Geomorphological evolution of the Rimac River's Alluvial Fan, Lima, Peru

Villacorta, Sandra P.; Evans, Kenneth G.; De Torres, Trinidad J.; Llorente, Miguel; Prendes, Nicanor

Published in:
Geosciences Journal

DOI:
10.1007/s12303-018-0049-5

Published: 01/06/2019

Document Version
Early version, also known as pre-print

Citation for published version (APA):
Villacorta, S. P., Evans, K. G., De Torres, T. J., Llorente, M., & Prendes, N. (2019). Geomorphological evolution of the Rimac River's Alluvial Fan, Lima, Peru. *Geosciences Journal*, *23*(3), 409-424. https://doi.org/10.1007/s12303-018-0049-5

Geomorphological evolution of the Rimac River's Alluvial Fan, Lima, Peru

Sandra P. Villacorta*[1,2], Kenneth G. Evans[3, 4], Trinidad J. De Torres.[1], Miguel Llorente.[5] and Nicanor Prendes[6]

1 Higher Technical School of Mining and Energy Engineers, Technical University, Madrid, 28003, Spain

2 Instituto Geológico, Minero y Metalúrgico - INGEMMET, San Borja, Lima41, Peru;

3 EnviroConsult Australia, Darwin NT Australia.

4 School of Engineering and Information Technology, Charles Darwin University, Darwin NT Australia.

5 Instituto Geológico y Minero de España - IGME, Madrid, 28003, Spain.

6 Oficina Española del Cambio Climático (Medio Ambiente). MAPAMA, Madrid, 28009, Spain

***Corresponding author:** sp.villacorta@alumnos.upm.es

Corresponding author's name: Sandra P. Villacorta

Telephone number +51-1-6189800; Fax number: +51-1-2254540

Running title: Geomorphological Evolution of the Rimac River Alluvial Fan, Lima, Peru

– End of title page –

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 Holocene age and was deposited about 4,000 years ago. 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 Holocene postglacial marine transgression. 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 regards of human intervention in attempts to prevent natural disasters in Lima.

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

– End of Abstract and Key word page –

1. INTRODUCTION

Alluvial fans occur at the change in grade between lowlands and highlands (Birch et al., 2016). The Rimac River alluvial fan is located 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. 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 (figure 1).

Figure 1. is about here.

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).

In order 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, 1978; 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 (Saito and Oguchi, 2005; Brunsden et al., 1981).

The evolution of the Lima fan is well described from the 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 Mid-Holocene 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 evolution of the fan.

2. THE STUDY AREA

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, 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 limolites of the Lima Group. This sedimentary sequence represents continental and marine sequence 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 vallies 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; Megard 1979et al., 1980; Cobbing, 1982). Geophysical studies have showen that material deposited by the main channels of the fan reaches hundreds of meters of thickness (Arce, 1984). The thickest sediments are in the palaeovallies 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 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 (figure 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).

Figure 2. is about here.

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.

The largest upwelling system in the world, which has a cooling effect on ocean waters 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 Pleistocene and early Holocene, it was weakened and diverted to a more western and northern position (Chauchat, 1987; Uceda, 1986). 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).

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 (figure 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 to say, arid/desert condition 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 local 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 seal 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 short highstand at a sea level similar to the present for a relatively short period of 1ka this was then 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 transgression during interglacial period, 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).

Figure 3. is about here.

A palaeoclimate record, derived using 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 relatively 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 heating became rapid cooling to temperatures of at least 2° C below the mean for the present. They also indicate that during this period the humidity increased until about 800 a BP when the conditions became relatively dry until a warm and relatively humid period between 640 and 155 a BP occurred.

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

According to Ortlieb and Macharé (1980), development of desert alluvial cones 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 (end of the last glaciation) and 6,000 ka BP (transgressive maximum of the Holocene).

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

The oldest corresponds to the maximum sea level transgression after the most recent glaciation period which corresponds to the lower Veguian defined by Paskoff, (1970) in the North of Chile and dated to 4 ka BC. In figure 3, the set of Holocene levels is set as Tm1.

This marine transgression 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 underlaying substrates; the sedimentation history of the fan and the reconstructed palaeo-relief of the fan area. This necessitated: geomorphological mapping; geological mapping; flood zone and debris flow mapping using dating, remotely-sensed data, and digital elavation model (DEM) construction.

Geomorphological maps were constructed at a scale of 1:10,000, using a GIS database and a high resolution DEM based on Pleiades satellite imagery.

To interpret the relationships between drainage patterns, sediment lithology and substrate geological structure, a new geological map was compiled (Figure 5), based on unpublished geological data provided by the Peruvian Institute of Geology, Mineralogy and Metalurgy (INGEMMET), field mapping, stereoscopic analysis, satellite imagery analysis and mophometric mapping. A new structural map of the study area was developed based on 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.

Samples were taken from various areas of fluvial-alluvial deposits that form the fan of Lima for analyze using Optically Stimulated Luminescence (OSL) techniques to determine age of sediments.

4. RESULTS

4.1. Geological and Geomorphological Mapping

The geological and geomorphic mapping identified previously unknown lineaments that are covered by recent deposits and urban expansion. NW-SE lineaments were identified towards the north of the Fan in the Callao district crossing the Rimac River towards San Miguel. Towards the east, several NW-SE alignments (eg, near of Cerro El Agustino, Figure 8) were identified along the apex of the Fan. Other lineaments extend in a NE-SW orientation parallel to the upper tributaries of the Rimac River (Canto Grande ravine and Huaycoloro River) flanking the Fan in the east. Two large 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 in the vicinity of the Canto Grande district. This mapping is schematically represented in Figure 5.

The area occupied by the Lima Fan is characterized by the presence of palaeo-channels with infills of heterometric sediments (2-3 cm to 40-50 cm), polymictic clasts (mostly plutonic), and unconsolidated sediments comprising imbricated clasts, sands, silt and clay and fluvial structures. These materials vary in thickness ranging from 10 to 300 m where the thickest deposits overlay Rimac-Chillon palaeo-channel. The Fan covers an area of approximately 216 km^2, with a characteristic asymmetric triangular shape in a SW direction attributed to the tilting related to the subduction activity of the Nazca plate under the South

American plate (Aleman, Benavides, and León, 2006; Le Roux et al., 2000); and it is truncated by the effect of the marine action, where cliffs are observed.

The apex of the Fan is located in the foothills of the Western Cordillera, near the town of Ate (figures 7 and 9) 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 (figure 7 and figure 12-1). The cliffs of the Lima Fan (Costa Verde cliffs, figure 9a), extend for about 21 km along the coastal strip with altitudes in the order of 80 m MSL in its central area (Miraflores and Larcomar areas).

Figure 4. is about here

Figure 5. is about here

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 (Figure 6). In this area the Lima Group crops out as intrusive inselbergs with corestones in progress.

In Metropolitan Lima, 6 levels of terraces have been identified whose development has been limited to a narrow border along the Rimac River (profile AA ', figure 8 and 13). In the south (in the areas of San Juan de Miraflores, Villa El Salvador and Chorrillos) there are alluvial glaciers, sandy deposits forming dunes and eolian flatness (figure 6).

4.2. OSL Dating

Nine samples were collected (Table 1 and Figure 11) for OSL dating. The ages determined using OSL techniques range from 5.8 to 1.1 ka BP indicating deposition on that part of the fan studied occurred during the Holocene.

Table 1. Calculated age and OSL dating parameters

Figure 6.. is about here.

Figure 7. is about here

5. MID- TO LATE-HOLOCENE EVOLUTION OF LIMA FAN

The evolution of the present day alluvial fan was controlled by palaeo-topography and structural geology. Originally, the 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 in a northerly direction aggrading the fan to the south as it migrated to its present-day position with an E-W alignment. There are several palaeo-river channels to the south of the present-day Rimac River channel. These are the Surco River, Huatica River, Magdalena River, Maranga River and la Legua River. These different stages of Rimac River channel were abandoned as the Rimac River migrated to the north. These rivers are now present as palaeo-channel infill in the southern fan and covered by urbanisation. The southern surface area of the fan was a developing erosion glacis but is now also covered by urbanisation. The depositional pattern of the alluvial fan is very complex and, based on geophysical data, the morpho-structural regionalization and the various lineaments found, is categorised into ten stages of development and formation (figure 7 and 10).

5.1. 1st Stage - Qf0 and Qf1

During the first stage of evolution (Figure 10[1st]), Qf0 and Qf1 sediments were deposited in the southern part of the fan controlled by fault strike direction and outcropping indurated Cretaceous sediments and Eocene-Miocene instusives along the southern boundary (figure 6). Deposition occurred during the sea level regression from 6 to 3.5 ka B.P. described by Wells (1996). The banks were aggraded to the north and south of the Rimac River stage 1 palaeo-channel and the Rimac's mouth was to the SE at Morro Solar (figure 8) near where the Surco River palaeo-channel debouched to the Pacific Ocean. Qf0 (RE1) was sampled at the southern edge of the fan at the sea cliff at a depth of 15.6 m and with an age of 4.92±0.18 ka. Qf1 was sampled at RE2 and RE3 near to the Qf0 (RE1) site, both at depths of 14.6 m and were dated as 3.98±0.29 ka and 4.02±0.18 ka respectively (figure 8). About 4 km to the north of the RE sites at Miraflores district, Qf1 was sample at site MI1 at a depth of 9.6 m and were 4.13±0.25 ka BP Qf1 comprises fluvial sand (quartz and feldspar sands with silts) and is exposed as river terrace 8 (T8) (figure 8 and 10) near the Regatas Club (Chorrillos district). The stage 1 Rimac River/Surco River palaeo-channel is show in figure 10.

5.2. 2nd Stage – Qf2

Stage 2 is shown in (Figure 10[2nd]). Qf2 sediments were sampled at site MI2 at Miraflores near the Qf1 sampling site, MI1. The sampling depth at the sea cliffs was 11.2 m compared with the 9.6 m depth of the Qf1 MI1 sample. The date of the Qf2 (M2) sample was 5.08± 0.26 ka BP compared with 4.13±0.25 ka BP for Qf1 (MI1) a difference of nearly 1000 y. In this location Qf2 sediments are not only older but deeper in the profile than Qf1. This may indicate deposition of Qf2, in this area, contemporaneously with Qf0 (depth=15.6 m, age=4.92±0.18 ka BP) sediment deposition in the south through the Surco River palaeo-channel but from different sources and then Qf1 being deposited from the south, over Qf0, to the north to a position higher in the column and younger than QF2 at the MI sites.

At sites MA1 and MA2, about 6 km north of the MI sites at Magdalena, Qf2 were sampled at depths of 8.6 m and and 8.5 respectfully. The ages of these samples were 5.07±0.63 ka BP and 5.66±0.24 ka BP In this case MA2 is shallower in the profile but older than sediments MA1. This indicates a river to the north that has deposited overbank sediment to the south i.e. MA2, and as time passed the river incised and reworked the MA2 site sediments depositing younger sediment (MA1) at a level lower than MA2 in the profile.

Another 4 to 5 km to the north of the MA sampling sites, sediments are the deepest in the study area, 500-600 m depth, near the coast. These sediments progressively thin to the east 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.

To the north of the fan, Qf2 sediments were deposited by the Rimac River in the east and the Huaycoloro River in the Northeast. To the North of the Rimac River, Qf2 sediments have mixed with sediments from the Canto Grande channel and Chillon River. Qf2 sediments are exposed as river terrace T6 and T7 (figure 8 and 10) at (locations). South of the present-day Rimac River channel, a palaeo-channel occupied and deposited Qf2 sediments in the reason of the thickest sediment and deposited Qf2 sediment to the south eventually meeting Qf1 sediments in the vicinity of the MA sites (figure 13).

5.3. 3rd and 4th Stages (4 to 2.5 ka BP)

Deformation of the Qf2 segment by a NW-SE fault exerted structural controls on the course of the Rimac River. As a result, during stage 3, the course of the Rimac River bed migrated to the north, isolating parts of Qf2. Now, occupying the Magdelena River palaeo-channel, Qf3 sediments were aggrading on the left and right bank, reworking Qf2 sediments which were overlain by Qf3 represented by river terrace 5 (T5) (figure 8, 10[3rd]).

During the 4th stage, the Rimac River channel continued to migrate north to a general SW flow direction truncating and reworking right bank sediments of the earlier stages. Deposition of Qf4 (T4) on Qf3 occurred. During this period the palaeo-river mouth was at Armendariz in Barranco (figure 8, 9, 10[4th]) and was infilled with Qf3 sediments.

5.4. 5th and 6th Stages (2.5 to 1 ka BP)

Following stage 4, a marine transgression resulting in stage 5 reworking and truncating stage 4 right bank sediments fine upwards and aggrading Qf5 (river terrace T3) sediments to the north and south (figure 10[5th]). This was the beginning of a more arid climate and an erosion glacis began to form towards the central and southern zones of the Fan.

During stage 6, approximately from 1.7 to 1 ka BP (Table 1), (Qf6, T1) (figure 10[6th]), an exceptional flood event caused channel abandonment and infilling. Presently Qf6 sediments are mostly exposed on the right bank of the Rimac River. The erosion surface of Qf6 in this area dips toward the North. This indicates that Qf6 (T2) may be over-bank flood deposits of the Huaycoloro River a palaeo-right bank tributary of the Rimac River. This is also justified by the nature of the deposits (boulders, gravel and fine sands silts and clay), found in the profile lifted at ATE crossing that are different from those observed in the deposits further west and by clast orientation indicating a difference in palaeo-currents.

Based on OSL dates, although a limited number of samples (Table 1), the period of deposition in stages 5 and 6, was an average of approximately 0.8 ka per stage and stage 1 to 4 also had similar depositional periods with an average of approximately 0.7 to 1 ka. However, sediment depositional area and depth for stages 1 (Qf1, T7) to 4 (Qf4, T4) are considerably more extensive than those of stages 5 (Qf5, T3) to 6 (Qf6, T2). This indicates a decrease in sediment transport, and deposition rate possibly associated with increasing aridity after about 2.5 ka BP resulting in a further reduction in deposition during stage 6 (T2) between 1.7 to 1 ka BP.

5.5. 7*th*, 8*th*, and 9th Stages (1ka^{-1} BP to present)

Migration of the Rimac River channel continued toward the north abandoning the channel which remained active as the Magdalena River which is now a palaeo-channel in central Lima (figure 10[7th]). Qf7 (T1) was deposited during this time to the north of the Huatica River. Erosion continued in the southern area of the fan as the glacis continued to form.

During the 8th stage of evolution, Qf8 (river terrace T0) was deposited to the north of the 7th stage deposits, Qf7 (figure 10[8th]). At present, small remnants of Qf7 can be recognized in the areas near the Rimac River, in the northernmost part of the study area, along the northwest side of San Cristobal Hill at San Juan de Lurigancho Ramiro Priale. Coalescences of channels occurred as a result of large flood events and isolation of the palaeo-channel of the Huatica River.

Stage 9 is the youngest fan surface and corresponds to more recent active deposition Qf8 (T0) with an east-west orientation (figure 10[9th]). The channel occupies a continuous and narrow channel presenting a surface dissected by the Rimac River. This surface can be correlated with the lower terrace of the Rimac River in the form of a possible meander abandoned around the El Agustino inselberg. Formation of a glacis towards the south of the fan and accumulation of eolian deposits.

5.6. 10th Stage – present period of urbanisation

The current channel of the Rimac River incises Qf8 sediments, with its flow contained by anthropogenic concrete blocks replacing the active river banks. The constructed canal now drives sediments from their source in the uplands to a developing prograding delta offshore with numerous distributary channels (figure 10[10th]). Presently Qf8 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 (figure 8).

Urbanisation on T8 has resulted in districts of Lima being on high risk geomorphological features. These are particularly susceptible to large fast moving floods which have required the construction of dikes. Consequently, the depositional segment Qf4 is restricted to a narrow area near the El Agustino inselberg (figure 10). Deposition in this area, like much of the fan, is paralyzed by anthropogenic urbanisation. Floods are restricted to the Qf8 and Qf7, affecting houses, buildings and infrastructure located 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 and Canto Grande ravines unleashed in 1987, 1998, 2016 and 2017 demonstrate the susceptibility of these districts 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 (Dávila and Valenzuela, 1998). An event occurred in 2017 influence by the occurrence of a "Coastal El Niño" event (ENFEN, 2017). As a result 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 cart was temporarily interrupted. As a consequence, there is the possibility of future flood events with potentially catastrophic consequences for those sectors of Metropolitan Lima.

Figure 9. is about here.

Figure 10. is about here

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, has to be considered. Cobbing (1982) used regional structural mapping to deduce that the coastal Lima segment central zone of the coastal batholith, 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 Andean uprising influenced the sedimentation patterns of the Pacific slope of South America. San Lorenzo Iland could be a remnant of wall of the large fault running NNW-SSE between San Lorenzo and the Lima coast.

In the Late-Pleistocene there have been well-recognise cyclic postglacial marine transgressions. The long (100ka), 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 palaeotopographical 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 very little coastal plain (Wells, 1992). Sea level reached a somewhat constant high stand between about 7- 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, 1988; Well, 1996; Wells and Noller, 1999) although Dollfus (1966) considered the fall to be about 2 m. During and after the transgression to 7ka BP deep river valleys/canyons that 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 occurred until a subarial surface appeared on which the present alluvial fan has developed. Due to the coriolis effect in the southern hemisphere (clockwise rotation) heavy 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 ages of stage 1 and 2 of fan deposition in the south suggest that the fan was well developed by about 6 ka BP. There was an increase in frequency of ENSO events between 3.2-2.8ka 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 stage 5 indicating an increase in aridity. There was possibly a further reduction in deposition rate and fluvial flow during stage 6 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 (which drains away from the Rimac River), consequently it is difficult to extrapolate this age data to the Rimac River fan.

In this study, the ages of the samples in the fan (exposed in the Costa Verde) of Holocene age varying from 1.0 to 5.2 ka BP. These data agree with the ages obtained in the southern zone of the fan by Viveen et al. (2016; 0.1 to 3.9 ka). 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 strata of the fan. It must be considered that only the upper levels of the fan have been sampled and dated. That is, from the exposed 100 m of the Costa Verde cliffs and in this study, all dated samples were above 15.6 m. Therefore, the remaining 84 m may contain sediments that are considerably older. In addition, at its thickest point the fan is up to 600 m thick again indicating that the fan sediments could be much older than the 5.7 ka dated in this study, the Pleistocene would also be represented therefore the regional evolution seems to indicate that this fan was already functional in the Pleistocene.

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 activity of the Nazca dorsal asismica 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 take into account 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. But more in-depth dating is needed to confirm this hypothesis.

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 major sea level fluctations a 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 500 m of sediment (Arce, 1984) show that the accumulation had to be produced by a sequence of processes as described above and that have been identified globally. The location of this maximum thickness of sediment are in a palaeo-river valley that persisted during the cyclic glacial lows 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 interbed with finer alluvial sand and mud deposits indicate a moving loci of deposition during sea level highstand, regression, lowstand 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 paralysed by anthropogenic urbanisation.

Future floods may not have the same extent as pre-urbanisation floods but the impact of them may be greater over a smaller area. 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 it banks to the north and south closer to its apex severely impacting communities in those areas. 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.

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 tilts toward the north which involved some hundreds of meters of mountain range uplift, and 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 source of the sediments comprising the fan. 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 comprising fan sediments are of Late-Pleistocene/Holocene age deposited since the last glacial sea level low. Previous geophysical studies found that underlying palaeo-valleys sediments were up to 600 m thick. Erosion and deposition of the fan sediments has been cyclic aligning with glacial see level lows. Valley incision and backfill was 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.

8. ACKNOWLEDGEMENTS

This research has been co-financed by the Geological, Mining and Metallurgical Institute of Peru (INGEMMET), the Geological and Mining Institute of Spain and the Polytechnic University of Madrid. Dating was possible thanks to the Peruvian Institute of Nuclear Energy and the National University of Engineering, the basic geological data were provided by Department of the Regional Geology from INGEMMET, the satellite data were transferred for this work by the National Commission of Aerospace Research and Development (CONIDA) and the Center for Estimating and Prevention of Disasters. Miguel Miranda, from CONIDA, has provided support in obtaining and processing MDEs. Luis Ayala and Carlos Benavente, provided support in the field work. Jesus Pernas has contributed as external reviewer adding value to the article.

REFERENCES

Aleman, A., Benavides, V., and León, W., 2006, Stratigraphy, Sedimentology and tectonic evolution of the Lima area. (Abstract), Geological Society of Peru. Field guide N°11.

Alfaro, E., Cid, L., and Enfield, D., 1998, Relations between the beginning and the end of the rainy season in Central America and the Pacific and Atlantic tropical oceans. Investigaciones Marinas, 26, 59–69.

Arce, J.R., 1984, Rimac-Chillon basement geoelectric structure. In: Lima: Geological Society of Peru. 60th Anniversary Jubilee Volume, Tribute to Dr. Georg Petersen G., (1)

Betancourt, J. L., Latorre, C., Rech, J. A., Quade, J., and Rylander, K. A., 2000, A 22,000-year record of monsoonal precipitation from northern Chile's Atacama Desert. Science, 289, 1542–1546.

Birch, S. P. D., Hayes, A. G., Howard, A. D., Moore, J. M., and Radebaugh, J., 2016, Alluvial Fan Morphology, distribution and formation on Titan. Icarus, 270, 238–247.

Bull, W. B., 1977, The alluvial fan environment. Progress in Physical Geography, 1, 222–270.

Brunsden, D., Jones, D.K.C., Martin, R.P., and Doornkamp, J.C., 1981, The geomorphological character of part of the low Himalaya of eastern Nepal. Zeitschrift Für Geomorphologie, 37, 25–72.

Carré, M., Azzoug, M., Bentaleb, I., Chase, M.B., Fontugne, M., Jackson, D., Ledru, M., Maldonado, A., Sachs, J.P., Schauer, A.J., 2011, Mid-Holocene mean climate in the southeastern Pacific and its influence on South America. Quaternary International, 253, 55–66.

Casas, A., 1995, Geomorphological and sedimentary features along an active right-lateral reverse fault. Zeitschrift Fur Geomorphologie, 39, 363–380.

Chauchat, C., 1987, Niveau marin, écologie et climat sur la côte nord du Pérou à la transition pléistocène-holocène. Bulletin of the French Institute of Andean Studies, Lima, 16,, 21–27.

Chavez, F.P., Bertrand, A., Guevara-Carrasco, R., Soler, P., and Csirke, J., 2008, The northern Humboldt Current System: Brief history, present status and a view towards the future. Progress in Oceanography 79, 95–105

Clapperton, C. (1993). Quaternary geology and geomorphology of South America. Elsevier Amsterdam,779 p.

Cobbing, E., 1982, The segmented coastal batholith of Peru; its relationship to volcanocity and metallogenesis. Earth-Science Reviews, 18, 241–251.

Colombo, F., 2010, Alluvial fans: processes of transport and accumulation of detrital materials. In Arche, A. (ed.), Sedimentology. From the Physical Process to the Sedimentary Basin. Madrid: Superior Council of Scientific Investigations Madrid, Spain, p. 85–130.

Cook, B.I., Cook, E.R., Smerdon, J.E., Seager, R., Williams, A.P., Coats, S., Stahle, D.W., Diaz, J.V., 2016, North American megadroughts in the Common Era: reconstructions and simulations. WIREs Clim Change 2016. Doi: 10.1002/wcc.394.

Craig, A. K., 1985, Cis-Andean environmental transects: Late quaternary ecology of northern and southern Peru. Andean Ecology and Civilization: An Interdisciplinary Perspective on Andean Ecological Complementarity, University of Tokyo Press, Tokyo, p. 23–44.

Dávila, S., and Valenzuela, G., 1998, Inspection of geological risks in prevention of the effects of the El Niño phenomenon in human settlements between the Chillon River and the Jicamarca Ravine. Lima: Technical Report, Geological, Mining and Metallurgical Institute, Peru.

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

DeVries, T. J., Ortlieb, L., Díaz, A., Wells, L., and Hillaire-Marcel, C. l., 1997, Determining the early history of El Niño. Science, 276, 965–967.

Dollfus, O., 1964, Prehistory and post-Würmian climate change in Peru. Bulletin from the French Association for the Quaternary Study, 1, 6–12.

Dollfus, O., 1966, The central Andes of Peru and their foothills (between Lima and the Péréné District). Geomorphological study. Alpine Geography Review, 54, 683–684.

Dollfus, O., and Lavallee, D., 1973, Ecology and occupation of space in the tropical Andes during the last twenty millennia. Bulletin of the French Institute of Andean Studies, 2, 75–92.

ENFEN., 2017, Official Communication ENFEN N° 06-2017. Lima. Retrieved from https://www.dhn.mil.pe/Archivos/oceanografia/enfen/comunicado-oficial/06-2017.pdf

Engel, Z., Skrzypek, G., Chuman, T., Šefrna, L., and Mihaljevič, M., 2014, Climate in the western cordillera of the central Andes over the last 4300 years. Quaternary Science Reviews, 99, 60–77.

Evans, K.G., 1990, Quaternary Stratigraphy of the Brisbane River Delta. BAppSc (Hons) thesis, The Queensland University of Technology, Brisbane, Australia. p. 137.

Evans, K.G., Stephens, A.W. and Shorten, G.G., 1992, Quaternary sequence stratigraphy of the Brisbane River Delta, Moreton Bay, Queensland, Australia. Marine Geology 107, 61–79.

Farina, R. A., Czerwonogora, A. and Di Giacomo, M., 2014, Splendid oddness: revisiting the curious trophic relationships of South American Pleistocene mammals and their abundance. Annals of the Brazilian Academy of Sciences 86, 311–331.

Harvey, A. M., 1989, The occurrence and role of arid-zone alluvial fans. In Thomas, D.S.G. (ed.), Arid Zone Geomorphology. Belhaven, London,, p. 136–158.

Heward, A. P., 1978a, Alluvial fan sequence and megasequence models, with examples from Westphalian D—Stephanian B coalfields, northern Spain. In Miall, A.D. (ed.) Fluvial Sedimentology: Canadian Society of Petroleum Geologists Memoir, 5, p. 669–702.

Heward, A. P., 1978b, Alluvial fan and lacustrine sediments from the Stephanian A and B (la Magdalena, Cinera-Matallana and Sabero) coalfields, northern Spain. Sedimentology, 25, 451–488.

Hindle, D., Kley, J., Klosko, E., Stein, S., Dixon, T., and Norabuena, E., 2002, Consistency of geologic and geodetic displacements during Andean orogenesis. Geophysical Research Letters, 29, 29-1-29–4.

Metropolitan Institute of Plannin (ed.), 2008, Environmental Atlas of Metropolitan Lima. Lima: IMP.

National Institute of Statistics and Informatics., 2014, A Look at Metropolitan Lima: Technical Report. Lima: INEI

Jacay, J., 2013, Evidence of paleosismicity in Lima region (central Peruvian coast). Journal of The Institute of Investigations of The Faculty of Geology, Mines, Metallurgy and Geographical Sciences, 16, 35–52. Available at: http://revistasinvestigacion.unmsm.edu.pe/index.php/iigeo/article/view/11324/10154

Jacay, J., Castillo, J., and Ingaruca, Y., 2000, Evidence of Transpressive Tectonics in Berriasian-Valanginian Land (Comas-Zapallal Segment). Proceedings of Abstracts Volume. 10th Peruvian Congress of Geology, Lima: Geological Society of Peru..

Jordan, T.E., Burns, W. M., Veiga, R., Pángaro, F., Copeland, P., Kelley, S., and Mpodozis, C., 2001, Extension and basin formation in the southern Andes caused by increased convergence rate: A mid-Cenozoic trigger for the Andes. Tectonics, 20, 308–324.

Kanner, L.C., Burns, S.J., Cheng, H., Edwards, R.L., and Vuille, M., 2013, High-resolution variability of the South American summer monsoon over the last seven millennia: Insights from a speleothem record from the central Peruvian Andes. Quaternary Science Reviews, 75, 1–10.

Kremenetskia, K.V., Boettgerc, T., MacDonalds, G.M., Vaschalovad, T., Sulerzhitskye, L., Hiller, A., 2004, Medieval climate warming and aridity as indicated by multiproxy evidence from the Kola Peninsula, Russia. Palaeogeography, Palaeoclimatology, Palaeoecology, 209, 113– 125.

Le Roux, J.P., Tavares Correa, C., and Alayza, F., 2000, Sedimentology of the Rimac-Chillon alluvial fan at Lima, Peru, as related to plio-pleistocene sea-level changes, glacial cycles and tectonics. Journal of South American Earth Sciences, 13, 499–510.

Le Roux, J.P., 2012, A review of tertiary climate changes in southern South America and the Antarctic Peninsula. Part 1: Oceanic conditions. Sedimentary Geology, 247, 1–20.

Lecarpentier, C., and Motti, R., 1968, Note on the Quaternary accumulations of the Chillon, Lurin and Chilca valleys (Peruvian Coastal desert). Dynamic Geomorphology Review 18, 73-82.

Lisson, C., 1907, Contribution to the geology of Lima and its surroundings. Imprenta Gil, Lima.

Macharé, J., Benavente, C., and Audin, L., 2009, Descriptive synthesis of the neotectonic map of Peru.. Bulletin 40 of the Geological, Mining and Metallurgical Institute, Lima, Peru

Macharé, J., and Ortlieb, L., 1993, Records of the El Niño phenomenon in Peru. Bulletin of the French Institute of Andean Studies, 22, 35–52.

McPherson, A, 2006, Estimating the influence of sediments on ground shaking. AusGeo News, Issue No. 82.

Mixmade SAC., 2008, In: Benavides V., Montoya M., Quevedo C. and Cardozo M. (Eds.), Lima: Geological routes and historical circuit (1a ed.). Lima: Mixmade SAC.

Nichols, G., 1987, Syntectonic alluvial fan sedimentation, southern Pyrenees. Geological Magazine, 124, 121–133.

Noble, D., Wise, J., Zanetti, K., Vidal, C., and McKee, E., 2009, Late Miocene age for conglomerates and "Quaternary" gravels in the coastal plains of central Peru and other evidence concerning the Neogene evolution in the western slope of the Peruvian Andes. Bulletin of the Peruvian Geological Society, Special Volume7, 90.

Ortlieb, L., and Macharé, J., 1989, Climatic evolution at the end of the Quaternary in the coastal regions of northern Peru: Abstract brief. Bulletin of the French Institute of Andean Studies, 18, 143–160.

Palacios, O., Caldas, J., and Vela, C., 1992, Geology of the Quadrangles of Lima, Lurín, Chancay and Chosica. Bulletin of the Geological, Mining and Metallurgical Institute, Lima, 43, 163 p..

Parsons, M. H., 1970, Preceramic subsistence on the Peruvian coast. American Antiquity, 35, 292–304.

Perry, L. B., Seimon, A., and Kelly, G. M., 2014, Precipitation delivery in the tropical high Andes of southern Peru: New findings and paleoclimatic implications. International Journal of Climatology, 34, 197–215.

Paskoff, R., 1970, Semi-Arid Chile. In: Geomorphological Research. Bordeau, France: Biscay Freres. 420 p.

Ramos, V., and Aleman, A., 2000, Tectonic evolution of the Andes. Tectonic Evolution of South America: 31 International Geological Congress, Rio de Janeiro. 635–685.

Richardson, J. B., III 1978, Early man on the Peruvian North Coast, early maritime exploitation and the Pleistocene and Holocene environment. In Bryan, A. L. (ed.), Early Man in America from a Circum-Pacific Perspective, Archaeological Researches International, Edmonton, p. 274–289.

Rockwell, T., Keller, E., and Johnson, D., 1985, Tectonic geomorphology of alluvial fans and mountain fronts near Ventura, California. Tectonic Geomorphology. Proceedings of the 15th Annual Geomorphology Symposium. Allen and Unwin Publishers, Boston, MA, 183–207.

Rodbell, D.T., Smith, J. A., and Mark, B. G., 2009, Glaciation in the Andes during the Late glacial and Holocene. Quaternary Science Reviews, 28, 2165–2212.

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.

Saito, K., and Oguchi, T., 2005, Slope of alluvial fans in humid regions of Japan, Taiwan and the Philippines. Geomorphology, 70, 147–162.

Sandweiss, D.H, Maasch, K.A, Burger, R.L., Richardson III, J.B., Rollins, H.B., and Clement, A., 2001, Variation in Holocene El Niño frequencies: Climate records and cultural consequences in ancient Peru. Geology, 29, 603–606.

Scherrenberg, A., Holcombe, R., and Rosenbaum, G., 2014, The persistence and role of basin structures on the 3D architecture of the Marañon fold-thrust belt, Peru. Journal of South American Earth Sciences, (51).

Sébrier, M., and Macharé, J., 1980, Observations on the Quaternary of central Peruvian Coast. Bulletin of the French Institute of Andean Studies, 9, 25–32.

Seager, R., Cook, E.R., 2007, Medieval megadroughts in the Four Corners region: Characterization and causes. Presentation to the Society for American Archaeology, Austin Texas.

Seltzer, G. O., 1990, Recent glacial history and palaeoclimate of the Peruvian-Bolivian Andes. Quaternary Science Reviews, 9, 137–152.

Seluchi, M. E., Garreaud, R. D., Norte, F. A., and Saulo, A. C., 2006, Influence of the subtropical Andes on baroclinic disturbances: A cold front case study. Monthly Weather Review, 134, 3317–3335.

Simpson, B. B., 1975, Glacial climates in the eastern tropical south Pacific. Nature, 253, 34–36.

Simpson, B. B., and Haffer, J., 1978, Speciation patterns in the amazonian forest biota. Annual Review of Ecology and Systematics, 9, 497–518.

Steel, R. J., Næhle, S., Nilsen, H., Roe, S. L., and Spinnangr, A., 1977, Coarsening-upward cycles in the alluvium of hornelen basin (devonian) Norway: Sedimentary response to tectonic events. Geological Society of America Bulletin, 88, 1124–1134.

Uceda, S., 1986. Paijanien of the region of Casma (Peru): Lithic industry and relations with other pre-ceramic industries. PhD. Thesis, University of Bordeaux, Bordeaux, 334 p..

Valle-Levinson A., 2011, Large Estuaries (Effects of Rotation). In: Wolanski, E. and McLusky, D.S. (eds.), Treatise on Estuarine and Coastal Science, Vol 2, pp. 123–140. Waltham: Academic Press.

Villacorta, S., Nuñez, S., Tatard, L., Pari, W., and Fidel, L., 2015, Geological Hazards in the Lima Metropolitan Area and the Callao Region (Lima-Perú). (59). Lima: Bulletin of the Geological, Mining and Metallurgical Institute, Peru

Viveen, W.; Sanjurjo, J.; Ayala, L.; Zevallos, L.; Schlunegger, F.; Litty, C., 2016, The age of the Costa Verde conglomerates in Lima: first results of the Barranco sector. In Lima: Peruvian Geological Society (Ed.), XVIII Congreso Peruano de Geología.

Webb, S. D., 1978, A history of savanna vertebrates in the new world. part II: South America and the great interchange. Annual Review of Ecology and Systematics, 9, 393-426.

Wells, L.E., 1992, Holocene landscape change on the Santa Delta, Peru: impact on archaeological site distribution. The Holocene, 2, 193–204.

Wells, L.E., 1996, The Santa Beach Ridge Complex: Sea-level and progradational history of an open gravel coast in central Peru. Journal of Coastal Research, 12, 1–17.

Wells, L.E. and Noller, J.S., 1999, Holocene Coevolution of the Physical Landscape and Human Settlement in Northern Coastal Peru. Geoarchaeology, 14, 755–789

TABLE

Table 1. Calculated age and OSL dating parameters

LIST OF FIGURES

Figure1. Location of the study area within the river Rimac basin.

Figure2. Compilation of structural systems in Peru and in study area. Based on: Le Roux et al., (2000); Macharé et al., (2009); Scherrenberg et al., (2014) and Villacorta et al., (2015).

Figure3. Schema of the Glaciation in Central Peru in correlation with the known 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).

Figure 4. Schematic block diagram of the study area and surroundings show 1: Eocene-Miocene exhumed intusives. 2: Pacific Ocean. 3: Jurassic-Cretaceous Outcrops. 4: Quaternary sediments. 5: Clays. 6: Sands and gravel. Not to scale.

Figure5. Generalized geological map of the Lima fan and surroundings showing the structures have been interpreted. Localities which are refered to in the text. 1: Huachipa, 2: San Juan de Lurigancho, 3: El Agustino, 4: Santa Anita, 5: Costa Verde Beach Circuit, 6: Morro Solar, 7: San Juan de Miraflores district.

Figure6. Geomorphological mapping of the Lima Fan area. 1. Fan apex, 2. Canto Grande ravine, 3: El Agustino Hill, 4: Santa Anita, 5: Costa Verde Beach Circuit, 6: Morro Solar, 7: San Juan de Miraflores district.

Figure7. Longitudinal profile of the Lima Range from Carapongo to Miraflores. 1. Qf0 (T8), 2. Qf1 (T7), 3. Qf2 (T6). 4. Qf3 (T5). 5. Qf4 (T4). 6. Qf5 (T3), 7. Qf6 (T2). 8. Qf7 (T1), 9. Qf8 (T0), 10. Intrusive substrate. 11. Debris flows sporadic deposits. 12. Pacific Ocean. 13. Glacis. 14. Beach deposit. (see Figures 10 and 11).

Figure8. Schematic cross-section showing the segments of alluvial fans. T0 to T4f: river terraces. 1. Cuaternary materials, 2. Pliocene materials, 3. Current channel, 4. Intrusive substrate. 5. Glacis.

Figure9. a) Panoramic view of the Costa Verde cliffs where the truncated distal fan is observed (Mixmade S.A.C., 2008). b) Club Regatas Chorrillos, with fining up grains. c) Conglomerate facies with lenticular geometry bodies surrounded by gravel deposits. d) Transgressive marine facies in the broken sector of Armendariz (Barranco). e). Detail of the ripples observed in sandy lenticular bodies that migrate towards the interior of the deposit.

Figure10. Different stages of the development of the Lima alluvial fan. (1st and 2nd) Sedimentation of the fan segment Qf2, on the surface of fan Qf1 (River Groove). The Qf2 segment is fed mainly from the east (Rimac River), but also from the North (Huaycoloro, Canto grande and Chillon Rivers). (3ª) Deformation of the segment Qf2 affected by a NW-SE fault that affected outcrops that controlled the Rimac River course and sedimentation of fan segment Qf3. (4ª) Migration of the Rimac river bed and sedimentation of the fan segment Qf4 isolating remains of the Qf3 segment. (5th) Sea deposit in the Holocene by rising sea level (6th and 7th) Deposition of segments Qf5 and Qf6 and formation of glacis towards the south of the fan. (8ª) Clogging of channels and abandonment of the channel of Surco river by event of exceptional flood in Huaycoloro river and Canto Grande ravine (deposit Qf7). (9th and 10th) Formation of glacis towards the south of the fan and positioning of a wind deposit.