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Sedimentology of the Rímac-Chillón alluvial fan at Lima, Peru, as related to Plio-Pleistocene sea-level changes, glacial cycles and tectonics

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Abstract

The Rímac and Chillón Rivers eroded deep valleys on the Lima coastal plain during the Late Miocene (before ca. 5.3 Ma), due to at least 485 m of uplift produced by the Nazca Ridge, combined with a sea level lowstand of around −50 m. The main paleo-Rímac channel along the southeastern boundary of the alluvial cone was apparently deflected by the Lima Anticline and reached the sea in the vicinity of Morro Solar, whereas the paleo-Chillón ran largely parallel to the anticline, breaching it to enter the Pacific at present-day Magdalena. These valleys were filled by fine-grained sediments, possibly during marine transgression at 1.7 Ma, which was followed by uplift and regression to below present sea level. Meltwater surges from the Andean Cordillera during subsequent interglacial stades caused an accumulation of coarse, reworked glacial moraine in the Rímac and Chillón fans, forming the Lima Conglomerate and drowning the Lima Anticline. The Rímac and Chillón Rivers subsequently migrated north and westward, possibly in response to tectonic tilting of the landscape, causing silt and mud to accumulate in abandoned channels along the southeastern boundary of the fan. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Alluvial cone; Paleovalley; Interglacial stades

1. Introduction

Lima, the capital of Peru, is situated on alluvial fan deposits of the Chillón and Rímac Rivers, a fact that has important implications with regard to the replenishment and pollution of the city's groundwater reserves, building practices, and the effects of frequent earthquakes on its 8 million inhabitants. However, in spite of good outcrops along the coast in close proximity to several universities, no detailed sedimentological interpretation of these deposits has ever been published. In this paper, we present the first such study based on vertical profiles measured along the coast between the suburbs of Chorrillos and San Miguel (Fig. 1), representing the Rímac paleofan and its coalescence with the paleofan of the Chillón River. Presently, the Rímac follows a course along the northern boundary of its alluvial plain, entering the Pacific north of Callao (Fig. 2).

2. Geomorphological and geological background

The geomorphology of the study area can be subdivided into four elements: the Andes Cordillera, coastal plain, coastal headlands and Holocene alluvial floodplains. The Rímac River has its origin in the Andes east of Lima, dropping from about 4800 m to sea level over a distance of only 120 km. Due to this steep gradient of 1:25, bedload transport is dominant, with boulders reaching diameters of more than 2 m in the upper parts of the river and up to 80 cm at the coast. The clasts reflect the composition of the Andean Cordillera, namely diorites, granodiorites, granites and gabbros of the Late Cretaceous Coastal Batholith, together with Mesozoic and Cenozoic volcanic and pyroclastic rocks.

The coastal plain lying between the Andes and the Pacific Ocean has a gently seaward-sloping surface, which averages about 1° in a westerly direction and 2–3° south-westerly between Chorillos and Callao. Coastal cliffs in the latter area reach a height of up to 82 m.

The coastal headlands represent the highest relief along the coast, being composed mainly of Cretaceous marine deposits of the Puente Piedra and Morro Solar Groups (Table 1). These rocks crop out south of Central Lima,

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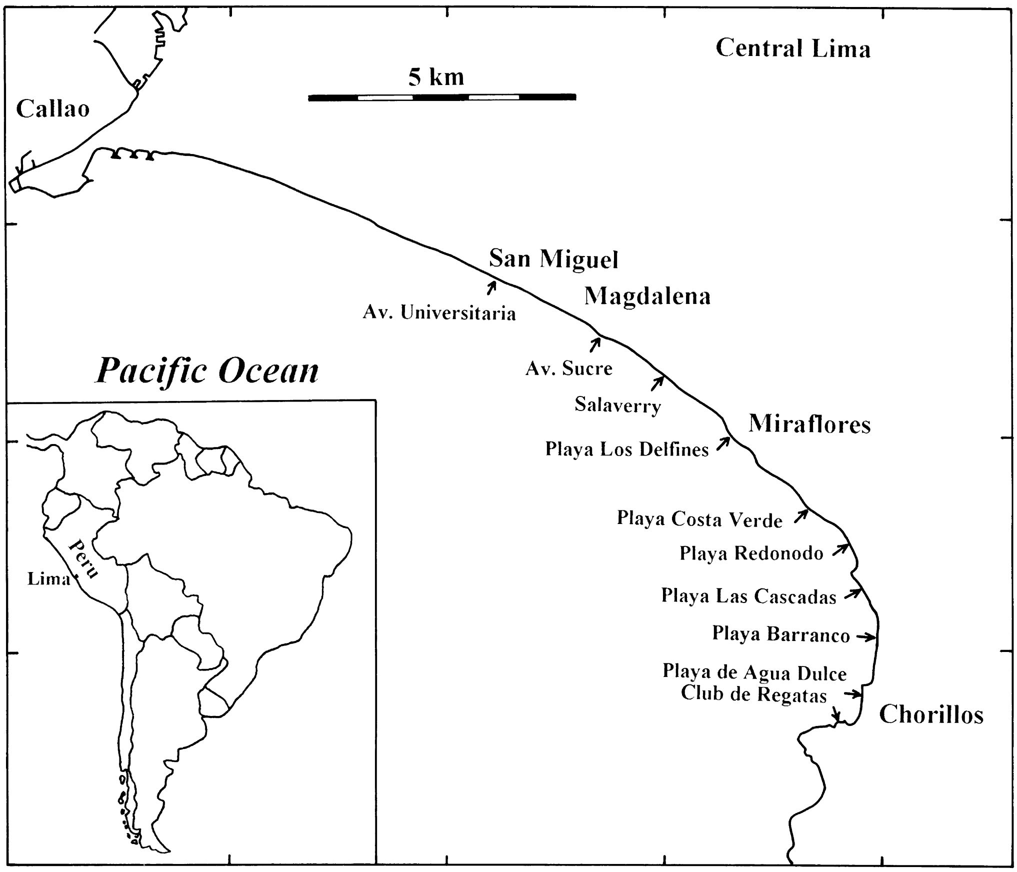

Fig. 1. Map of Lima, showing location of measured sections along the Pacific coast.

forming the southeastern limits of the Chillón and Rímac paleofans.

Holocene floodplains include areas historically affected by recurrent floods along the present-day river valleys. They are composed mainly of gravel and sand with subordinate, finer overbank deposits. Fluvial incision of the coastal plain varies between 10 and 20 m and was triggered by more recent changes in base level.

The most prominent structural feature underlying the coastal plain is the Lima Anticline, which trends in a north-northwesterly direction from Morro Solar (Fig. 2) and has a width of about 25 km. Dips reach 20° on its southwestern flank and 35° on its northeastern flank. This structure resulted from compression during the Andean orogeny (Karakouzian et al., 1996) and appears to have had some influence on the development of the paleo-Rímac and -Chillón Rivers.

3. Study methods

This study concentrated on the coastal outcrops of the Lima Conglomerate, which form a prominent 15–80 m high cliff along the entire city seafront. As the poor consolidation of the conglomerates made the use of ropes too dangerous, measured sections were restricted to concrete steps and access roads exploiting the natural 'quebradas' or gullies oriented normal to the coastline. In most cases, the uppermost part of the cliffline is inaccessible or could not be measured due to an extensive talus cover; in other localities the basal portions of the cliffs are somewhat obscured by a thin crust of tufa formed during groundwater seepage. In each section, the maximum clast sizes (long axes) were recorded for every recognized stratigraphic unit or bed, although stratification is commonly indistinct. Sand and silt grain sizes were measured with an American/Canadian Stratigraphic grain size chart and hand lens. Vector analysis of clast imbrication and other paleocurrent indicators was performed on a spreadsheet (Le Roux, 1991).

The time scale used here is that of Gradstein and Ogg (1996).

4. Stratigraphy

The Rímac Group is composed of three main stratigraphic units (Table 1). The basal deposits consist of fine-grained sandstones, siltstones and mudstones, of which thicknesses exceeding 37 m have been recorded in wells (Lisson, 1907). Electric resistivity measurements indicate that this unit

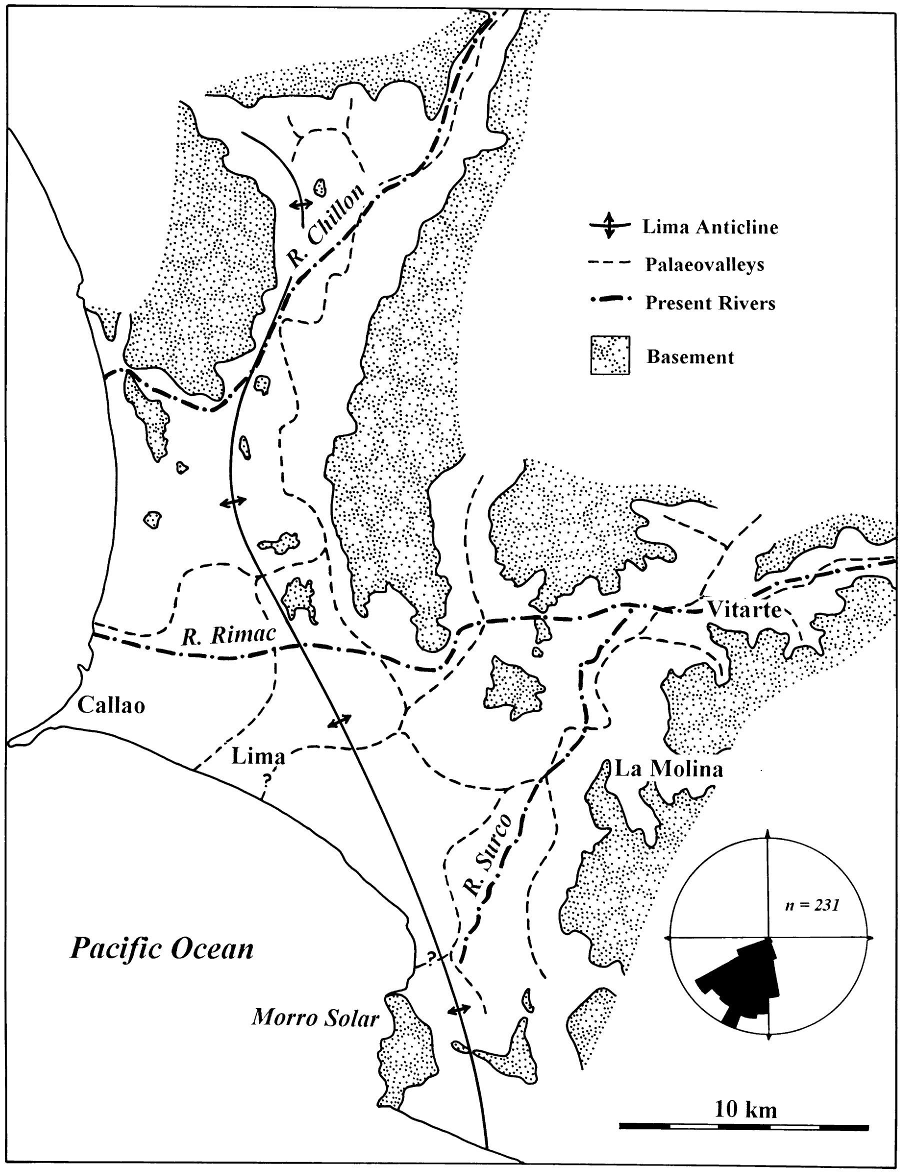

Fig. 2. Paleovalleys and present river courses of the Rímac fan. Rose diagram shows imbrication of clasts and direction of trough crosslamination.

Table 1
Stratigraphy of the Rímac Group and underlying formations

Period/epoch	Lithostratigraphic unit	Rock types
Pleistocene	Upper unit	Siltstone, shale
	Lima Conglomerate	Conglomerate, sandstone, siltstone, shale
	Basal unit	Sandstone, siltstone, shale
Cretaceous	Casma Group	Lavas, volcanic sediments
	Atocongo Formation	Limestone
	Pamplona Formation	Limestone, shale, mudstone
	Morro Solar Group	Sandstone, shale, limestone
	Puente Piedra Group	Shale, sandstone, volcanic breccias

reaches a thickness of about 400 m in the deeper parts of the Rímac valley (Arce, 1984; Fig. 2). Overlying these deposits is a succession of coarse conglomerates with minor interbedded sandstones and mudrocks known as the Lima Conglomerate (Karakouzian et al., 1996). A thickness of at least 86 m has been recorded in wells, which conforms more or less to the average thickness revealed by geophysical methods (Arce, 1984). In some areas, e.g. La Molina and the Chorrillos district (Fig. 1), the Lima Conglomerate is succeeded by more than 16 m of fine siltstones and mudstones (Karakouzian et al., 1996), which occur in semi-isolated depressions along the southern boundary of the Rímac valley and probably represent overbank lakes.

Karakouzian et al. (1996) suggested a Pleistocene age for the Lima Conglomerate, without giving any reasons. A middle Pleistocene age is proposed by Noller (personal

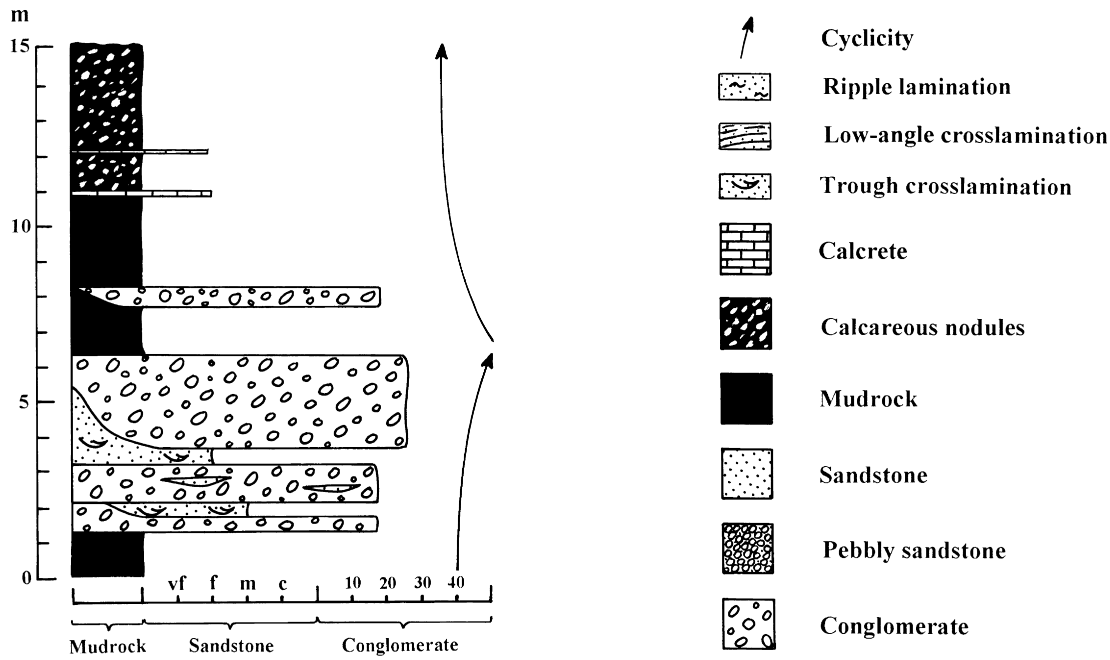

Fig. 3. Measured section at Club de Regatas, Chorrillos, representing the distal, southern edge of the Rímac fan. M = mudrock; Sf = fine-grained sandstone; Sc = coarse-grained sandstone; C_{10}, C_{30}, C_{50} = long axis diameters of largest clasts in centimeters.

communication), on the grounds of geomorphologic, stratigraphic and soil stratigraphic evidence. The only fossil evidence that we are aware of is from the top of this formation, where a molar of *Equus curvidens* Owen, which is of Pleistocene age, was recovered (Lisson, 1907).

5. Sedimentology of the Rímac fan

5.1. Facies description and interpretation

Along the southern edge of the Rímac fan at Club de Regatas (Fig. 1), conglomerates constitute only 29% of the measured profile (Fig. 3), with a maximum recorded cobble size of 25 cm. They show erosional basal contacts. The rest of the section is composed of silt- and mudstone, sandstone, and thin limestone (calcrete) beds. The mudrocks are light gray with occasional ripple lamination. They grade upward into mudrocks with calcareous nodules, which probably represent arrested soil profiles. Sandstones commonly form lenses within the conglomerate and are trough cross-laminated, with individual troughs less than 20 cm wide. Some exhibit a reddish color. These deposits are typical of shallow, braided channels developing at some distance from the fan axis, with deposition dominated by silt and clay during overbank flow. The partial development of caliche soil profiles toward the top of the section, however, indicates relatively long periods undisturbed by deposition or erosion.

Away from the southern fan edge, the succession is dominated by conglomerates, which vary between 75 and 100% in the recorded profiles (Fig. 4). Maximum cobble sizes range from a few up to 50 cm in diameter (with the exception of one boulder 80 cm across), with a primary mode between 25 and 30 cm (Fig. 5). The clasts are composed mainly of plutonic and volcanic rocks, but sandstone and occasional, irregular clumps of claystone were also observed, which were probably derived from bank undercutting and collapse. The harder clasts are well to very well rounded, but poorly sorted. Cylindrical shapes are dominant. Imbrication is moderate to fair, varying between 130 and 300° with a mean azimuth of 206° (Fig. 2). This correlates very well with the southwesterly slope of the fan in this area, as well as with the trends of the valley axes as revealed by bedrock elevation contours. There is no clear correlation between bed thickness and maximum clast sizes (Fig. 6), suggesting that deposition in this part of the fan was mainly by streams rather than mass flow processes (Nemec and Steel, 1984). If the few beds thicker than 5 m are ignored, however, there does seem to be a vague positive correlation between clast size and bed thickness, which might indicate pulses of hyperconcentrated flow.

Stratification within the conglomerate is diffuse, being exhibited mainly by a change in clast size and occasional erosional surfaces. With the exception of imbrication, no internal sedimentary structures were discerned. However, at 'quebradas' or gullies along the base of the cliffs, small secondary debris cones produce steeply dipping sets of pebbly sandstone interbedded with conglomerate. These reworked gravels merge with the older fan deposits and could easily be mistaken as such. They typically form tabular or convex-up units flanking the gullies (Fig. 7).

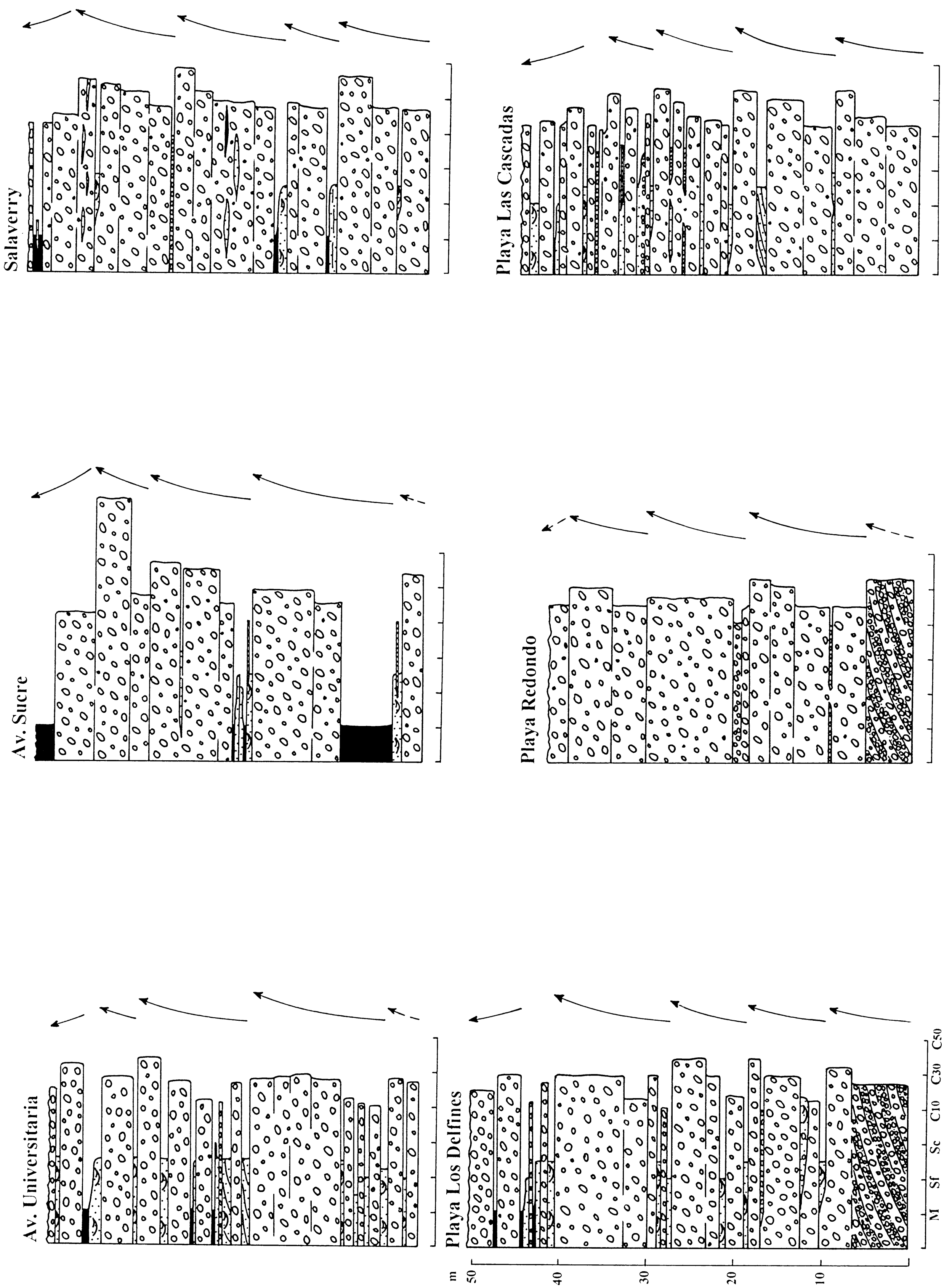

Fig. 4. Measured sections along the coast between Chorrillos and San Miguel. Legend as in Fig. 3.

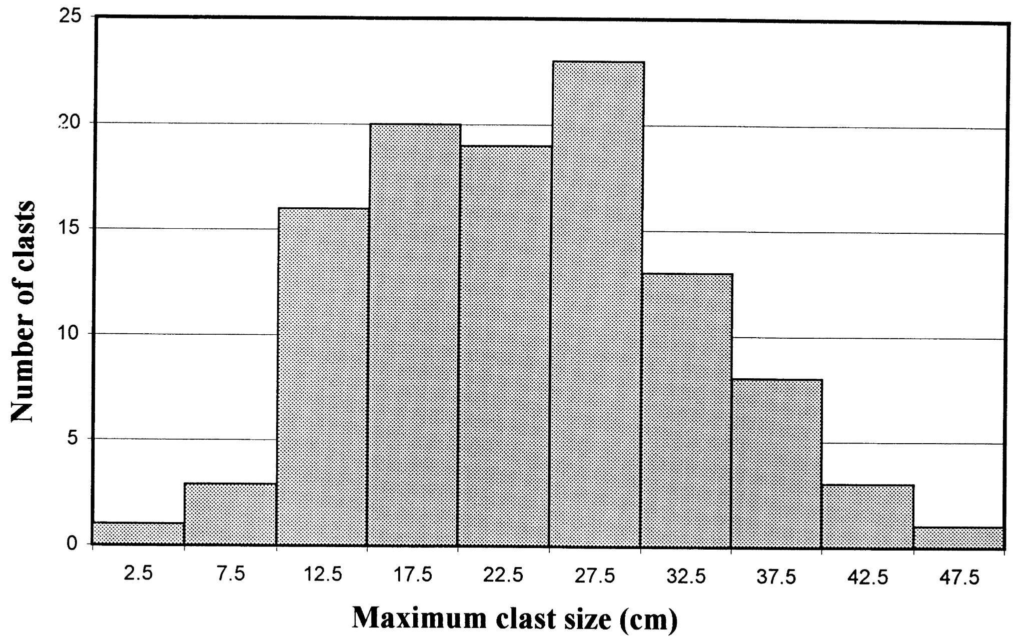

Fig. 5. Histogram of maximum clast sizes in the Lima Conglomerate.

Sandstones within the conglomerate are mostly lenticular, overlying erosional surfaces and in turn being eroded by younger conglomerates. Contacts may be highly irregular, with bank undercutting displayed in some areas indicating relatively high cohesion strength due to a clay matrix. Most of the sandstones are trough cross-laminated (Fig. 8), although antidune cross-lamination and low-angle tabular cross-lamination were also observed. Troughs trend toward

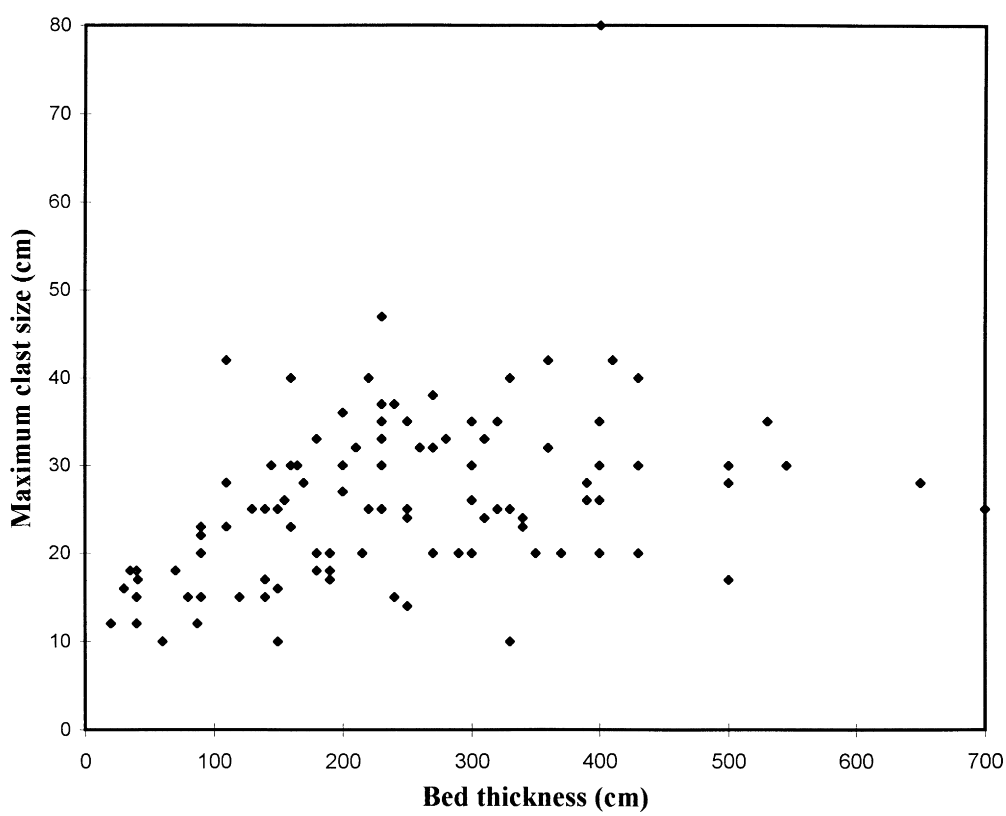

Fig. 6. MPS/BTh diagram of Lima Conglomerate. The general lack of correlation suggests deposition by stream flow rather than mass flow processes.

Fig. 7. Secondary debris cone developed at the mouth of a 'quebrada' or gully incised into the fan. Note beds dipping steeply to the left (northwest) behind persons.

Fig. 8. Trough crosslamination in sandstone lens. Note sharp basal and upper contacts.

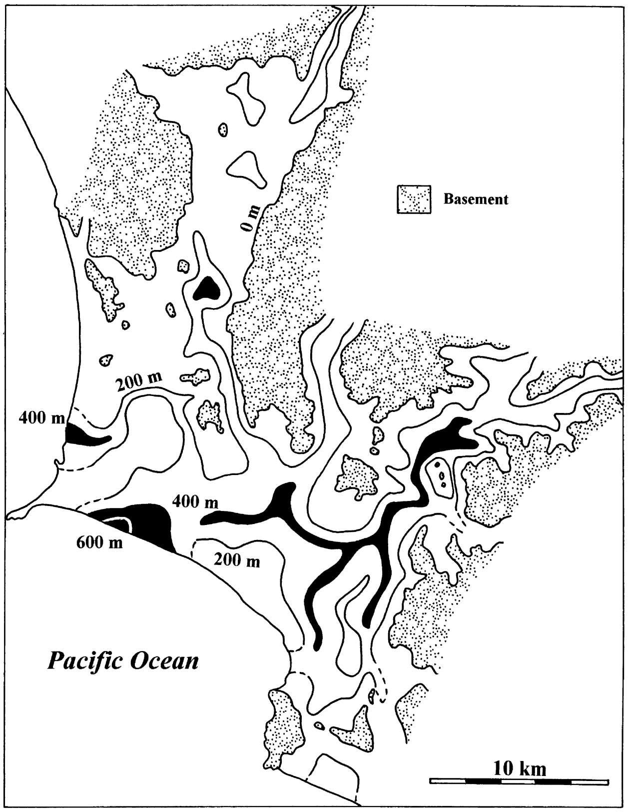

Fig. 9. Depth to basement (m) according to electric resistivity measurements (redrawn from Arce, 1984).

the southwest, supporting the direction indicated by imbrication. (Fig. 2). Sandstone beds or lenses commonly fine upward into siltstone and mudstone, suggesting waning currents following high-discharge episodes.

Mudrocks in the Lima Conglomerate exhibit light gray to pale purple colors. Although they normally form lenses within the conglomerate or cap sandstone beds, thicker (up to 5 m), more persistent units make their appearance northwest of Avenida Salaverry (Figs. 1 and 4), where they constitute up to 25% of the exposed part of the Lima Formation. Mudrocks are also prominent at the boundary between Barranco and Chorrillos towards the southeast. These rocks generally become more common towards the top of the succession throughout the study area, but could not be included in the profiles due to their inaccessibility or a soil/talus cover. Most of the lenticular units display erosive basal contacts, which indicate deposition in abandoned anabranches after extremely rapid channel flow. The thicker, more persistent beds were possibly deposited during overbank flooding in fluvial lakes at some distance from an active fan axis.

Overall, the sedimentary facies and general absence of macrofossils in the Lima fan indicate deposition in a high-energy environment of rapidly shifting braided channels. This is supported by a sinuosity value of only 1.1, as calculated from the paleocurrent distribution (Le Roux, 1992, 1994). There is a complete absence of any signs of marine influence (e.g. beach imbrication or stratification) in the

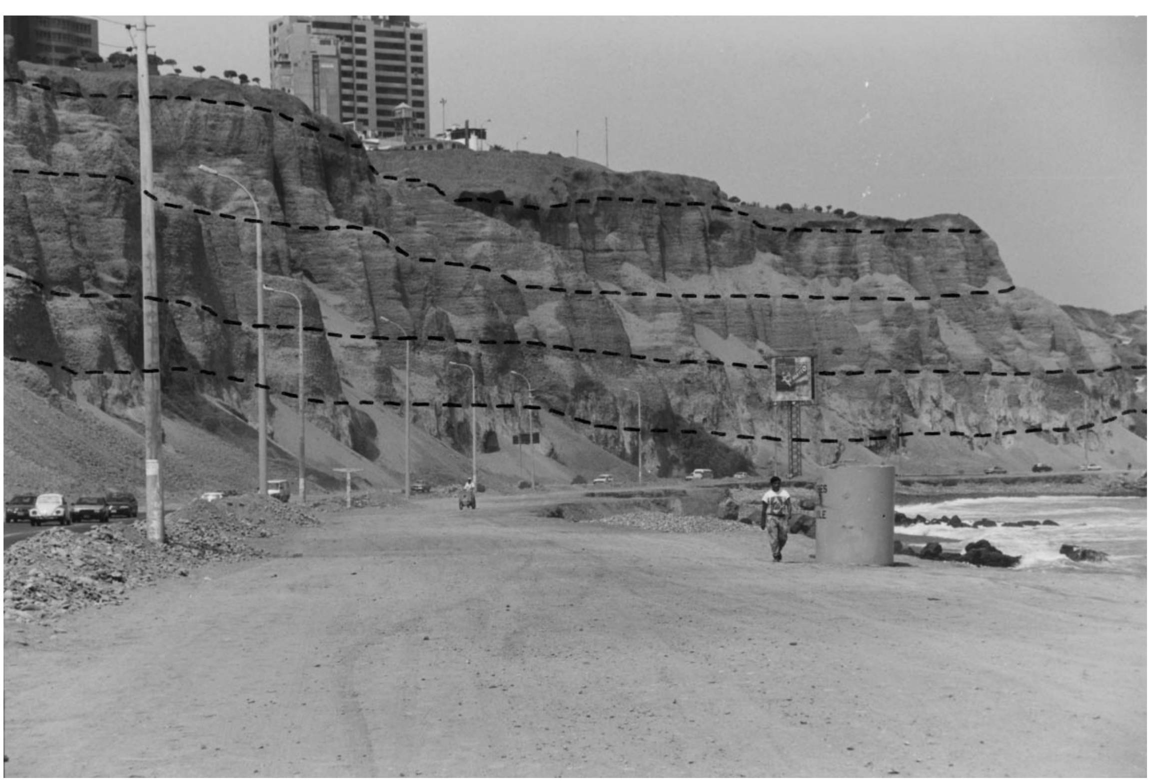

Fig. 10. Coarsening-upward cycles in the Lima Formation. View towards southeast.

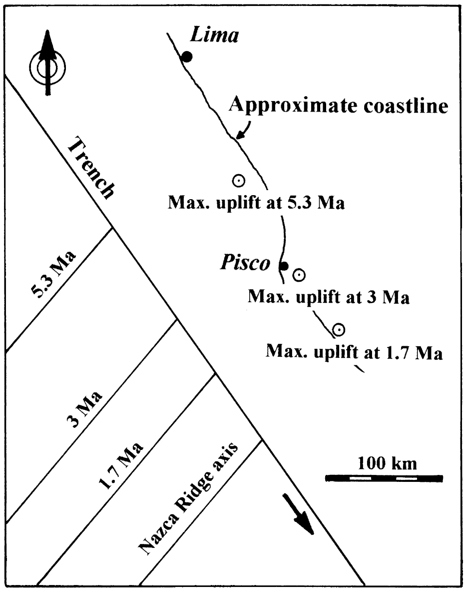

Fig. 11. Schematic reconstruction of the position of the Nazca Ridge at different dimes during the Plio-Pleistocene.

exposed part of the succession, which probably rules out a fan delta environment.

5.2. Relationship between the Rímac and Chillón fans

The present course of the Chillón River runs along the western border of its alluvial plain, which might indicate a gradual westward tilting of the landscape due to tectonic uplift in the east.

Basement elevation contours as determined by electric resistivity measurements (Arce, 1984), show that both rivers previously occupied deep valleys to the east and southeast of their present positions (Figs. 2 and 9). From Vitarte, the paleo-Rímac apparently flowed south southwesterly along the present-day southeastern border of its alluvial plain towards Chorrillos, where it may have broken through to the coast in the vicinity of Morro Solar. Imbrication of clasts at Chorrillos supports a southwesterly direction of flow. The presence of the Lima Anticline probably played an important role in blocking the direct access of the paleo-Rímac to the sea, as its valley seems to have been deflected parallel to the fold axis. The Surco River, which drains part of the water of the Rímac (Fig. 2), occupies the surface expression of this ancient Rímac valley northwest of La Molina, but peters out towards the southwest. West of La Molina, a distributary of the paleo-Rímac broke away to the west and split into two channels, the southern branch again paralleling the axis of the Lima Anticline, and the northern branch following the latter for a short distance before breaking through the crest of the anticline at present-day Central Lima.

The main channel of the Chillón River likewise paralleled the anticline and followed the eastern boundary of its alluvial plain southward toward Central Lima, joining the northern distributary of the Rímac River in this area. The Magdalena-San Miguel area thus represents a merging of the ancient Rímac and Chillón fans, which probably explains the rather sudden increase in the percentage of sand- and mudrock from Salaverry towards the northwest (Fig. 4). Karakouzian et al. (1996) mention a predominance of finer deposits in northern Callao, which are actually derived from the Chillón River. The paleo-Chillón also had a distributary entering the Pacific north of Callao, which is presently occupied by the Rímac near its mouth.

5.3. Cyclicity in the Lima Conglomerate

At first glance, the Lima Conglomerate is a rather homogeneous succession without any obvious subdivisions. However, maximum clast sizes measured in every discernible unit disclose coarsening- and fining-upward cycles which can apparently be correlated from section to section (Fig. 4). This is most clearly displayed at Playa Los Delfines and Avenida Salaverry, where four coarsening-upward cycles can be discerned at the base, succeeded by a fining-upward cycle at the top (Fig. 10). Similar cycles can be distinguished in the other sections, each varying in thickness from about 5–18 m. These medium-scale coarsening-upward cycles are laterally far too extensive to represent bar migration, and probably resulted from slow fan progradation followed by rapid retrogradation. This may be related to either pulses of tectonic uplift in the interior, cyclic lowering and elevation of the sea level, climatic pulses causing an increase and decrease in river discharge, or regular lobe-switching at the fan apex. It is not clear which of these effects controlled the cyclicity of the Lima Conglomerate, but we consider a combination of climatic and eustatic causes to be most likely. Eustatic sea-level lowstands are generally correlated with extensive glaciation, which would lock up most glacial debris within the cordilleran ice caps. However, at the onset of glacial interstades, meltwater released from the ice caps would rework the moraine and allow the seaward progradation of alluvial fans before a substantial rise in sea level can take place. During prolonged sea-level highstands, however, the new accommodation space created inland would probably not have allowed coarse material to reach the present coastline. We therefore consider the Lima cycles to be related to periods of meltwater release at the end of sea-level lowstands, when the climate was beginning to warm up sufficiently to melt the cordilleran ice-caps at lower elevations.

Four glacial cycles have been described in the vicinity of La Paz, Bolivia (Dobrovolny, 1962), as well as in Colombia (Gonzalez et al., 1965, as quoted by Flint, 1971). At least three cycles have also been recognized in Peru (Lanning and Patterson, 1967), although the timing of these cycles is uncertain.

According to oxygen-isotope data (Haddad et al., 1993), a pronounced eustatic lowstand occurred at 0.62 Ma (stage 16), which could possibly be correlated with the first cycle in the Lima Conglomerate. Recently, Rohling et al. (1998) combined evidence of extreme high-salinity conditions in the glacial Red Sea with a hydraulic control model of water flow through the Straight of Bab-el-Mandab, to determine global lowstand periods during the last 500 000 years. Their curve shows four additional cycles of alternating high- and lowstands in the Middle Pleistocene. We would tentatively correlate their lowstands at 0.46 Ma (stage 12) and 0.15 Ma (stage 6) with cycles 2 and 4 in the Lima Conglomerate. Lowstands at 0.35 and 0.27 Ma (stages 10 and 8) are isotopically less distinct (Haddad et al., 1993) and may be correlated with cycle 3 of the Lima Conglomerate.

6. Tectonism and eustatic sea-level changes

The development of the Rímac and Chillón valley-fills is probably related to a combination of eustatic sea-level changes and local tectonic movements. Various authors have examined sea-level changes along the Peruvian coast (e.g. Teves, 1975; Hsu, 1988; DeVries, 1988; Ortlieb and Macharé, 1990), but it remains difficult to identify them precisely due to the lack of geochronological data (Macharé and Ortlieb, 1992). We can therefore only speculate on the relative influence of these effects, although we do so within the constraints of available information.

Arce (1984) conducted electric resistivity measurements at more than 2000 stations in the lower part of the Rímac and Chillón valleys over a period of nearly 20 years, of which about 1100 penetrated the sedimentary cover to define the basement elevation. During this period, different instruments were employed, varying in potential from 100 to 2500 W and in output from 584 to 1500 V. The configurations of Wenner and Schlumberger were used depending on field conditions, which were reported to be generally good.

According to the bedrock elevation as interpreted from these measurements, the valley floor of the Rímac lies at a maximum depth of 525 m below present sea-level at the coast between Magdalena and Miraflores (Arce, 1984, p. 11; Fig. 9), if the cliff height between these localities is taken into account. This indicates tectonic downwarp of the valley floor, which was probably preceded by uplift and erosion as suggested by the shape of the incised channels. During the Pliocene/Pleistocene, maximum sea-level lowstands were of the order of −125 m according to isotopic sea level curves (Chappel and Shackleton, 1986; Prentice and Matthews, 1988; Quinn and Matthews, 1990), so that these alone cannot account for the total depth of fluvial incision. This could imply an uplift of at least 400 m. We would tentatively terminate this erosional period at the end of the Miocene, as outlined below.

There is good reason to believe that the Lima coastal area underwent substantial elevation during the Miocene. Macharé and Ortlieb (1992) discuss evidence for uplift of the south central Peruvian coast during the latest Pliocene/earliest Pleistocene due to the approach of the Nazca Ridge. Adapting an earlier model of Moretti (1982), they proposed an asymmetrical dome-shaped uplift with a maximum elevation of 900 m developing some 70 km south of the landward projection of the ridge axis. The uplift had a total range of influence of about 500 km along the coast, with the ridge beginning to affect the coastal segment some 4–5 Ma ago (Macharé and Ortlieb, 1992). Due to its southeastward migration, the ridge would have been located several hundred kilometers further north during the Pliocene (Dewey and Lamb, 1992).

To reconstruct the position of the Nazca Ridge at different periods in the past, we used a sinistral strike-slip component of 145° with a velocity of 42.4 mm/year, based on vector relationships in Dewey and Lamb (1992, Fig. 4c) and the relative plate velocities of Stein et al. (1986). Taking the strike of the ridge axis as 040°, it would therefore have been located about 110 km southwest of Pisco at 1.7 Ma, with the area of maximum uplift 115 km from the trench/ridge intersection and 75 km southeast of Pisco (Fig. 11). At 3 Ma, the ridge would have been located 225 km south of Lima and the area of maximum uplift just southeast of Pisco, 210 km to the southeast. Using a slope of 0.0036 (900/250 000), uplift of less than 150 m would have been produced in the Rímac-Chillón area. Combined with the sea-level lowstand of about −70 m at the time (Prentice and Matthews, 1988), this would account for erosion of less than 220 m preceding deposition of the basal fine-grained member. Before the end of the Miocene at 5.3 Ma, however, the uplift could have been at least 485 m, which together with a lowstand of ca. −50 m at the time (Prentice and Matthews, 1988) could account for the observed erosion at Lima. During the Pliocene, subsidence in the wake of the southeastward-migrating Nazca Ridge would have precluded the extent of erosion required to produce the deep Rímac-Chillón valleys.

The fine-grained basal unit filling these valleys up to a depth of 400 m and presently occurring at a maximum elevation of about 480 m above the modern sea level (Arce, 1984, Fig. 2), indicates sedimentation in a relatively low-energy environment. A suggestion was made that these mudrocks are of marine origin in the vicinity of Callao (Karakouzian et al., 1996, p. 35), although no evidence was presented. Assuming that this is indeed the case (which seems likely in view of their fine-grained nature), it would indicate at least partial drowning of the former river valleys. This implies tectonic downwarp, as eustatic changes alone cannot account for such a pronounced relative rise in sea level. The maximum highstand as derived from oxygen isotope curves of deep-sea foraminifer tests (Williams, 1990) occurred at 1.7 Ma (early Pleistocene), with an elevation of only about 50 m above present sea level. Together with the maximum lowstand of about −125 m during the Pliocene, eustatic processes could therefore have produced a relative sea-level rise of only 175 m, leaving at least 225 m to be accounted for by subsidence. However, we would tentatively correlate deposition of the basal fine-grained unit with the transgression at 1.7 Ma. At this time the Nazca Ridge would have been located more than 250 km south of Lima, so that this area would have fallen largely outside its sphere of influence. Macharé and Ortlieb (1992, p. 101) note that the area to the north of the present-day Nazca Ridge probably underwent subsidence during the Quaternary, which may also have been the case following the migration of the ridge past Lima.

The fact that no coarse material reached the valleys at this time is unlikely to be related to the continued presence of an ice cap over the Andean Cordillera. Klein et al. (1999) showed that the late Pleistocene snowlines in the Central Andes were only 500–1200 m lower than their present 5100 m elevation. If a similar situation existed earlier in the Pleistocene, this would not have restricted river erosion on the lower slopes, even if the glaciers extended down the valleys for another 1000–2000 m. During transgression, on the other hand, accommodation space would have been created towards the interior, preventing coarse material from reaching the present coastal area.

Subsequent relative marine regression must have taken place before deposition of the Lima Conglomerate, as suggested by the complete absence of any marine influence (e.g. beach imbrication) in the exposed part of the Rímac fan along the coast. An eustatic fall in sea level occurred between 1.3 and 0.62 Ma, as shown by oxygen-isotopic data (Quinn and Matthews, 1990; Haddad et al., 1993). At the end of this lowstand cycle, warming and melting of the cordilleran ice cap would have caused the glaciers to retreat, exposing ground and valley moraine and increasing the capacity and competence of rivers transporting this material to the coast. During this time, the Lima Conglomerate was presumably deposited.

After 1.7 Ma, a total uplift of at least 430 m must have occurred in parts of the Rímac-Chillón fan to account for the fact that the upper contact of the basal fine-grained deposits occur at an elevation of 480 m above present sea-level (taking into account the early Pleistocene highstand of 50 m). This implies an elevation rate of about 0.25 mm/year, which is more than twice the general rate of uplift in the Andes (Benjamin et al., 1987). This upper contact, which presumably was horizontal at the time of deposition, declines to below sea level at the coast, indicating that the rate of elevation increased markedly toward the east.

Although the timing of this upwarp in the interior is not known, it does seem to have affected the drainage pattern on the Rímac-Chillón fan. The Chillón migrated toward the western limit of its alluvial plain, whereas the Rímac apparently abandoned its course toward the southeast and made use of the increased westward slope to take a shortcut to the Pacific Ocean.

7. Conclusions

The Rímac and Chillón Rivers eroded deep valleys southeast and east of their present courses, probably during the ca. −50 m global sea-level lowstands of the Late Miocene (ca. 10–5.3 Ma). Erosion was strongly accentuated by uplift caused by the passing Nazca Ridge. Due to the presence of the Lima Anticline, which blocked its direct access to the sea, the Rímac flowed into the Pacific near Morro Solar, but also had a distributary possibly entering the sea near Magdalena. In the Central Lima area, the latter distributary was joined by the main thalweg of the Chillón River. In turn, this river had a secondary distributary entering the Pacific north of Callao, which is presently occupied by the River Rímac. Southeastward migration of the Nazca Ridge allowed subsidence along the coast, which may have coincided with a period of marine transgression at around 1.7 Ma. The resultant transgression caused the deposition of fine-grained sediments in the river valleys, which may thus be partly of estuarine origin.

A slow fall in relative sea level from about 1.3–0.62 Ma allowed deposition of the Lima Conglomerate to take place without marine influence. The release of meltwater and glacial debris during warmer interglacial stades resulted in the deposition of coarse gravels in coalescing alluvial fans. Distal fan deposits at Chorrillos indicate that the Rímac had already commenced to abandon its former main channel along the southeastern border of the alluvial plain at this time. In this area, semi-isolated depressions later formed shallow lakes receiving only overbank fines from the active thalweg to the northwest. The Lima Anticline was probably drowned in sediment with time, lessening its influence on the subsequent drainage pattern so that the thalwegs were free to migrate. Westward tectonic tilting of the landscape possibly accelerated this process, causing the present-day Rímac and Chillón Rivers to occupy the northern and western limits of their alluvial plains.

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References

Arce, J.E., 1984. Estructura geoelectrica del subsuelo Rímac. Chillón. Sociedad Geológica del Perú, Jubilar, LX Aniversario, pp. 1–13.

Benjamin, M.T., Johnson, N.M., Naeser, C.W., 1987. Recent rapid uplift in the Bolivian Andes: evidence from fission track dating. Geology 15, 680–683.

DeVries, T., 1988. The geology of late Cenozoic marine terraces (tablazos) in northwestern Peru. Journal of South American Earth Sciences 1, 121–136.

Chappel, J., Shackleton, N.J., 1986. Oxygen isotopes and sea level. Nature 324, 137–140.

Dewey, J.F., Lamb, S.H., 1992. Active tectonics of the Andes. Tectonophysics 205, 79–95.

Dobrovolny, E., 1962. Geología del Valle de La Paz: Bolivia. Boletín Departamento Nacional de Geología, vol. 3, 153pp.

Flint, R.F., 1971. Glacial and Quaternary Geology. Wiley, New York (892pp.).

Gonzalez, E., et al., 1965. Late Quaternary glacial and vegetational sequence in Valle de Lagunillas, Sierra Nevada del Cocuy, Colombia. Leidsche Geologische Mededelingen 32, 157–182.

Gradstein, F., Ogg, J., 1996. Geological time scale. Episodes, 19.

Klein, A.G., Seltzer, G.O., Isacks, B.L., 1999. Modern and last local glacial maximum snowlines in the central Andes of Peru, Bolivia and Northern Chile. Quaternary Science Reviews 18, 63–84.

Haddad, G.A., Droxler, A.W., Kroon, O., Muller, D.W., 1993. Quaternary $CaCO_3$ input and preservation within Antarctic intermediate water: Mineralogic and isotopic results from Holes 818B and 817A, Townsville Trough (northeastern Australia margin). Proceedings of the Ocean Drilling Program: Scientific Results, Ocean Drilling Program, 133, Texas, pp. 203–233.

Hsu, J.T., 1988. Emerged Quaternary marine terraces of southern Peru: sea level changes and continental margin tectonics over the subducting Nazca Ridge. PhD thesis (unpublished), Cornell University, 310pp.

Karakouzian, M., Candia, M., Watkins, M.D., Wyman, R.V., Hudyma, N., 1996. Geology of Lima, Peru. Geotechnical aspects. Boletín Sociedad Geológica del Perú 85, 27–59.

Klein, A.G., Seltzer, G.O., Isacks, B.L., 1999. Modern and last local glacial maximum snowlines in the central Andes of Peru, Bolivia, and Northern Chile. Quaternary Science Reviews 18, 63–84.

Lanning, E.P., Patterson, T.C., 1967. Early man in South America. Scientific American 217, 44–50.

Le Roux, J.P., 1991. Palaeocurrent analysis using Lotus 1-2-3. Computers and Geosciences 17 (10), 1465–1468.

Le Roux, J.P., 1992. Determining the channel sinuosity of ancient fluvial systems from paleocurrent data. Journal of Sedimentary Petrology 62 (2), 283–291.

Le Roux, J.P., 1994. The angular deviation in circular statistics as applied to the calculation of channel sinuosities. Journal of Sedimentary Research A 64, 86–87.

Lisson, C.I., 1907. Contribución a la Geología de Lima y sus Alrededores. Libreria e Imprenta Gil, Lima.

Macharé, J., Ortlieb, L., 1992. Plio-Quaternary vertical motions and the subduction of the Nazca Ridge, central coast of Peru. Tectonophysics 205, 97–108.

Moretti, I., 1982. Subduction des rides aséismiques. PhD thesis, Univ. Paris XI, Orsay, 107pp.

Nemec, W., Steel, R.J., 1984. Alluvial and coastal conglomerates: their significant features and some comments on gravely mass-flow deposits. In: Koster, E.H., Steel, R.J. (Eds.), Sedimentary Gravels and Conglomerates. Canadian Society of Petroleum Geologists, Memoirs, vol. 10, pp. 1–31.

Ortlieb, L., Macharé, J., 1990. Quaternary marine terraces on the Peruvian coast and recent vertical motions. Symp. Intern. Géodynamique Andine, ORSTOM, Paris, pp. 95–98.

Prentice, M.L., Matthews, R.K., 1988. Cenozoic ice volume history: development of a composite oxygen isotope record. Geology 16, 963–966.

Quinn, T.M., Matthews, R.K., 1990. Post-Miocene diagenetic and eustatic history of Enewetak Atoll: model and data comparison. Geology 18, 942–945.

Rohling, E.J., Fenton, M., Jorissen, F.J., Bertrand, P., Ganssen, G., Caulet, J.P., 1998. Magnitudes of sea-level lowstands of the past 500 000 years. Nature 394, 162–165.

Stein, S., Engeln, J.E., De Meto, C., Gordan, R.G., Woods, D.R., Lundgren, P., Argus, D., Quibble, D., Stein, C., Weistein, S., Wiens, D.A., 1986. The Nazca-South America convergence rate and the recurrence of the great 1960 Chilean earthquake. Geophysical Research Letters 13, 713–716.

Teves, N., 1975. Aspectos sedimentarios y estructurales del sector costanero peruano frente a la dorsal de Nazca. Boletín del Sociedad Geología de Perú 50, 87–98.

Williams, D.F., 1990. Selected approaches of chemical stratigraphy of time-scale resolution and quantitative dynamic stratigraphy. In: Cross, T. (Ed.). Quantitative Dynamic Stratigraphy. Prentice Hall, Englewood Cliffs, NJ, pp. 543–565.