the northern part of the sea cliff, only the l_2 and l_{3a} horizons can be identified. Toward the southern extremity of the sea cliff (Huaca Luna), the horizon l_1 wedges out. Only the l_2 layer can be followed continuously along the cliff (Fig. 3).

The Marine Units

Shallow-marine and coastal deposits dominate in the northern part of the terrace. We recognised six major "marine" units, informally called (also in ascending stratigraphic order) m_1 to m_6 (Figs. 3 and 4).

Unit m_1. Unit m_1 crops out in the lowermost part of the sea cliff (below +3 metres) with usually poor exposures. The recorded thickness is around 3 metres of fossiliferous gravel, commonly cemented forming conglomerates, and bioclastic sandstone. The internal structure in parallel lamination in sandstone layers, and faint, crude horizontal bedding in conglomerates. Clast sizes are usually below 10 cm. We found *in situ* fauna (*Argopecten purpuratus, Choromytilus chorus, Mulinia* cf. *M. edulis*, and *Mesodesma donacium*) mostly in the southern part of the area.

As sedimentary structures are not characteristic enough, our environmental interpretation relies upon fossils. According to these, sedimentation of unit m_1 took place in a shallow, open-marine embayment.

Unit m_1 overlies an abrasion surface cut into the granodiorite substratum or into alluvial deposits preserved on top of the granodiorite (Fig. 3). This planation surface is interpreted as a transgressive ravinement surface eroded by wave activity prior to the deposition of unit m_1. We favour this interpretation better than erosion during a relative fall of sea level because we did not find evidence of older marine units in this particular area.

Unit m_2. Unit m_2 is about 5 m thick. It consists of clast-supported, fossiliferous, fine to medium gravel and sand with crude parallel or gently-undulating bedding. The lower limit of the unit is an erosional surface with local irregular relief less than 1 m high. The upper limit of the unit is an erosional surface that remains basically horizontal when observed along the coastal sea cliff (Fig. 3). Faunal remains include *Eurhomalea lenticularis, Mesodesma donacium, Mulinia* cf. *M. edulis* and *Trachycardium procerum.*

The shallow-marine character of the faunal content and the lack of other conspicuous sedimentary structures favours the interpretation of these deposits as formed in the shoreface.

Unit m_3. This unit consists of four metres of fossiliferous, clast-supported fine gravels with layers of medium to coarse sands. This unit overlies the lagoonal layer l_1. The boundary between both units may be conformable or gently erosional, and remains almost horizontal along the

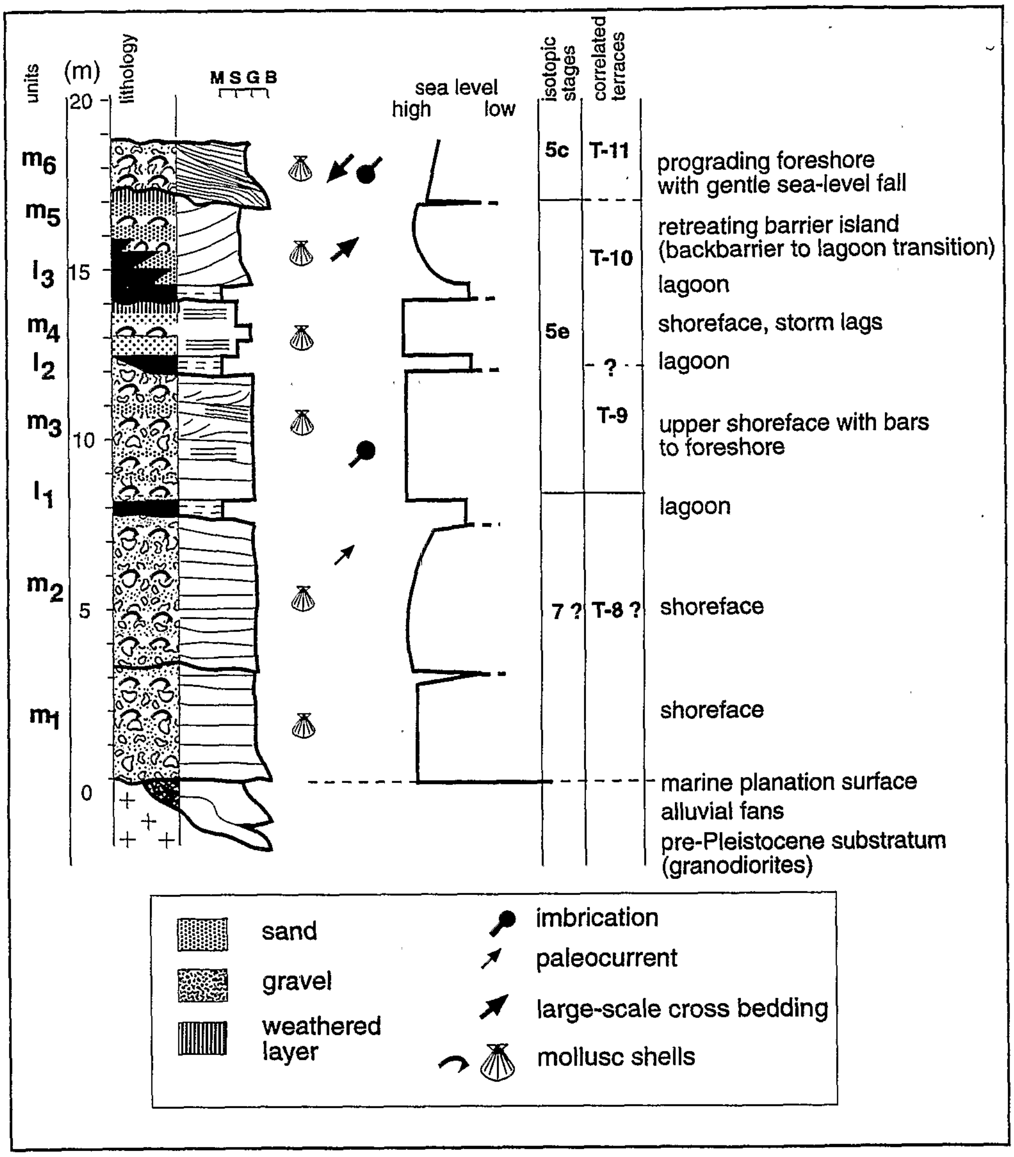

Fig. 4. Vertical and lateral correlation of marine and coastal units outcropping in the sea-cliff and in the gypsum quarry.

sea cliff (Fig. 3). In the quarry section, the base of the unit is not exposed (Fig. 4). The top of the m_3 unit in the quarry is a flat erosional surface. In the cliff units m_3 and m_4 are separated by the lagoonal layer l_2.

The internal structure consists of parallel or gently undulating lamination. In the quarry (Fig. 4) the overall internal structure is parallel lamination, with laminae several centimetres thick. Lamination exhibits a large-scale gentle inclination towards the southwest (seaward). Besides the former structure there are sets of landward-directed, low-angle, cross bedding up to 0.75 m thick. Flat, seaward-inclined, erosional surfaces truncate these deposits. These surfaces are overlain by sets of seaward-inclined, parallel-laminated medium to coarse sands that in places onlap the erosional surface. The faunal content (*Eurhomalea lenticularis, Mesodesma donacium, Mulinia* cf. *M. edulis* and *Trachycardium procerum*) is similar to that of unit m_2.

Unit m_3 is interpreted as deposited in the shoreface of a coast that prograded roughly towards the southwest. Some low-relief bars (as those exposed in the quarry) migrated in the shoreface towards the ancient shore (NE) generating isolated sets of cross bedding.

Most probably the top of unit m_3 was subaerially exposed inland from the shore during the sea level fall associated to deposition of lagoon l_2. The idea is supported by the geometry of the boundary with the overlying units (Figs. 3 and 4): the top of unit m_3 occurs in the quarry at elevations slightly higher than in the cliff, with no preserved lagoon deposits. We infer that the lagoon did not reach that far inland, and that the area was subject to subaerial erosion because it was topographically more elevated. However, it should be mentioned that we did not find evidence for subaerial exposure.

Unit m_4. Unit m_4 is a comparatively-thin unit made up of medium sands and decimetre-thick layers of coquina with fragments and complete shells of marine pelecypods similar to those described in the underlying units. The internal structure of sand is parallel lamination that locally may be obliterated by burrowing. In the quarry, unit m_4 lies upon a flat erosional surface cut in the underlying m_3 unit. In the sea-cliff it crops out between the lagoonal layers l_2 and l_3 (Fig. 3).

According to the fossil content and the scarce information supplied by sedimentary structures, unit m_4 is interpreted as deposited in the upper shoreface adjacent to a sandy shore. The coquina layers are interpreted as shelly storm lags. Sedimentation of unit m_4 took place after the sea inundated the underlying l_2 lagoonal deposits, during relative rise of sea level and transgression (Fig. 5).

The upper 15–20 cm of the unit are reddish in colour; this is interpreted as the result of subaerial weathering, but no specific mineralogical or pedological studies were carried out. Further support for emersion is given by the overlying lagoonal deposits indicative of sea-level fall after deposition of unit m_4 (Fig. 5).

Unit m_5. Unit m_5 consists of sands and coquina, with a high content of *Mulinia* cf. *M. edulis* shells.

In the cliff, the base of this unit is conformable with the underlying lagoon unit (l_{3a}) but in the walls of the gypsum quarry trending normal to the coast, a rather different picture is observed. There, the m_5 unit consists of a complex facies arrangement including three subunits.

The subunit located more to the SW consists of shelly gravels that depict a landward-migrating large-scale cross bedding. Coarse-grained toesets of the cross beds interfinger with a subunit made up of gypsum beds, biogenic carbonate layers and mudstones. They form the evaporitic l_{3b} lagoon disposed more or less horizontally with small, but prominent, post-depositional deformations (Figs. 3 and 4). As the transition from the conglomeratic to the evaporitic subunits shifts landwards and upwards, the resulting facies change occurs clearly oblique to bedding.

Inland from the gypsum deposits, and interfingering partly with them, a third sub-unit is preserved. It consists of sands and gravels with large-scale, high-angle, cross bedding with paleocurrent direction indicative of migration towards the SW (seaward). The 2 to 3 m high set exhibits well-preserved topset, foreset and bottomset. It is interpreted as a coarse-grained subaqueous Gilbert-type delta prograding into the lagoon from the adjacent alluvial plain (Fig. 4).

According to this depositional arrangement of facies and the faunal content, unit m_5 is interpreted as the manifestation of the landward migration of a retreating barrier island (spit bar?) coeval with a sea-level rise. The wall of the quarry displays the transition from the back barrier into the lagoon and further landwards, into the Gilbert delta fed by the adjacent alluvial plains.

The m_5 marine deposits extend to the south-eastern extremity of the Pampa del Palo area and interrupt the Huaca Luna alluvial sequence (Fig. 3): this may be interpreted as being the result of a major transgression. Besides, the lateral and vertical facies relationships of sub-units marking the inland retreat of the m_5 barrier island complex, evidence a (relative) sea-level rise coeval with the deposition of this marine unit.

Unit m_6. The 1.5 m-thick unit m_6 is the youngest coastal-marine unit exposed in the Pampa del Palo terrace, apparently covering the whole terrace.

The lower boundary is an erosional surface with well-preserved irregularities. Near the Balneario locality (northern end of the sea cliff), m_6 rests upon a red weathering indicative of subaerial exposure after the deposition of unit m_4. Local faulting is responsible for the low elevation at which the marine units outcrop near the Balneario (m_6 is preserved between +11 and +12.5 m, instead of +15–18 m elsewhere). The upper boundary is the present-day surface.

It consists of fossiliferous gravels and sands arranged in sets of parallel lamination with relatively-thick (5 to 10 cm) laminae dipping gently (3°–6°) to the SW. In many cases these parallel laminae curve down in the lower part forming tabular sets of cross bedding oriented towards the

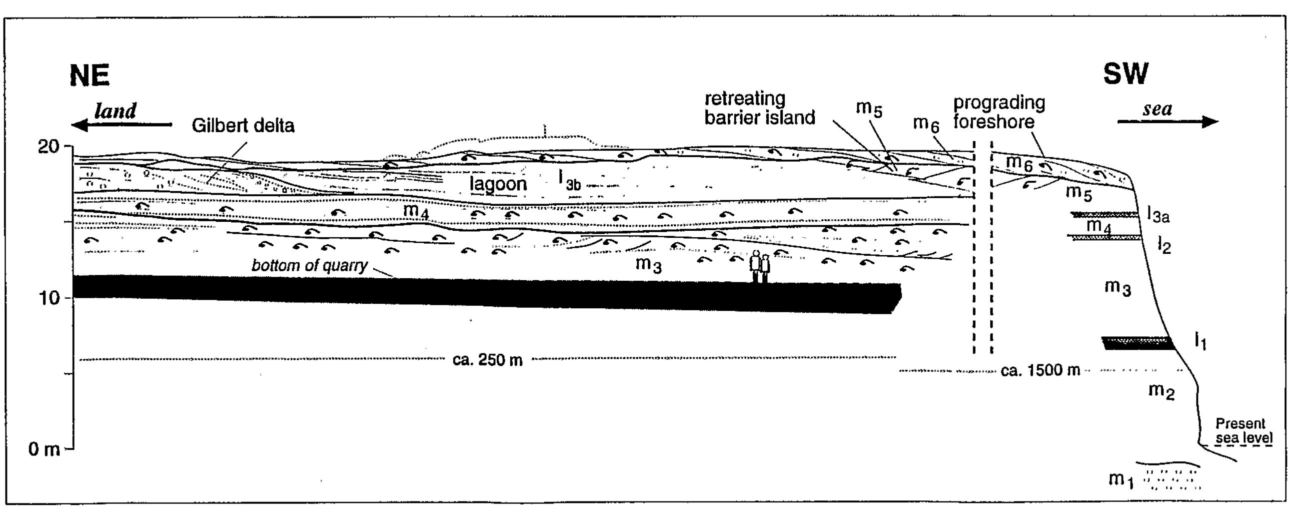

Fig. 5. Synthetic stratigraphical section of the Pampa del Palo terrace.

SW (seawards). Adjacent sets are separated by erosional surfaces. The topographic levels reached by the transition from parallel lamination to cross bedding clearly shift back and forth in a NE-SW direction in the various sets.

This unit is interpreted as deposited in the prograding foreshore of a coarse-grained coast characterised by a well-developed topographic step in the lower part of the foreshore. The step, also called plunge-step by Davis *et al.* (1972), is up to 30 cm high. Erosional surfaces separating the parallel-laminated sets are related to major stormy episodes that partly reworked the foreshore. These materials exhibit vertical sequences similar to those described by Dabrio *et al.* (1985) in prograding gravely coasts of tectonically active settings. Lateral and vertical shifting of the plunge-step facies have been related to fluctuations of sea level by Somoza *et al.* (1986–87) and Bardají *et al.* (1987).

In conclusion, the complex nature of the sedimentary record in the Pampa del Palo (Fig. 5) area suggests a relatively-long history of deposition that encompass several sea-level fluctuations. Flat, erosional surfaces were cut during sea-level falls. There is not a clear record of lowstand deposits. Lagoonal deposits were laid down during the ensuing transgressions related to the rise of sea level, as witnesses by the retreating barrier islands associated (and overlaying) to them (Fig. 4). Accordingly, lagoonal units are considered as transgressive systems tracts. Highstand systems tracts are represented by the shallow marine to coastal units.

Available Geochronological Data

In a previous paper, Ortlieb *et al.* (1992) approached the age determination of marine deposits in the Ilo region by comparing aminoacid data with $^{234}U/^{238}U$ and $^{230}Th/^{234}U$ measurements. The U-series data on molluscan shells proved to be of limited help in discriminating substages of the last interglacial.

A re-evaluation of the complete set of U-series from Peruvian marine terraces is currently performed. The previously published $^{230}Th/^{234}U$ apparent ages had been calculated on the basis of beta counting values, which proved to be less reliable (from a technical point of view) than the spectrometric alpha counting. The revised results do not substantially modify the earlier interpretation. To summarise the new data, 8 age measurements of mollusc shells from the m_6 and m_5 marine units yield apparent ages between 84 and 123 ka, with a statistical peak at about 100 ka.

Because of the intrinsic limitations of the aminoacid geochronological method (see above) and the restricted suitability of the sample set, it would be unwise to rely on aminostratigraphic data alone. A major problem with the Pampa del Palo deposits, is that most shells have (or may have) been reworked from older units, and that *in situ* shells are limited to a few localities. Another limitation comes from the large predominance of *Mulinia* shells, which proved to yield relatively inconsistent allo/iso ratios (Hsu, 1988). An additional problem is the difficulty in determining the equivalency, in terms of allo/iso ratios, between shells of *Eurhomalea lenticularis* and the other species analysed (*Mulinia* sp., *Eurhomalea rufa, Mesodesma donacium, Protothaca thaca*).

Nevertheless, the aminoacid racemization data available from the Pampa del Palo area (excluding *E. lenticularis* data) proved to be sound in most of the sampled localities (Ortlieb *et al.*, 1992; Ortlieb *et al.*, in prep.) (Table 1).

The marine units m_1, m_2 and m_3 did not yield aminoacid data. The units of the upper part of the Pampa del Palo sequence seem to encompass two aminozones, both older than terrace T_{12}.

Chronostratigraphic Interpretation of the Pampa del Palo Sequence

Sedimentology, isotopic measurements, and aminoacid racemization (Fig. 5 and Table 1) suggest that unit m_6, the youngest in the study area, is probably coeval with substage 5c (100 ka, Zazo *et al.*, 1994). Aminostratigraphic and field data suggest that it is younger than unit m_5, but older than the youngest marine terrace preserved north of Ilo (correlated with substage 5a, Ortlieb *et al.*, 1992).

According to aminoacid and U-series data, unit m_5 is assigned to the isotopic substage 5e (Table 1). This is in agreement with field data: Units m_5 and m_6, are separated by a prominent erosional surface near the Ilo Balneario (Fig. 2). Besides, the reddened top of unit m_5 below this surface is interpreted as a weathering episode. All these features support a fall of sea level between the isotopic substages 5c and 5e.

What is the age of the marine units underlying m_5? As we know, there are discrepancies (Pirazzoli, 1993) about the length of the last interglacial, namely 11 k.y. (127–116 ka BP) for the $\delta^{18}O$ deep sea core substage 5e and about 22 k.y. (139–117 ka BP) for the Vostok ice core stage G (Genthon *et al.*, 1987). On the other hand, recent results of the GRIP ice core (Greenland Ice-core GRIP Members, 1993) demonstrate three short, but well represented warm periods during substage 5e.

In the southern coast of Peru (Chala area, north of Ilo), Goy *et al.* (1991) distinguished and mapped at least two highstand layers deposited during substage 5e.

In other areas as in the Mediterranean, Zazo *et al.* (1993) distinguished three mappable highstand units deposited during isotopic substage 5e.

Taking into account the lack of dating of these marine units and the problems associated to the number of highstands that occurred during the isotopic substage 5e, we tentatively consider that this substage is represented by the marine units m_3, m_4 and m_5. According to this, the lagoonal episode l_1, represents a period of relatively-lower sea-level (fall) separating the highstands of isotopic stages 5 and 7.

Table 1: Summary of aminostratigraphic data from Pampa del Palo units and surrounding areas (Ortlieb *et al.*, in prep). Mean allo/isoleucine ratios are indicated for aragonitic shells (except *Eurhomalea lenticularis* which does not racemize at the same rate as the other species). In situ samples (paired shells) are underlined. Morpho-stratigraphic units are indicated in Fig. 1 and 2. Chronostratigraphic interpretation is expressed in isotopic substages.

Locality (maximum elevation)	Morpho-stratigraphic unit	Sample #	Species of pelecypod	Allo/isoleucine Mean ratios	std	(n)	chronostratigraphic interpretation (isotopic substage)
Mineroperú N. of Ilo (+10m)	T 12	P.363	<u>*Protothaca thaca*</u>	0.38	± 0.04	(2)	5a
			Mulinia cf. M. edulis	0.41	± 0.03	(6)	5a
Ilo Balneario (+12m)	m 6	P.356	*Mesodesma donacium*	0.48	± 0.03	(2)	5c?
			Mulinia cf. M. edulis	0.75	± 0.04	(2)	Reworked (7)
NW. of Ilo Balneario (+6m)	m 4 + m 5 ?	P.374	<u>*Protothaca thaca*</u>	0.65	± 0.04	(5)	5e
			<u>*Eurhomalea rufa*</u>	0.67	± 0.05	(4)	5e ?
			Mulinia cf. M. edulis	0.57	± 0.04	(3)	(Anomalous ?)
SW. of Ilo Airstrip (+17m)	m 5	P.360	*Mesodesma donacium*	0.58	± 0.04	(3)	5e
			Mulinia cf. M. edulis	0.59	± 0.05	(3)	5e
Gravel pit #1 (+17m)	m 6 + m 5 ?	P.127	*Mesodesma donacium*	0.53	± 0.08	(9)	5c/e?
			Mulinia cf. M. edulis	0.59	± 0.07	(6)	5e
S. Pampa Palo (+20m)	m 5	P.6	*Mulinia cf. M. edulis*	0.61	± 0.02	(3)	5e
Ilo Balneario (+7m)	m 5	P.354	*Mesodesma donacium*	0.61	± 0.02	(4)	5e
S.W. of Ilo Airstrip (+17m)	m 4		*Mesodesma donacium*	0.67	± 0.02	(3)	5e?
	m 5 ?	P.359	*Mulinia cf. M. edulis*	0.57	± 0.04	(3)	5e
Gravel pit NW Pampa del Palo (+25m)	m 5+ reworked T 8 ?	P.162	*Mulinia cf. M. edulis*	0.60	± 0.04	(3)	Anomalous ?
			Eurhomalea rufa	0.75	± 0.06	(3)	7
			Mesodesma donacium	0.76	± 0.02	(3)	7
NE. P. Palo (+50m)	T 6	P.362	*Mulinia cf. M. edulis*	1.08	± 0.04	(3)	(racemic) 9 ?
NE. P. Palo (+60m)	T 7	P.10	*Mulinia cf. M. edulis*	0.95	—	(1)	9 ?
NE. P. Palo (+70m)	T 7	P.164	*Mulinia cf. M. edulis*	0.95	± 0.07	(2)	9 ?
Old abrasion platform NE. P. Palo (+35m)	T 4 ?	P.14	*Mulinia cf. M. edulis*	1.01	—	(1)	(racemic) >9 ?
			Mesodesma donacium	1.22	—	(1)	(racemic) >9 ?
			Eurhomalea rufa	1.26	± 0.04	(2)	(racemic) >9 ?

NEOTECTONIC AND PALEOGEOGRAPHIC EVOLUTION

The geodynamic evolution of the Ilo area can be reconstructed from the number of sequences of marine and terrestrial deposits, type of sedimentary environments, fault systems affecting these deposits, and a series of geomorphic features indicative of tectonic activity.

Uplift of the entire Ilo area since the beginning of the Quaternary has resulted in the development of a series of 13 marine layers or terraces (T_1 to T_{13}) that form a staircase profile and several sequences of alluvial fans (Fig. 2).

In the Pampa del Palo block, bounded by N120°E and N20°–40°E trending faults, this general trend of uplift was interrupted following deposition of the +40 m marine terrace (T_8 in Fig. 2). From this time (corresponding to the isotopic stage 7?) the Pampa del Palo tectonic block remained independent from the regional uplift trend, with subsidence resulting in deposition of barrier islands and lagoon systems. This resulted in the development of several vertically-stacked marine deposits as in the case of the anomalous superposition of deposits of isotopic substage 5c (unit m_6) upon those of substage 5e (units m_5, and probably m_4 and m_3).

Subsidence ceased after isotopic substage 5e (m_5 unit) when the Pampa del Palo was incorporated into the regional uplift trend. This is indicated by the common elevation of deposits corresponding to isotopic substage 5c: m_6 and T_{11} occur nowadays at approximately the same elevation (ca. +20m) on both sides of Punta Coles. This implies that three marine terraces (T_9, T_{10} and T_{11}) were deposited in the area north of Punta Coles during the deposition of the "Pampa del Palo terrace" (marine units m_3, m_4, m_5, m_6, and the interbedded lagoon l_2 and l_3). We consider that the marine units m_1 and m_2 may correspond to the isotopic stage 7.

Uplift rates deduced for the Ilo area according to the present elevation (+25 m) of the T_{10} terrace — corresponding to isotopic substage 5e (120 ka) — and assuming a sea level 6 m higher than the present, amount up to 160 mm/10^3 y.

CONCLUSIONS

The coastal region of Ilo has been subjected to continuous uplift during Quaternary times. The staircase disposition of the marine platforms, the facies, and the reduced thickness of associated marine deposits are typical of the southern Peruvian coast. Deposits of thirteen successive Pleistocene highstands occur north of Ilo town, if one includes the +360 m surface (which might be of Pliocene age) and the Holocene shoreline. As well as the regional vertical motion, the area was repeatedly faulted during the Quaternary, particularly by N160°E and E-W trending faults.

South of Punta Coles, there are almost as many Early and Middle Pleistocene marine terraces as in the northern sector of the study area. Terrace elevations and sedimentary deposits are similar to their respective, but better preserved, equivalents, in the area north of Punta Coles. The major difference between the two sectors concerns the terraces below the +40 m elevation: three staircase terraces in the northern sector (T_9, T_{10} and T_{11}) correspond to a single depositional terrace (the so-called Pampa del Palo), in the area to the SE of Punta Coles. The superimposition of marine units, the development of successive barrier-island systems, and the anomalously-thick deposits that constitute the emerged Pampa del Palo terrace, all point to a distinct tectonic regime for the area south of Punta Coles (the Pampa del Palo block) bounded by faults trending N120°E and N20°–40°E.

In spite of some methodological difficulties, the geochronological control on the most recent marine units is good enough to identify deposits of substages 5a, 5c and 5e. Abundant new aminostratigraphic and U-series data (Ortlieb *et al.*, 1992; Ortlieb *et al.*, in prep.) combined with a detailed morpho-stratigraphical and sedimentological analysis, provide the basis for a new and more-precise reconstruction of the tectonic evolution of the Ilo region for the period after terrace T_8 up to immediately (?) after the deposition of unit m_5 (substage 5e).

Uplift of the Pampa del Palo block proceeded at a much slower rate than the rest of the Ilo area and, in comparison, was subject to relative subsidence. Since substage 5c time, differential vertical motion of the block ceased and the whole region was uplifted. Since ca. 120 ka, uplift rates measured in the Ilo area amount up to 160 mm/10^3y.

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