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Geomorphological evolution of the Rimac River's alluvial fan, Lima, Peru

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ABSTRACT: The alluvial fan of Lima is a complex landform, resulting from the sediment contributions of the Rimac River and the coalescence of the alluvial fans of the tributaries of the Rimac River. Depositional zones in the fan and changing main channel and distributary channels are influenced by the palaeo-relief inherited from a semi-arid climate and by the climatic changes. The upper sedimentary sequence of the fan, dominant on the Costa Verde, is of Upper Pleistocene–Holocene age. The sediments forming it are non-cohesive and are highly mobile during floods and earthquakes. The dominant features in this sequence, intertwined channel facies and laminar flows, were influenced by the Pleistocene–Holocene postglacial marine transgressions. A deeper understanding of the evolution of the Lima alluvial fan provides insight in to the fan's future evolution in the framework of active tectonics and climate change. The Lima fan is an area with high human population density and is subjected to floods and debris flows resulting in subsequent loss of human life and properties. Therefore, the improved understanding of the fan's evolution, resulting from this study, will contribute to a better definition of high risk areas of potential human disaster caused by these natural processes. Cyclic-fan-development, presently controlled by glacial sea level lows and palaeo-topography will continue regardless of human intervention in attempts to prevent natural disasters in Lima.

Key words: Holocene, Andean tectonics, marine transgression, climate change, geomorphology

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1. INTRODUCTION

Alluvial fans occur at the change in grade between lowlands and highlands (Birch et al., 2016). The Rimac River alluvial fan is in the central and western part of Peru where the Rimac River emerges from is fault-controlled alignment in the steep Andes onto the low lying coastal plain. Metropolitan Lima is located on the alluvial fan and almost 31% of the Peruvian human population live in this region (INEI, 2014) where earthquakes, floods and landslides have resulted in large losses of human life. Lima's alluvial fan is derived from the Rimac and Chillon Rivers.

In Peru, the continuous movement of the Nazca Plate resulted in subsidence and a marine transgression during the Pleistocene about 1.7 M.a. followed by uplift and cyclic marine regression/transgression (Le Roux et al., 2000).

To explain the succession of events resulting in the formation of the present-day alluvial fan, the convergence of multiple factors must be understood. The main alluvial fan depositional controls in tectonically active regions are topographical relief and structural geology as confirmed in several studies (Steel et al., 1977; Heward, 1978a, b; Rockwell et al., 1985; Nichols, 1987; Harvey, 1989; Casas, 1995). Substrate lithology of the topographic relief is another significant determinant of alluvial fan morphology (Colombo, 2010). Large alluvial fans reflect continuous sedimentation processes contributed from smaller systems, characteristic of many mountain environments (Brunsden et al., 1981; Saito and Oguchi, 2005).

The evolution of the Lima fan is well described from the

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Pliocene to the mid-Pleistocene (Le Roux et al., 2000). It is likely that tectonic uplift of 17 Ma BP and following cyclic eustatic sea level changes have set the template for fan morphological changes during the Late-Pleistocene and Holocene. Therefor this study focuses on evolution of the fan from Late Pleistocene to present. Based on this the objectives of the study are: 1) to confirm the main role of the Andean tectonics in the configuration of the Fan of Lima; 2) to establish the role of alluvial processes in the basin history and 3) assign chronology to the temporal development of the fan.

2. THE STUDY AREA

The Rimac River basin has a surface area of 3,300 km^2, and a length of about 160 km. Its headwaters rise in the highest peaks of the Western Cordillera of the central Andes, about 5,000 meters above sea level (Fig. 1).

2.1. Geology

The most important post-orogenic unit that appears in the substrate of the fan is represented by the clastic and volcanic deposits of a series of extensional and transtensional basins in the Cretaceous (Palacios et al., 1992; Aleman et al., 2006). The basal stratigraphic column unit of the Lima's alluvial fan substrate, comprises pyroclasts, volcanic breccias and lavas from the Puente Piedra Group; sandstone and shale of the Morro Solar Group; as well as calcareous limestones, marls and calcareous siltstones of the Lima Group. This sedimentary sequence represents continental and marine sequences occurring in the chrono-stratigraphic interval of the Upper Jurassic–Lower Cretaceous. The sequence concludes with pyroclastic breccias from the Chilca Formation of Upper Cretaceous age. Post-sedimentary intrusions of the plutonic complexes of Coastal Batholith of Peru with ages between 84 and 102 million years are observed within the Lima City region (Ramos and Aleman, 2000; Scherrenberg et al., 2014).

Overlaying basal units are sediments of gravitational, alluvial and aeolian origin. The pre-existing valleys were probably infilled by these deposits between the late Miocene and early Pliocene (Palacios et al., 1992). In this sense, the facies of the Lima Alluvial Fan suggest deposition in a high-energy environment with cross-linked channels that rapidly became avulsive (Le Roux et al., 2000; Villacorta et al., 2015). Palaeo-drainage systems are visible in the sedimentary sequence in exposed cliff faces of the Costa Verde. These palaeo-drainage systems incised pre-existing basin fill. The influence of Andean tectonics in the central part of South America is well known (Dollfus, 1966; Lecarpentier and Motti, 1968; Cobbing, 1982). Geophysical studies have shown that material deposited by the main channels of the fan reaches hundreds of meters of thickness (Arce, 1984). The thickest sediments are in the palaeo-valleys of the Rimac and Chillon River. These sediments are episodic flood deposits. According to some authors, the sedimentation of conglomerates in the Fan could represent the fluvial reworking of glacial moraines (Le

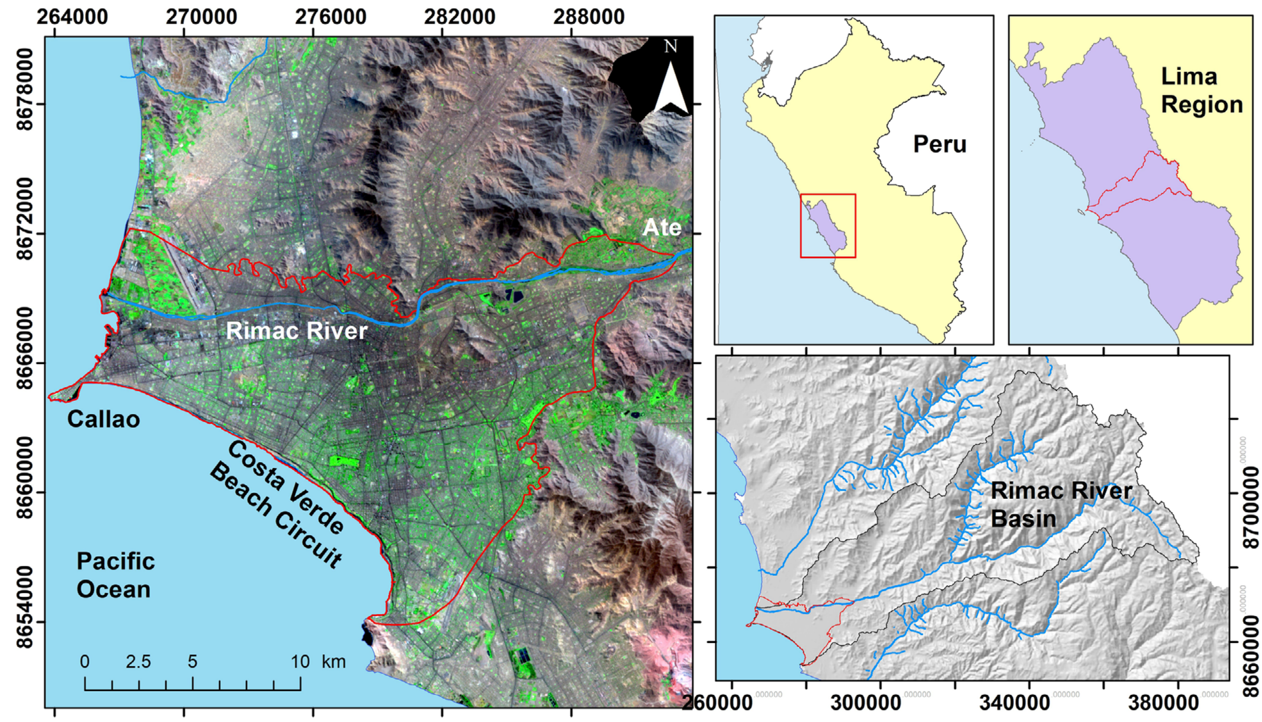

Fig. 1. Location of the study area within the river Rimac basin. Projection UTM Datum Ellipsoid WGS84. 18 S Zone.

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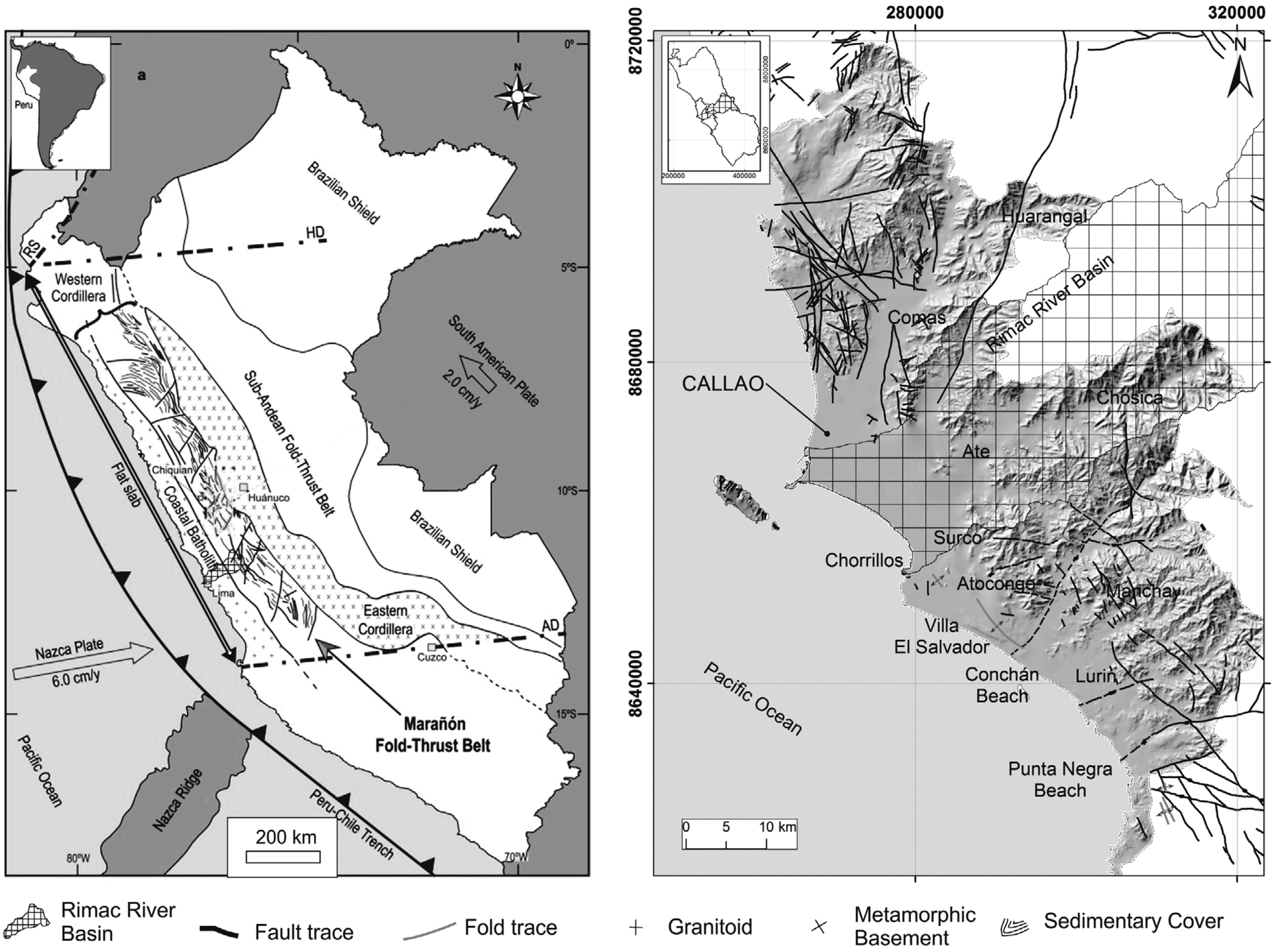

Fig. 2. Compilation of structural systems in Peru and in the study area. Based on Le Roux et al. (2000), Macharé et al. (2009), Scherrenberg et al. (2014), and Villacorta et al. (2015).

Roux, 2000; Aleman et al., 2006; Villacorta et al., 2015).

The longest fault mapped in the area is 24 km long, inferred from a regional lineament with a NE-SW direction, observed to the east of Comas (Fig. 2). The smaller deformation structures (between 2 and 20 km in length) and are also inferred from parallel NE-SE lineaments east of Villa El Salvador and towards Manchay (Macharé et al., 2009). Other structural lineaments with predominant NW-SE, E-W and N-S directions exist between Ancon and Rimac, Pachacamác, and Lurín and in San Bartolo Rivers respectively (Villacorta et al., 2015). Some authors consider that subsidence was continuous during the sedimentation on the alluvial fan and that the faults in the Lima area are still active (Jacay et al., 2000; Jacay, 2013).

2.2. Palaeoclimatic Regime of Central Peru

From the 1970s, there was great debate regarding the occurrence of climate change in Peru during the recent Quaternary, specifically in the early Holocene. Parsons (1970) and Craig (1985), based on geological, geomorphological and palaeoecological data, considered that climatic change in the region was minor and that the region along the Peruvian coast has remained arid during most of the Quaternary. Richardson (1978) and Dollfus and Lavallee (1973) using data from Southwest Ecuadorian Piedmont considered that the climate had been much more humid towards the end of the Pleistocene and during the first half of the Holocene.

The location of the Central Andes within large atmospheric circulation systems explains their climate sensitivity and makes this mountain region a key site for palaeo-climatic reconstruction (Kanner et al., 2013) because they modulate atmospheric circulation at meso-planetary and planetary scales (Seluchi et al., 2006).

The variability of the climate system over the Central Andes, to a large degree, is due the frequency and intensity of the El Niño-Southern Oscillation (ENSO); to the surface temperatures of the tropical Pacific and the Atlantic and, according to Perry et al. (2014), other factors that are still unknown.

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The largest upwelling system in the world, which has a cooling effect on ocean waters, lies along the Pacific west coast of Peru and neighbouring countries influencing aridity (Alfaro et al., 1998; Chavez et al., 2008). Some researchers have assumed that, during glacial periods, the Humboldt Current was strengthened and extended further north than at present (Simpson, 1975; Simpson et al., 1978; Webb, 1978). Other authors have proposed that, during the postglacial period at the end of the Pleistocene and early Holocene, it was weakened and diverted to a more north westerly and northern position (Uceda, 1986; Chauchat, 1987). According to DeVries (1997), it seems unlikely that the Eastern Pacific circulation system has undergone major changes during the latest climate fluctuations. The available data on the faunistic composition of the raised marine terraces, locally known as "tablazos" of the Peruvian northwest (DeVries, 1988) suggest that the biogeographic limit that is currently observed near Paita has remained at least during the interglacial stages of the last million years. However, temporal variations in the Humboldt Current can't be dismissed, especially during glacial–interglacial transitions (Ortlieb and Macharé, 1989).

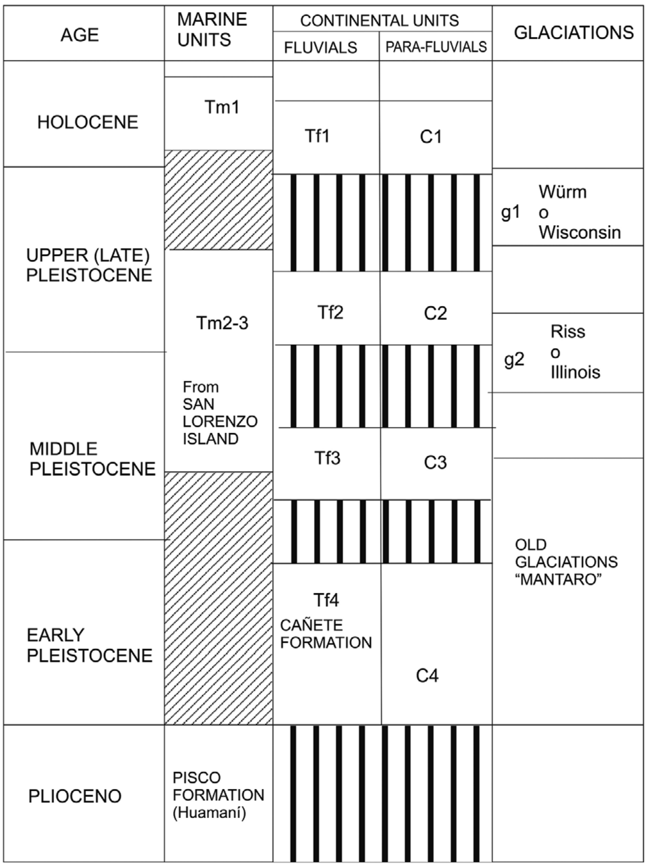

Fig. 3. Schema of the Glaciation in Central Peru correlated with glaciations in Europe and North America. Tm1 represents the set of Holocene sea levels. Fluvial terraces (Tf) and accumulations of sporadic debris flows (C) are numbered from most recent to oldest. Note that the terrace Tf1 correlates with the moraines of the last glaciation g1 and that there is a similar relationship between Tf2 and the moraines of the penultimate glaciation Sebrier and Macharé (1980).

According to their geomorphological studies in Asia, Cañete (south of Lima) and the Chillon River (north of Lima), Dollfus (1964) and Sébrier and Macharé (1980) describe different levels of alluvial terraces associated with interglacial periods in Central Peru (Fig. 3). These researchers also point out that the presence of wind forms in the cones of sporadic detrital flows indicates that, despite increased rainfall, the prevailing conditions resulted from an arid desert. The study of the oldest deposits (Cañete Formation in that area) suggests an identical conclusion, that is, arid/desert conditions persisted throughout the Quaternary. During the latter part of the Quaternary, sea level changes have impacted sedimentation in marine embayments globally (Evans et al., 1992). Cyclic periods of glaciation during the Quaternary have resulted in eustatic adjustments to sea level. Superimposed on eustatic sea level change are tectonic, hydro-isostatic adjustment, and climatic factors which adjust sea level locally (Thom and Chappel, 1978; Chappell, 1983). Since 500 ka BP there have been possibly 5 major global postglacial sea level transgressions (Rohling et al., 1998) preceded by glacial sea levels dropping to approximately 150 m lower then present. From the sea level curve of Rohling et al. (1998), the most significant of these cycles commenced at about 185 ka BP when at the end of the interglacial highstand sea level began to regress over a period of 50 ka to a sea level of about –150 m. There was then a rapid postglacial transgression over 2 ka to a brief highstand at a sea level similar to the present for a relatively short period of 1 ka followed by a long slow regression of about 100 ka to about –120 m at 18 ka BP. During these periods of sea level regression, the loci of deposition for rivers debouching to the sea moved in a seaward direction. Therefore, these rivers incised the subaerially exposed sea floor creating valleys and increasing their length. During subsequent sea level transgressions during interglacial periods, the valleys were infilled (Evans, 1990). These periods of incision and deposition would have had a large influence on development of rivers on the Peruvian coast and Le Roux et al. (2000) considered they were the major determinant in developing the morphology of the Rimac River. However, based on rainfall levels, the region remained an arid desert during these periods (Sébrier and Macharé, 1980).

A palaeoclimatic interpretation, which was obtained from stable carbon isotope analysis and the % C and C/N ratios in Distichia peat cores extracted from the Nevado Mismi (Arequipa, southern Peru), indicate that warm and humid conditions prevailed in the Andes of southern Peru from 4.3 to 3 ka BP, with a short dry cooler episode at about 3.8 ka BP (Engel et al., 2014). These researchers also identified subsequent climate change between 3 and 2.8 ka BP when initial warming changed into rapid cooling and temperatures of at least 2 °C below the mean for the present were reached. They also indicate that during this period the humidity increased until about 0.8 ka BP when the conditions became relatively dry until a warm and relatively humid period between 0.64 and 0.16 ka BP occurred.

The temporal-spatial patterns of Holocene glaciation show ice advance from the early and mid-Holocene in many regions. However, this may not have occurred in the arid subtropical Andes where records of moraine deposition during the LIA mark the maximum advance of Holocene glaciers (Rodbell et al., 2009).

According to Ortlieb and Macharé (1980), the development of arid alluvial cones in Lima have required more frequent higher-intensity rainfall then occurs today. These rainfall regimes should have been present between the end of each glacial period and the subsequent transgressive interglacial maximum. The period of deglaciation (transition from glacial to interglacial) represents a time of climate instability that favours a weakening of the Pacific anticyclonic zone and therefore occurrences of rainfall in the desert (Betancourt et al., 2000). This event would have occurred between 10,000 (approximate end of the last glaciation) and 6,000 y BP.

With respect to sea level transgression at the beginning of the Holocene, Dollfus (1966) describes two Holocene age marine levels on the Coast of Central Peru: 1) the oldest corresponds to a transgression and was 4–5 m above the present day sea level; and 2) the most recent was 2 m above its present day level.

The oldest one corresponds to the maximum sea level transgression after the most recent glaciation period: the lower Veguian defined by Paskoff, (1970) in the north of Chile and dated to 6 ka BP. In Figure 3, the set of Holocene levels is marked as Tm1. This episode is represented by: abandoned coastal barrier, cliffs, reefs and fossils (Ortlieb and Macharé, 1989).

3. METHODOLOGY AND DATA

Achieving the objectives of this study required an evaluation of: the spatial distribution of the alluvial fan; its relationship with the structural geology of the underlying substrates; the sedimentation history of the fan and the reconstructed palaeo-relief of the fan area. This required: geological and geomorphological mapping through dating, remote sensing, and digital elevation model (DEM) construction.

Geomorphological maps were constructed at a scale of 1:10,000,

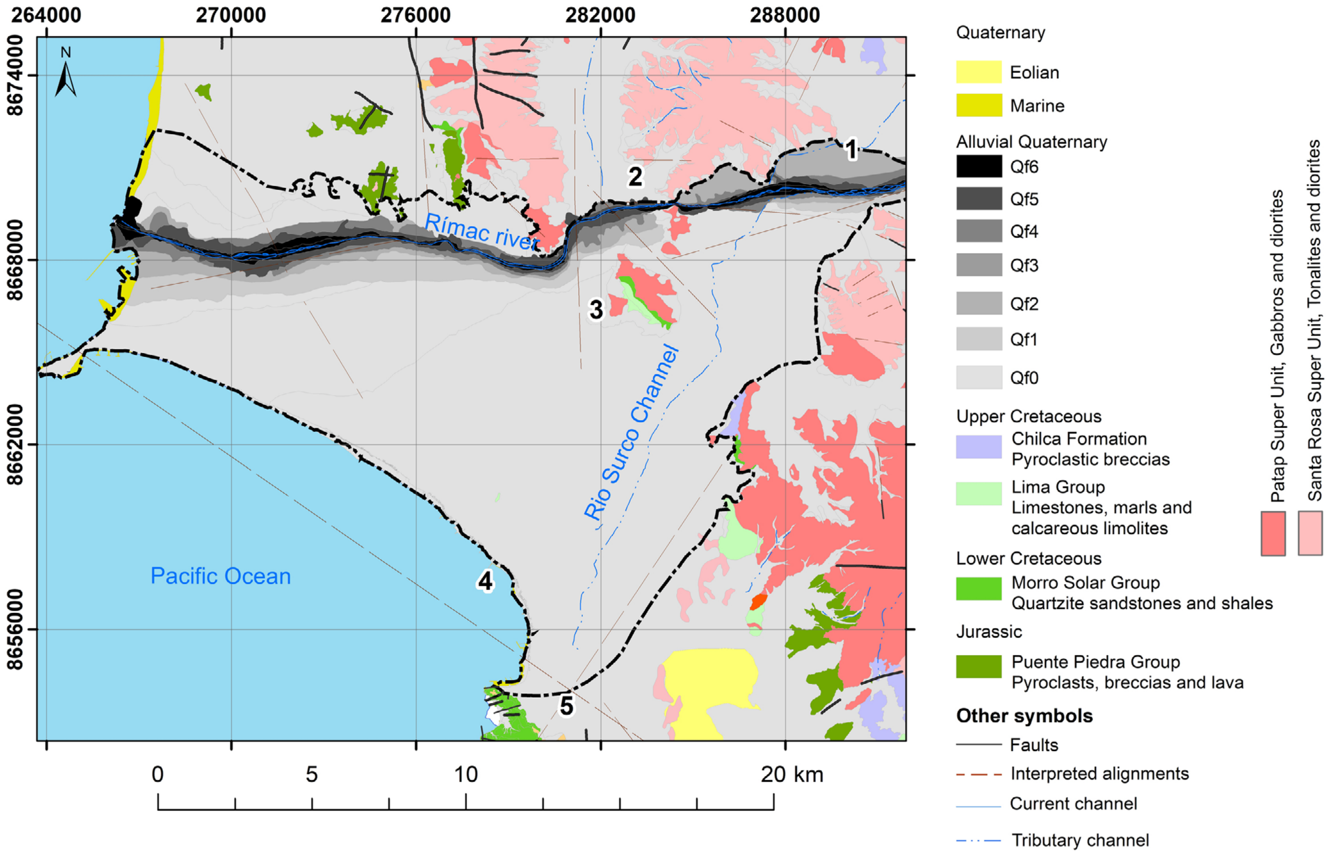

Fig. 4. Generalized geological map of the Lima fan and surroundings showing the structures have been interpreted. Localities which are referred to in the text. 1: Huachipa, 2: San Juan de Lurigancho, 3: El Agustino Inselberg, 4: Santa Anita district, 5: Costa Verde Beach Circuit, 6: Morro Solar, 7: San Juan de Miraflores district.

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using a GIS database and a high-resolution DEM from Pleiades satellite imagery.

To interpret the relationships between drainage patterns, sediment lithology and substrate geological structure, a new geological map was compiled (Fig. 4), based on unpublished geological data provided by the Peruvian Geological Mining and Metallurgical Institute (INGEMMET), field mapping, stereoscopic analysis, satellite imagery analysis and morphometric mapping. A new structural map of the study area was developed using Landsat 742 image interpretation, an evaluation of a DEM of the area provided by the National Commission for Aerospace Research and Development (CONIDA), and field work.

For Optically Stimulated Luminescence (OSL) dating some samples were recovered from different outcrops of fluvial-alluvial deposits of the Lima's fan. The selected methodology has followed the protocol proposed by Aitken (1985) which indicates that it is most important to choose representative profiles in a sampling area where external material exposed to the sun's rays, is cleaned away (extracting at least 10 cm). Then, the sediment is extracted at different depths (terrace levels) and samples are protected from sunlight during their transfer to the laboratory.

4. RESULTS

4.1. Geological and Geomorphological Mapping

The geological and geomorphic mapping identified unknown lineaments that are covered by recent deposits and urban expansion. NW-SE lineaments were identified towards the north of the Lima Fan in the Callao district crossing the Rimac River towards San Miguel. Eastwards, several NW-SE alignments (e.g., near of El Agustino inselberg, Fig. 5) were identified along the apex of the Lima Fan. Other lineaments extended in a NE-SW controlling the direction of the upper tributaries of the Rimac River (Canto Grande ravine and Huaycoloro River). Two long NEE-SWW lineaments are responsible for the direction of the Rimac River course and a N-S lineament has modified the course of the Rimac River near the Canto Grande district. This mapping is schematically represented in Figure 4.

The area occupied by the Lima Fan, is characterized by the

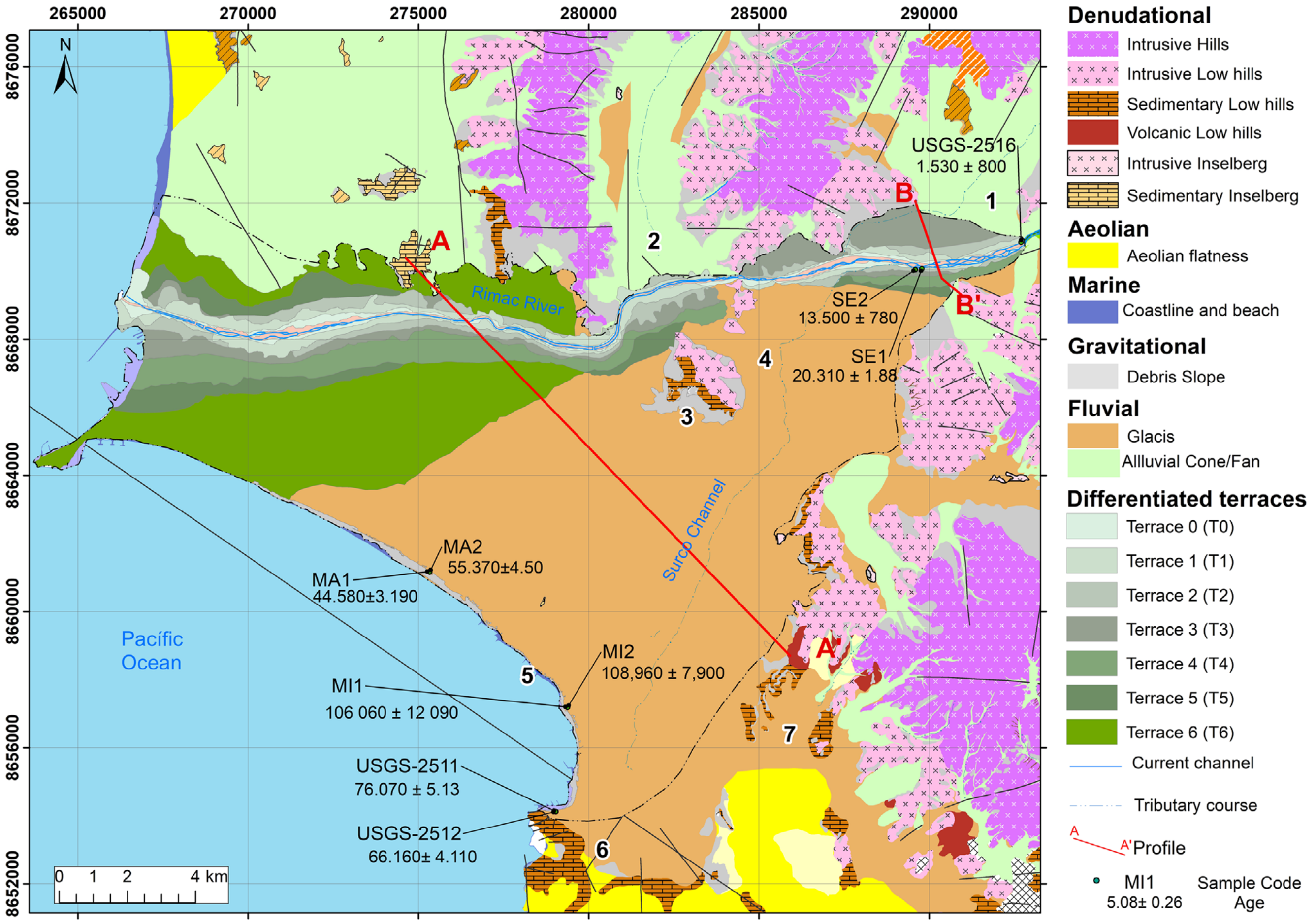

Fig. 5. Geomorphological mapping of the Lima Fan area. 1: Fan apex, 2: Canto Grande ravine, 3: El Agustino Inselberg, 4: Santa Anita district, 5: Costa Verde Beach Circuit, 6: Morro Solar, 7: San Juan de Miraflores district.

presence of palaeo-channels infilled with poorly sorted (2–3 cm to 40–50 cm), and polymictic sediments (clasts mostly plutonic) including gravels, sands and shales. They are unconsolidated and among other structures, imbrication and other fluvial structures appear (Figs. 8c–e). These materials vary in thickness ranging from 10 to 300 m where deposits overlay the Rimac-Chillon palaeo-channel. The Lima Fan covering an area of approximately 216 km^2, asymmetrically triangular shaped and is orientated in the direction of the tilting related to the subduction of the Nazca plate under the South American plate (Le Roux et al., 2000; Aleman et al., 2006). The fan is truncated by the effect of the marine action, resulting in shore-line cliffs.

The apex of the Fan is in the foothills of the Western Cordillera, near the town of Ate (Figs. 5 and 6) about 20 km from the coast. The distal zone is truncated by the effect of the marine action; giving rise to the Costa Verde cliffs between 30 and 90 m high (Figs. 6 and 9 [1st]). The cliffs of the Lima Fan (Costa Verde cliffs, Fig. 8a), extend for about 21 km along the coastal strip with altitudes in the order of 80 m AMSL in its central area (Miraflores and Larcomar areas).

Between El Agustino and Santa Anita districts, the Fan sediments are interrupted by the cropping out of sedimentary rocks of the Lima Group as seen in El Agustino, El Pino and La Atarjea hills (Fig. 6). In this area the Lima Group is confined by inselbergs with corestones in the progress developing.

In areas of metropolitan Lima, six levels of terraces have been identified along the Rimac River (profile A–A', Figs. 4 and 7). In the south (in the areas of San Juan de Miraflores, Villa El Salvador and Chorrillos districts) there are proglacial and sandy deposits forming dunes and sand sheets (Fig. 5).

4.2. OSL Dating

Nine samples were collected (Table 1, Fig. 5) for OSL dating by the US Geological Survey laboratories in Denver, Colorado. The ages determined using OSL techniques range from 110 to 1.5 ka BP allowing definition of a Pleistocene–Holocene age for the alluvial fan.

5. UPPER-PLEISTOCENE TO HOLOCENE EVOLUTION OF LIMA FAN

The evolution of the present-day alluvial fan was controlled by the palaeo-topography and structural geology. Originally, the

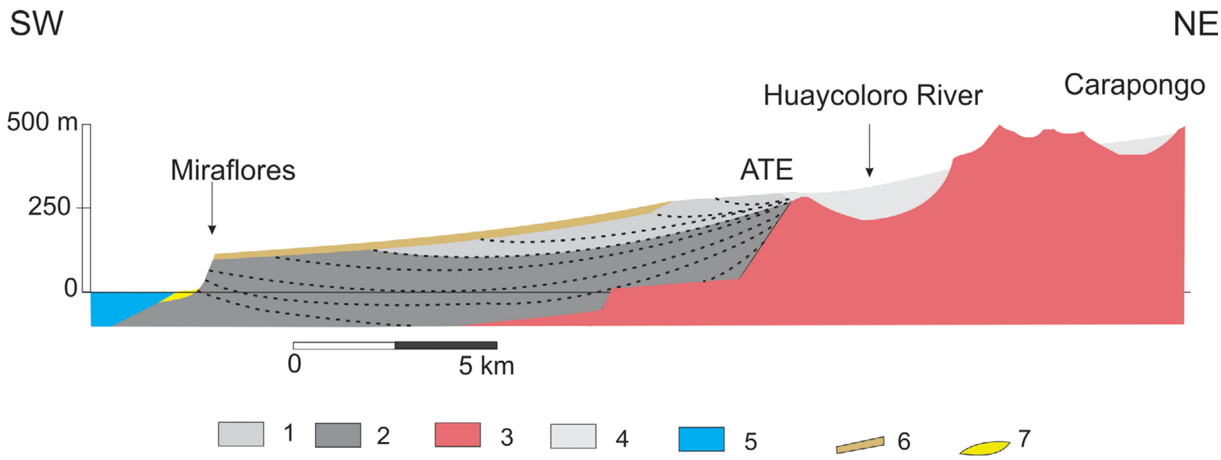

Fig. 6. Longitudinal profile of the Lima Range from Carapongo to Miraflores. 1: Holocene materials (Qf6, Qf5), 2: Pleistocene materials (Qf4 to Qf0), 3: Intrusive substrate, 4: Debris flows sporadic deposits, 5: Pacific Ocean, 6: Glacis, 7: Beach deposit (see Figs. 9 and 10).

Table 1. Calculated age and OSL dating parameters

Code	Field site	Geological unit	Depth (m)	Total Dose (Gy/ka)	Equivalent Dose (Gy)	Age (yrs)
MI1	Miraflores	T6 (Qf0)	9.6	2.97 ± 0.07	315 ± 35	106.060 ± 12.090
MI2	Miraflores	T6 (Qf0)	11.5	2.79 ± 0.11	304 ± 20	108.960 ± 7.900
USGS-2511	Regatas (Chorrillos)	T5 (Qf1)	15.6	3.97 ± 0.16	302 ± 14	76.070 ± 5.13
USGS-2512	Regatas (Chorrillos)	T5 (Qf1)	14.6	4.61 ± 0.15	305 ± 21	66.160 ± 4.110
MA1	Magdalena	T4 (Qf2)	8.6	4.24 ± 0.14	189 ± 12	44.580 ± 3.190
MA2	Magdalena	T4 (Qf2)	8.5	4.75 ± 0.14	263 ± 20	55.370 ± 4.50
SE 1	Sedapal (ATE)	T2 (Qf4)	4.5	4.91 ± 0.14	66.3 ± 3.3	13.500 ± 780
SE 2	Sedapal (ATE)	T2 (Qf4)	4.5	4.47 ± 0.14	77.8 ± 3.9	20.310 ± 1.88
USGS-2516	Sedapal (ATE)	T1 (Qf5)	1.5	5.04 ± 0.12	7.71 ± 4.0	1.530 ± 800

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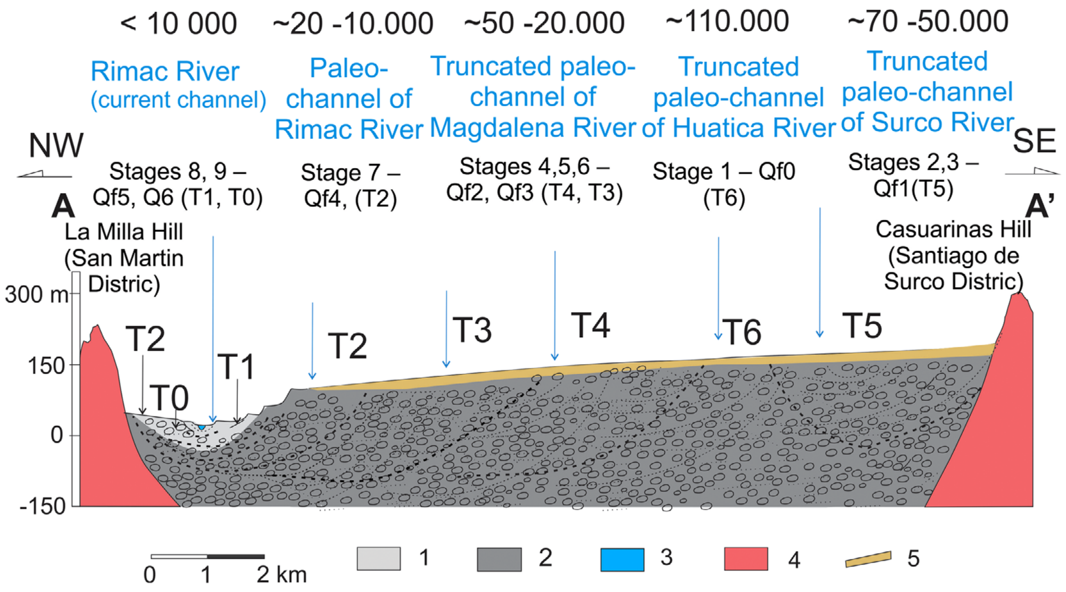

Fig. 7. Schematic cross-section showing the segments of alluvial fans. T0 to T6: river terraces. 1: Holocenematerials, 2: Pleistocene materials, 3: Current channel, 4: Intrusive substrate, 5: Glacis.

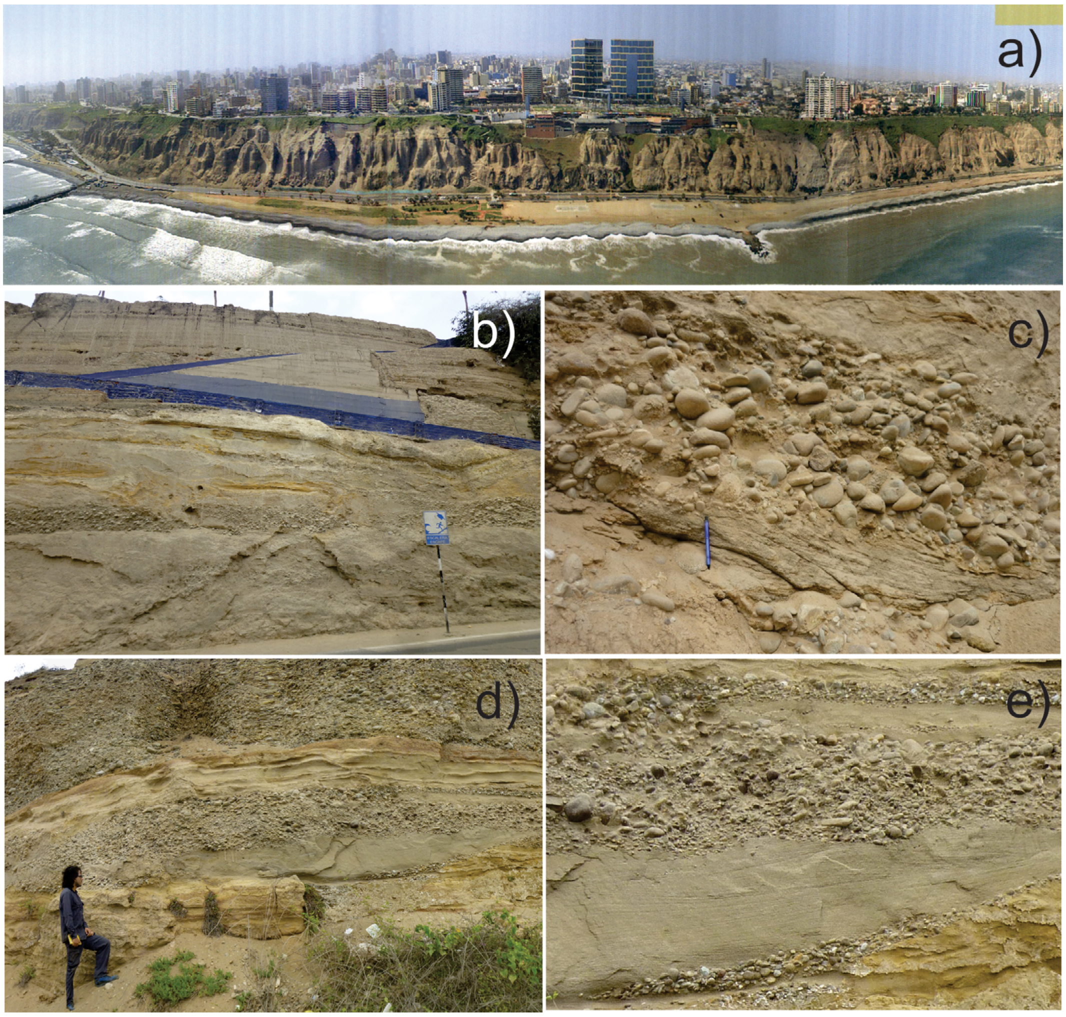

Fig. 8. (a) Panoramic view of the Costa Verde cliffs where the truncated distal fan is observed (Mixmade, 2008). (b) Club Regatas (Chorrillos district), with fining up deposits. (c) Conglomerate facies with lenticular bodies. (d) Transgressive marine facies in Armendariz stream (Barranco district). (e) Detail of the ripples observed in sandy lenticular bodies that migratde towards the interior of the deposit.

Rimac River course had a NE-SW alignment near the southern boundary of the present-day fan with its mouth at Morro Solar. The river has migrated northwards aggrading the fan to the south as it moved to its present-day E-W aligned position. There are several palaeo-channels to the south of the present-day Rimac River: Surco River, Huatica River, Magdalena River, Maranga River and La Legua River. They correlate to different avulsion periods as the Rimac River migrated to the north. They appear as infilled palaeo-channels in the southern fan now covered by housing developments. The southern area of the fan evolved into an erosive glacis also covered by housing developments. The depositional pattern of the alluvial fan is very complex and, based on geophysical data, the morpho-structural regionalization and the lineaments, it is categorised into nine stages of development and formation (Figs. 7 and 9).

5.1. 1st Stage - Qf0 (~110 ka BP)

During the first stage (Fig. 9 [1st]), Qf0 sediments were deposited in the southern part of the fan controlled by fault strike direction and relief comprising indurated sedimentary rocks of Cretaceous ages and Eocene–Miocene intrusive rocks (Fig. 5). Deposition occurred during the sea level regression linked to the Würm Glaciation as described by Clayton et al. (2006). South of Lima, at Miraflores district, Qf0 was sampled at sites MI1 and MI2 at depths of 9.6 and 11.5 m and obtained ages were from 106 ± 12.1 and 109 ± 7.9 ka BP. Qf0 comprises fluvial deposits (quartz and feldspar sand with silt) and is exposed as river terrace 6 (T7) (Figs. 7 and 9) near Memory Museum (Miraflores district).

To the north of the Rimac River, Qf0 sediments interfinger with contemporaneous sediments from Chillon River (Sébrier and Macharé, 1980). Huaycoloro River, a palaeo-right bank tributary of the Rimac River and Canto Grande ravine deposited sediments to the northeast edge of the fan. South of the present-day Rimac River channel, a palaeo-channel deposited Qf0 sediments and the sediment thickness suggests this sediment eventually mixed with Qf2 deposits near Magdalena (Fig. 7).

5.2. 2nd and 3rd Stages - Qf1 (70 to 50 ka BP)

During the second stage (Fig. 9 [2nd]), deposits of Qf1 (USGS-2511 and USGS-2512 samples) were deposited in the southern edge of the fan (near the Regatas Club in Chorrillos District). These materials were sampled at the sea cliff at depths of 15.6 and 14.6 m (from the top) and were dated as 76.1 ± 5.1 and 66.2 ± 4.1 ka BP (Fig. 5).

Approximately 5 km north of Magdalena, near the coast, sediments appear at 500–600 m depth thinning eastward along the Rimac-Chillon palaeo-channels in abroad and deep palaeo-valley. To the NW and SE, the palaeo-valley sediments thin laterally to the south of the thickest sediments.

During 3rd stage, activity from NW-SE fault was reflected in changes in the course of the Rimac River. As a result, the course of the Rimac River bed migrated to the north, isolating parts of Qf0 and Qf1 (Fig. 9 [3rd]).

5.3. 4th, 5th and 6th Stages - Qf2 and Qf3 (50 to 20 ka BP)

During stage 4, Qf2 (T4) was deposited (MA1 y MA2, depths = 8.5 and 8.6m, ages = 44.580 ± 3.190 and 55.370 ± 4.50 ka BP). River palaeo-channel sediments (Qf2) were aggrading on both right and left banks and by reworking of previous sediments (Figs. 7 and 9 [4th]).

In this period, the Rimac River channel continued migrating northwards with a general SW flow direction eroding and reworking right bank sediments of its earlier stages and deposition of sediments on the central area of the fan occurred. During this period the palaeo-river mouth was at Magdalena disctrict (Figs. 7–9 [4th]) and infilled with Qf2 sediments. At this stage, a probable marine transgression resulted in reworking and truncating right bank sediments aggrading the fining upwards segment Qf3 (river terrace T3).

During the 5th stage, the Rímac River channel continued to migrate northward with a general direction of SW flow eroding and reworking the sediments of its previous stages, leaving palaeo-riverbeds abandoned in central Lima (Fig. 9 [5th]). Erosion continued in the southern area of the fan while the glacis continued to form.

During stage 6 (Fig. 9 [6th]), a possible flood event caused channel infill and abandonment (Surco, Huatica and Magdalena Rivers) indicated by the nature of deposits (boulders, gravel, fine sand, silts, and clay) found in the profile located at Tokyo-Los Laureles site (ATE district), which are different from those observed further west. The clast orientations marked different palaeo-current directions indicating the location of the contact between Rímac River deposits and the Huaycoloro River's over-bank flood deposits (Fig. 7).

5.4. 7th Stage - Qf4 (20 to 10 ka BP)

During the 7th stage of evolution, Qf4 (river terrace T2) was deposited to the north of the 6th stage deposits, Qf3 (Fig. 9 [7th]). At present, small remnants of Qf4 can be recognized in the areas near the Rimac River, in the northernmost part of the study area, along the northwest side of La Milla Hill (San Martin district) and Ramiro Priale Avenue (San Juan de Lurigancho district). In this last sector, Qf4 was sampled at a depth of 4.5 m (SE1 and SE2) and ages of 13.5 ± 780 and 20.3 ± 1.8 ka BP were

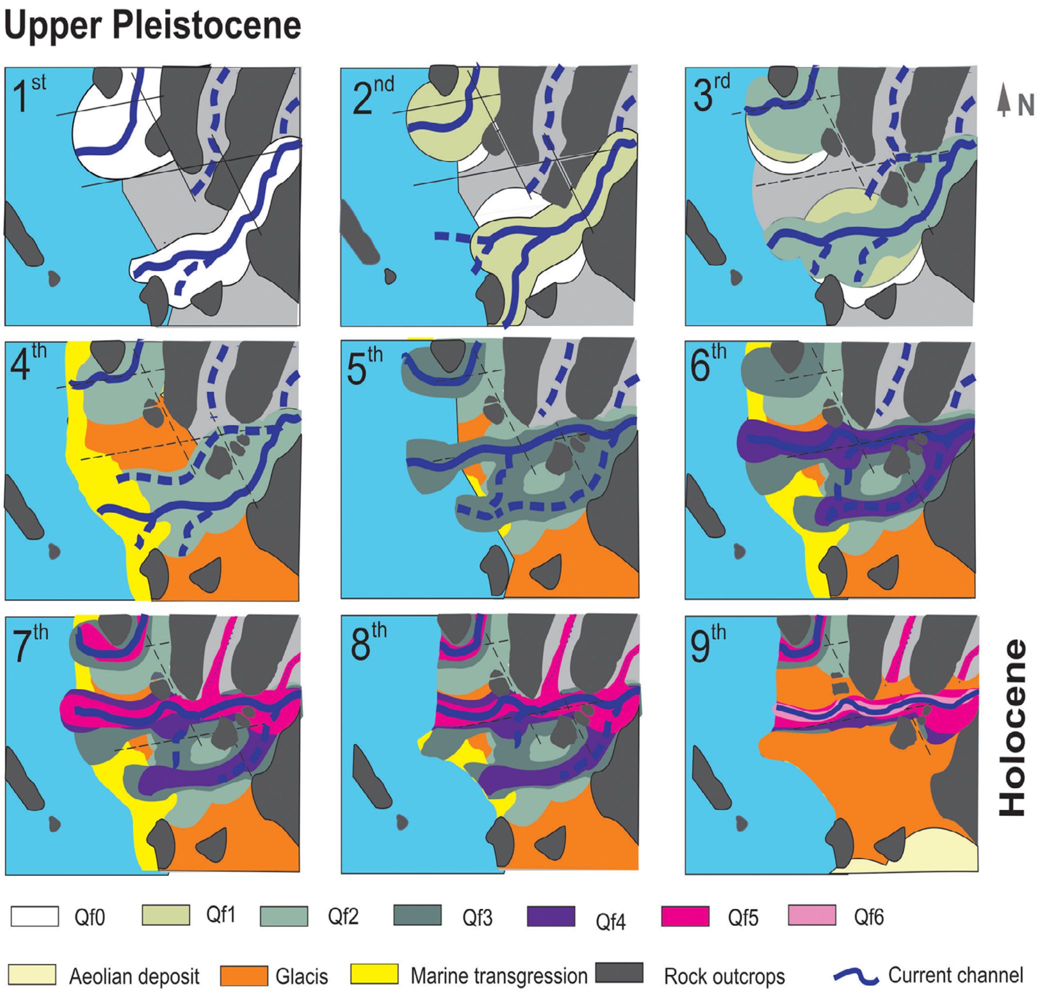

Fig. 9. Different stages of Lima alluvial fan development (1st, 2nd, and 3rd). Sedimentation of the fan segment Qf1, on the surface of Qf0 at southern edge of alluvial fan (Chorrillos-Miraflores) (4th, 5th, and 6th). Deformation by a NW-SE fault affected outcrops that controlled the Rimac River course and sedimentation of fan segment Qf2. Migration of the Rimac river bed and sedimentation of the fan segment Q3 isolating remains of the Qf2, Qf1 and Qf0 segments (7th). Sea deposit in the Holocene by rising sea level. Deposition of segments Qf4 and Qf5 and formation of glacis towards the south of the fan. The Qf4 segment is fed mainly from the east (Rimac River), but it borders with sediments from Chillon River in the North and to the north-east by Huaycoloro River and Canto Grande ravine. Formation of glacis towards the south of the fan and positioning of a wind deposit (8th and 9th). Clogging of channels and abandonment of the paleochannels of Surco, Huatica and Magdalena rivers by events of exceptional floods (deposit Qf6). consolidation of glacis at south continued.

obtained Coalescences of channels occurred during large flood events and isolation of previous palaeo-channels on the southern fan.

5.5. 8th and 9th Stages - Qf5 and Qf6 (10 ka BP to present)

Stage 8 started at the beginning of the Holocene and corresponds to more recent active fan deposition with an east-west orientation (Fig. 9 [8th]). Some deposition events were developed during humid phases in this stage. For example, those sediments sampled on terrace T1 (Qf5, USGS-2516, depth: 1.5 m, age: 1.5 ± 0.8 ka BP), which are correlated with those described by Engel et al. (2014).

The presents a surface dissected by the current Rimac River can be correlated with the lower terrace of that River as possible meander abandonment around the El Agustino inselberg. The Formation of a glacis continued towards the south of the fan also with accumulation of Aeolian deposits.

Based on OSL ages, in spite of the limited number of samples (Table 1), the period of deposition in stages 5 and 6, was about 0.8 ka on average and stages 1 to 4 also had similar depositional periods –0.7 to 1 ka on average. However, the sediment depositional area and depth for Qf0 (T6) to Qf4 (T2) are considerably more extensive than those of Qf5 (T1) and Qf6 (T0). This indicates a decrease in sediment transportation and deposition rates possibly associated with increasing aridity after about 2.5 ka BP resulting in a further deposition shortening since stage 7 (T1) between 1.7 and 1 ka BP.

During stage 9, The current channel of the Rimac River incises

Qf6 sediments, and its flow is controlled by concrete blocks replacing the active river banks. The constructed canal now drives sediments from their source in the uplands to a prograding delta offshore (Fig. 9 [9th]). Presently Qf6 sediments are deposited laterally by over-bank flow during large floods.

Urbanisation has restricted development of the glacis, but an arid climate persists. Prior to urbanisation the Lima piedmont was developing through erosion and aridity to the south of the fan where its elevation is the highest (Fig. 7).

In Lima the urbanisation on T6 are in zones of high geomorphological risk because the districts are particularly susceptible to large flash floods which have required the construction of dikes. Consequently, the depositional segment Qf6 is restricted to a narrow area near the El Agustino inselberg (Figs. 5 and 9). Deposition in this area, like much of the fan, is slowed by anthropogenic activity. Floods are restricted to the Qf6 and Qf5, affecting houses, buildings and infrastructure on both sides of the Rimac River (mainly the districts of Rimac, ATE and San Juan de Lurigancho). Debris and mud flows from the Huaycoloro River and Canto Grande ravine unleashed in 1987, 1998, 2016 and 2017 demonstrate the susceptibility of modern communities to the devastation caused by high-risk geomorphological features. During the summer of 1998, extreme events affected Lima. The Huaycoloro mud and debris flows impacted streets and houses of downtown Lima (Davila and Valenzuela, 1998). An event occurred in 2017 influence by the occurrence of a “Coastal El Niño” event (ENFEN, 2017). Because of this event, 1 to 2 m of sediment was accumulated near the confluence of the Huaycoloro River and the Rimac River, at Huachipa and the transit of vehicles along the Ramiro Priale Avenue was temporarily interrupted. Consequently, there is the possibility of future events, with potentially catastrophic consequences for those sectors of Metropolitan Lima, due to climate change effects were higher rainfall intensity and glacial lake outburst may result in higher peak discharge in fluvial flooding (Gosling et al., 2011).

6. DISCUSSION

The scarcity of data on recent tectonics has contributed to some misconceptions that the Lima area is less tectonically active compared to other areas of Peru. However, the probability that tectonics will continue to operate here, given the complex geological environment in which it is located, must be considered. Cobbing (1982) used regional structural mapping to deduce that the coastal Lima segment of the central zone of the coastal batholith (Fig. 10), where the Rimac River fan is located, was formed by the collapse of faulted blocks, in the framework of Andean tectonism. The location of lineaments, drainage course changes and varying thickness of fan deposits exposed in the Costa Verde cliff correspond to this theory and are considered evidence that the Fan is tilting towards the north of Lima (Le Roux et al., 2000).

This hypothesis also corresponds to the proposals of Jordan et al. (2001), Hindle et al. (2002) and Le Roux (2012) that the

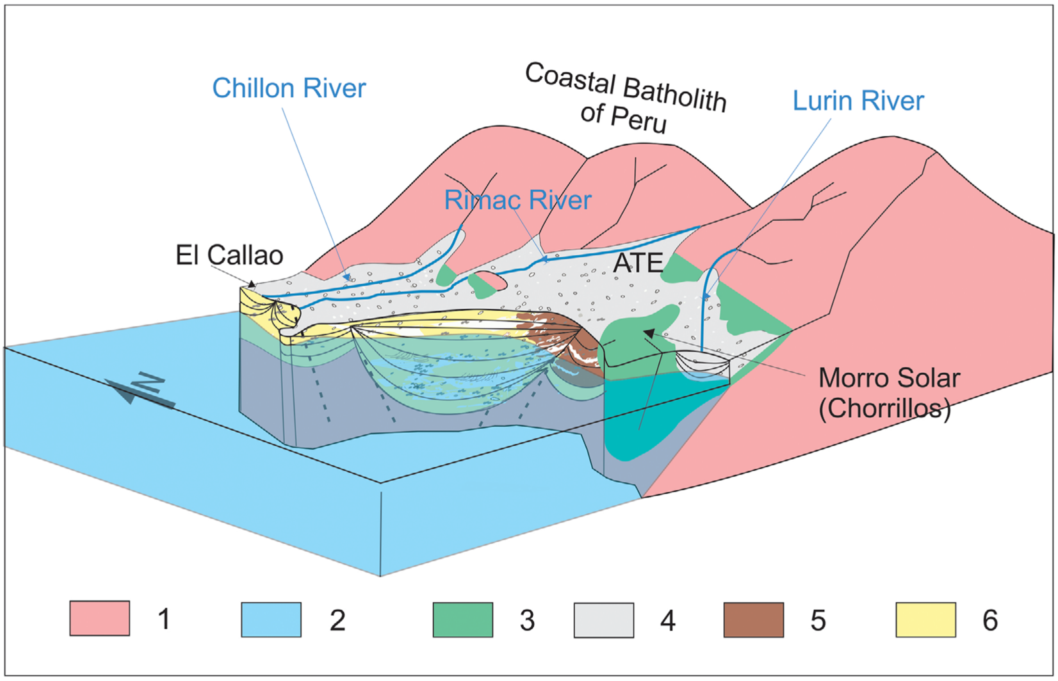

Fig. 10. Schematic block diagram of the study area and surroundings show 1: Eocene–Miocene exhumed intusive rock (intrusions), 2: Pacific Ocean, 3: Jurassic–Cretaceous Outcrops, 4: Quaternary sediments, 5: Clays, 6: Sand and gravel. Not to scale.

Andean uplift influenced the sedimentation patterns of the Pacific slope of South America. San Lorenzo Island could be a remnant of the wall of the large fault running NNW-SSE between San Lorenzo and the Lima coast.

In the Late-Pleistocene there have been well recognised cyclic postglacial marine transgressions. The long (100 ka), steady sea level regression to the most recent sea level low of about –120 m (18 ka BP), would have allowed large scale erosion controlled by the palaeo-topographical template resulting from earlier episodes rise and fall, deposition and erosion. The sea level transgression following the 18 ka BP sea level low would have created a marine embayment with a shoreline at the foot of the Andes with a very narrow coastal plain (Wells, 1992). Sea level reached an almost stable high-stand between 7 and 6 ka BP and then began to fall after 6 ka BP until 3.5 ka BP where it remained constant until about 0.5 ka BP when it dropped about 1 m to its present height (Wells, 1992; Well, 1996; Wells and Noller, 1999) although Dollfus (1966) considered the fall to be about 2 m. During and after the transgression that took place at 7 ka BP, river valleys/canyons, wich were incised during the sea level low, started to in-fill through fluvial deposition and sub-marine deltaic deposition on the sea floor of the marine embayment. During the sea level low (around 15 ka) an indurated sub-aerial plain developed on which the present alluvial fan has developed. Due to the Coriolis effect in the southern hemisphere (clockwise rotation) sea water would have entered the Rimac River estuary/embayment in the north forcing the lighter fresh water of the Rimac River to the south (Valle-Levinson, 2011) resulting in the building of the fan from the south to the north.

The stages 8 and 9 of fan deposition ages suggest that the highest sedimentary sequence of the Lima fan was well developed by about 10 ka BP. In the Holocene stages, there was an increase in frequency of ENSO events between 3.2 and 2.8 ka BP which correlates with a reduction of anthropogenic cultural development (Sandweiss et al., 2001). However there is controversy as to whether ENSO is responsible for aridity in the coastal plane and Western Andes of Peru in the mid-Holocene (Carré et al., 2011). This corresponds with a reduction in deposition rate in the last stages indicating an increase in aridity. There was possibly a further reduction in deposition rate and fluvial flow during stage 8 of the fan that correlates with the mega-drought of 1.3 to 0.9 ka BP identified globally (Kremenetskia et al., 2004; Seager and Cook, 2007; Cook et al., 2016) and a subsequent reduction in erosion and fluvial discharge. The fan is now parallised by urbanisation.

Regarding the age of the Rimac River Fan, Lisson's reference (1907) to Lujanian age: late Pleistocene–early Holocene (Farina et al., 2014) is based on a Pleistocene age molar of *Equus curvidens* (Owen, 1895), discovered on the top of an alluvial terrace. However, the location of the fossil corresponds to the basin of the Mantaro River (next to the Rimac River basin), these data agree with the age obtained in this study of the samples from the fan (exposed in the Costa Verde) of Pleistocene–Holocene age varying from 110 to 2 ka BP. Although the data found in this study confirm the speculations of Aleman et al. (2006) who point out that, because of their sedimentological characteristics, it was possible that the materials on the Costa Verde cliffs were younger members of the fan. It must be considered that only the upper levels of the fan have been sampled and dated. At its thickest point the fan is up to 600 m thick again indicating that the fan sediments must be considerably older than the 100 ka dated in this study, indicating that this fan was already functional before the Pleistocene period.

Le Roux et al. (2000) identified four different stratigraphic units in the conglomerates of the Costa Verde, based on the reconstruction of vertical movements of the Nazca Ridge in the area and deposition would be influenced by the seismic activity of that structure during the Late Miocene–Pliocene (between 10 and 5.3 Ma), which has been interpreted as the cause of the incision of the Rimac River in this sector. In addition, it is necessary to consider the data of Noble et al. (2009), who, based on dating by radio nuclides Ar-Ar of volcanics interbedded with alluvial deposits in Mala (south of Lima) obtained ages of 8 Ma BP and 7 Ma BP (late Miocene). Based on this, Le Roux (2000) proposed that the Fan of Lima could be of the same age. In addition, Noble et al. (2009), used radionuclides Ar-Ar to date volcanics interbedded with alluvial deposits in Mala (south of Lima) and obtained ages of 8 Ma BP and 7 Ma BP (late Miocene) which supports the interpretation of Le Roux et al. (2000).

The Miocene–Pliocene tectonic activity may have formed the Rimac River resulting in deposition of a palaeo-fan but superimposed on this are the Late-Pleistocene major sea level lows and the subsequent postglacial marine transgressions of the Pleistocene and Holocene. In each of the major sea level fluctuations, pre-existing fan deposits would have been eroded and incised during the sea level low period and then infilled with deltaic sediments followed by alluvial fan sediments during the transgressions and subsequent high stands. The presence of 600 m of sediment (Arce, 1984) shows that the accumulation had to be produced by a sequence of processes as described above and which have been identified globally. The location of this maximum thickness of sediment are in a palaeo valley that persisted during the cyclic glacial lowstands and subsequent transgression of the Pleistocene–Holocene caused by palaeo-climate changes identified by Sebrier and Macharé (1980) and Le Roux (2000). According to Le Roux (2000) the facies of the Lima Fan indicate deposition in a high-energy environment dominated by interlocking channels that rapidly changed position.

Conglomerate interbeded with finer alluvial sand and mud deposits indicate moving loci of deposition during sea level high stand, regression, low stand and transgression.

About the future evolution to Metropolitan Lima, Urbanisation has resulted in districts of Lima being on high risk geomorphological features. Inhabitants near the current river are particularly susceptible to large fast-moving floods which have required the construction of dikes for management. River migration and deposition on the fan is now paralysed by anthropogenic urbanisation. Mud and debris that were deposited overbank prior to urbanisation is now cleaned away either increasing sediment loads and deposition or reducing flood plain accretion.

Future floods may not have the same extent as pre-urbanisation floods but the impact to modern human occupancy may be greater (Sara et al., 2016). The Rimac River is a young, sediment laden river and it will need to continue to evolve with climate oscillations. If high sediment loads are deposited in the anthropogenic channel reducing its drainage efficiency the Rimac may break its banks to the north and south closer to its apex severely impacting communities in San Juan de Lurigancho, Ate and Lurigancho districts. Lima is also constructed on relatively unconsolidated sediments which amplify earthquake damage through reducing wave velocity and increasing the amplitude (McPherson, 2006). River evolution and tectonics cannot be controlled by anthropogenic amelioration because these parameters act at a regional level.

7. CONCLUSIONS

Evidence of structural lineaments, drainage course changes, sediment thickness variability in the Costa Verde cliffs, and the direction of movement of the Nazca and South American Plates, as well as the position of the San Lorenzo Island created a topographic template for cyclic deposition and erosion of the Lima Fan. The fan substrate tilted northwards thus involving some hundreds of meters of mountain range uplift that would have caused the Rimac and Chillon Rivers to form two coalescing alluvial fans where the distal sediments have been eroded by the marine action, creating the Costa Verde cliffs.

The sediment sequences exposed in the Costa Verde cliffs confirms the alluvial nature of the sediments. Generally, the sequences are fining upwards and are truncated. Also, there are some differences between the north and south parts of the fan as the channel size and incision seem to indicate.

The results of the dating indicate that the materials of the exposed cliff faces comprising fan sediments are of Late-Pleistocene/Holocene age deposited since the last glacial sea level low. Previous geophysical studies found that underlying palaeo-valley sediments were up to 600 m thick. Erosion and deposition of the fan sediments has been cyclic, aligning with glacial sea level lows. Valley incision and backfill has driven paleo-sea level shift. The outlet to the fan from the Andes has remained constant so episodes of deposition have commenced from the fan apex. The erosion and deposition on the fan will continue to be cyclic with or without anthropogenic intervention.

To summarize, a significant control of future fan development is active tectonics which will expose more areas to erosion and change the loci of deposition. This will be exacerbated by climate change where more frequent and higher intensity rainfall events will result in greater flooding bring more sediments to the fan and changes in geomorphological configuration of Peruvian capital substrates.

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