SEDIMENTARY FACIES AND ARCHITECTURE OF THE TERTIARY DELTAIC DEPOSITS OF CAMANÁ FORMATION, SOUTHERN PERU

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INTRODUCTION

Cenozoic sedimentary rocks of Camaná Fm. in Southern Peru, Southwestern Arequipa, have been studied and defined as coarse-grained deltaic deposits accumulated in shallow marine water at the seaward edge of the Coastal Cordillera. From Ocoña in the NW to Quilca in the SE, these strata overlay the Proterozoic and Paleozoic basement rocks of the Coastal Cordillera, which is faulted by the Atico-Ocoña-Camaná Fault System. Sedimentation of Camaná Fm. is accompanied by synsedimentary normal faulting that in turn might be associated with transtensional deformation (Sempere et al., 2004), and/or differential uplift of blocks in the region (Wipf, 2006). The aim of this paper is to describe the sedimentary facies associations and the stratigraphic architecture of Camaná Fm., highlighting the main causes of stratigraphical variation, architecture and internal geometry of delta deposits, in the framework of sea level changes and/or tectonic influences through time.

GEOLOGICAL CONTEXT

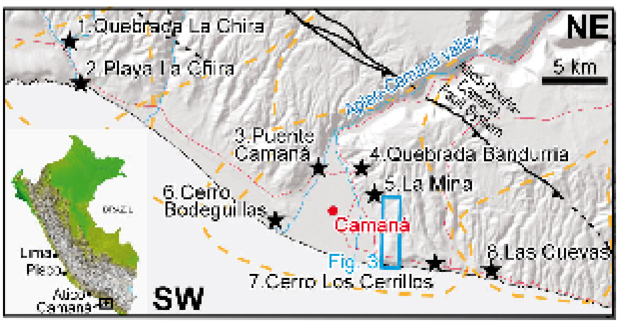

Fig. 1. Location of the studied area. Yellow dotted lines represent aproximate extension of Tertiary deltas.

At the western edge of South America, the Nazca plate is being subducted beneath the continental South American plate between 14°S and 17°S, since Jurassic/Cretaceous times (Pitcher et al., 1985), producing during Cenozoic the onset of crustal thickening and Andean Orogeny (Oncken et al., 2006). It is widely accepted due to a variety of subduction parameters that diverse magmatism occurred during the tectonic evolution of the Central Andean margin (Mamani et al., 2010), showing pronounced shifts of the western magmatic front through time (Pitcher et al., 1985; Jaillard et al., 2000). The Basal Coastal Complex, consisting of Proterozoic migmatites, granulites and gneisses (Martignole & Martelat, 2003) together with Ordovician granites of the Atico-Camaná-Mollendo Batholith, is faulted by the Atico-Ocoña-Camaná Fault System (Carlotto et al., 2009), that places the Atico-Camaná-Mollendo Batholith against the Precambrian rocks. Transtensional stress due to Nazca ridge oblique migration (Jacay et al., 2009) dominate the tectonic setting of the forearc, arc and SW Altiplano (Sempere & Jacay, 2006), and likely creates accommodation space in the forearc zone of Southern Peru since Eocene (Bianchi, 2004; León et al., 2005). As a consequence, Moquegua and Pisco forearc basins were created and filled with the respective eroded material of the uplifted blocks (Jaillard et al., 1997). Tertiary marine sediments outcropping around Camaná city and Camaná river (Fig. 1) are known as Camaná Fm. (Rivera, 1950), of Late Oligocene to Lower/Middle Miocene age (Pecho & Morales, 1969), and consist of several deltaic clinoforms controlled by synsedimentary normal faulting (Sempere et al., 2004). The Camaná "A" unit (Fig. 2, Sempere et al., 2004) consists mainly of progradational and retrogradational stackings, which lithologically consists of bioclastic sandstones, mostly clinostratified and passes seawards into finer grained sediments. These deltaic successions are overlain by Lower Miocene beds of Camaná "B" unit which is composed of conglomerates and sandstones with abundant volcanic material, partially contemporaneous with MoqC2 unit of Moquegua Group (Sempere et al., 2004; Decou et al., 2011).

DESCRIPTION OF SEDIMENTARY FACIES IN CAMANÁ FORMATION

In Camaná and surrounding areas (Fig. 1), sedimentary facies types (FT) in Camaná Fm. have been described, and classified according to their similarities in lithology, sedimentary structures (including tempestite thickness, distinguishing interaction of waves based on their grain size and bioclast size/quantity, Myrow & Southard, 1996), and fossil content. Finally defined five facies associations (FA) inspired by Miall (1999) and Longhitano (2008), grouped from NE to SW in fluvio-deltaic (FA: G), deltaic (FA: S1, S2 and S3) and offshore facies (FA: F).

FA: G (FT *Gcs* and *Sl*): Fluvial and fluvio-deltaic facies/delta plain

Description. FT *Gcs* is observed in sections 3, 4 and 5 (Fig. 1). It consists of normally graded clast-supported conglomerates, poorly sorted, composed of andesite, rhyolite, granite and gneiss pebbles, with little matrix of grayish to reddish medium-grained sandstone (3, 4), often intercalated with sandstones containing marine shell fragments (FT *Ss* and *Shx*) (4, 5). Above all the conglomeratic lithofacies *Gcs*, fine to medium grained reddish sandstones appear (FT *Sl*) which are generally laminated, and contain amphiboles, iron oxides and volcanic glass. This association of facies types forms mainly horizontal and subhorizontal layers in topsets.

Interpretation. FT *Gcs* represents prograding depositional units, reflecting continental sedimentation with abundant coarse debris flows, with some sand-dominated layers that may reflect overbank deposits (FT *Sl*). This fluvial facies are intercalated with marine ingression in a delta plain setting, which is interpreted as a fan-delta system connected to shallower marine waters (foreshore, shoreface). Pebbles reflect local Precambrian and Paleozoic basement lithologies, plus a significant contribution from the Western Cordillera (mainly andesites and quartzites).

FA: S1 (FT *Sm* and *Sb*): Mouth bar and foreshore deposits in delta front

Description. Facies type *Sm* is observed at site (5) only (Fig. 1), and consists of highly bioclastic massive very coarse-grained sandstone to microconglomerates (mainly balanids, equinoid spines and shells fragments), which are truncated by clinostratified sandstones of Seq1 (Figs. 2 and 3). Here Vega & Marocco (2004) mentioned Upper Oligocene shark teeth. FT *Sb* is observed in site (2), and consists of reddish fining-upward sandstone containing feldspars, amphiboles and bioclasts such as equinoids spines and balanids. It shows slightly oblique to parallel laminations, and contains some scattered subrounded granules of quartzite imbricated in Southeast direction.

Interpretation. FT *Sm* was formed by unidirectional currents with uniformity in the sedimentation energy, and could correspond to mouth bars or beach bar aligned parallel to the coast. Facies type *Sb* is related to shallow marine environments related to a swash zone in foreshore environments.

FA: S2 (FT *Sxt* and *St*): Delta front facies, lower to upper shoreface

Description. Facies types *Sxt* and *St* are arranged in tabular beds, and consist of bioclastic fining-upward sequences characterized by well cemented clinostratified sandstone, with grains of feldspar, quartz glauconite, chert, foraminifers and radiolarians. Both FT´s include bioclastic tempestites at their base, observed in almost all outcrops, being the coarsest-grained and thickest beds at sites (1, 3, 5 and 8) (Fig. 1). FT *Sxt* represents oblique and planar stratified, sometimes clinostratified bodies, containing pebbles of reworked ashes (3), low angle cross laminations, some convolute laminations and low degree burrowing (4, 5). FT *St* shows plane-parallel bedding (4), hummocky cross stratification (hcs) and cross laminations above tempestites (5). Bedding is up to 1 m thick.

Interpretation. Facies types *Sxt* and *St* are clinoforms of a typical delta front foreset geometry. These are interpreted as deposited in shoreface environments in a progradational deltaic setting highly influenced by wave oscillations, storms deposition and erosion.

FA: S3 (FT *Sfb*, *Ss* and *Shx*): Delta front facies, lower shoreface

Description. FA S3 are finer-grained than FA S2, consists of poorly cemented fining-upward sandstone sequences, highly bioclastic, with some subangular feldspar grains. Synsedimentary faulting is common in these facies types. FT *Sfb* consists of tabular sandstones beddings highly bioturbated, above thick laminated tempestites (up to 50 cm) (3, 8) (Fig. 1), and often shows reworked ashes at the top of beddings. FT *Ss* consists of structureless (3, 4), slightly planar bedding and cross bedded sandstones (2, 4, 5), with rare occurrences of thin tempestites at the base. FT *Shx* shows parallel laminations/beddings (1, 3), ripples (4, 5), and also cross beddings (5), containing no or few thin tempestites at the base, and at the top of the beddings reworked ash layers, with little bioturbation. Interpretation. FA S3 represents delta front lobes in lower shoreface. FT´s *Sfb* and *Ss* were formed due to density-induced flows by storm currents and wave oscillations in a shoaling wave zone (Myrow & Southard, 1996). FT *Shx* represents lower shoreface to offshore transition deposits, both deeper waves and less wave energy, and possibly occurs at the interface of offshore sands bars and rip currents.

FA: F (FT *Ft* and *Fml*): Offshore, prodelta to platform deposits
Description. This FA consists of micrites to marls with few grains of plagioclase, chert, foraminifers and radiolarians, with low bioturbation. Facies type *Ft* consists of fining upward sequences, highly bioturbated, showing thin tempestites at the base, and structureless siltstone or mudstone above, with abundant *Globigerina*, benthic foraminifers and some gastropods (9) (Fig. 1). Facies type *Fml* consists of massive micrites, often with parallel bedding, also intercalated with grayish marls. Inside FT *Fml*, usually is observed thin reddish layers composed of medium grained sandstone (6, 7).
Interpretation. Facies type *Ft* consists of fine particles deposited possibly below the mean fairweather wave base, after storms and tempestites settlement from offshore transition to offshore environments. Further in offshore, the deposition of suspended fall-out particles below the mean storm wave base offers good conditions for carbonated deposition (FT *Fml*). This FA was deposited in a prodelta.

DISCUSSION
1. Stratigraphic framework and depositional architecture

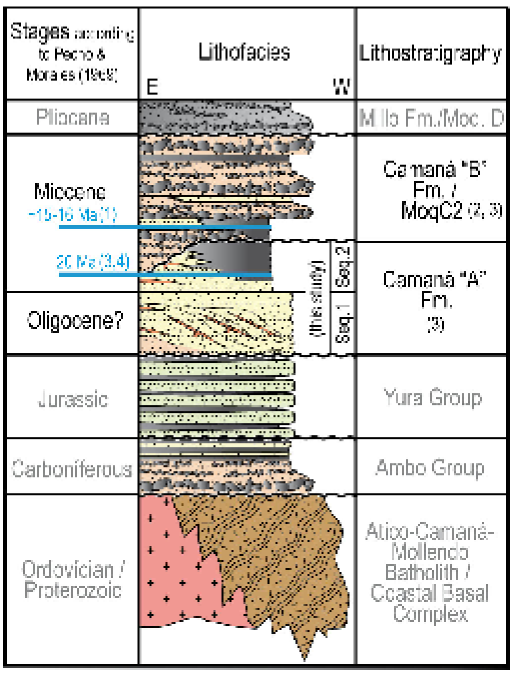

Fig. 2. Generalized stratigraphy of Camaná. (1) Ibaraki (1992), (2) Decou et al. (2011), (3) Sempere et al. (2004), (4) Schildgen et al. (2009).

Camaná Fm. Tertiary deposits correspond to a wave dominated coarse-grained delta, with recognizable bottomsets, foresets and topsets. The basal part of Camaná Fm. deposits might be represented by FT *Sb* in Playa La Chira. Above an unconformity lies Camaná "A" Fm. which is divided into two sequences (Figs. 2 and 3) (i) progradational deltaic lobes in foresets (Seq1), followed by (ii) topsets of Seq2, both separated by a ravinement surface (*rs*) (Fig. 3). Seq1 of Camaná "A" Fm. consists of clinothems containing the coarsest sediment fraction with incised channels. Seq1 was formed during a relative sea level fall, showing high progradational rate with offlaps and downlaps (Catuneanu, 2002), e.g. in Puente Camaná (site 3, Fig. 1). The sea level fall may correspond to the Upper Oligocene global sea level fall reported by Haq et al. (1987). In the same age, during Aymara tectonic phase (Jaillard et al., 2000), Tacaza volcanism was active in the Peruvian Altiplano (30-24 Ma, in Mamani et al., 2010). The *rs* is produced by a subsequent sea-level rise marked by waves at the shoreface, having relative flat morphology due to the distribution of waves (Postma, 1995; Catuneanu, 2002). Seq2 of Camaná "A" Fm. above the *rs* is thus deposited during a relative sea level highstand. Shallow marine facies of Seq2 are represented by onlapping healing-phase deposits (Posamentier & Allen, 1993) that accumulate in lower shoreface plus a transgressive lag that blanket the *rs* in the upper shoreface (Catuneanu, 2002), and could correspond to Upper Oligocene to Lower Miocene. However, an (U-Th)/He age of 19.6 Ma obtained from zircons grains in Quebrada Bandurria (Schildgen et al., 2009) collected few meters above the *rs*, suggest the that onset of the sea level rise in Seq2 correspond to Lower Miocene, contemporaneous with the Huaylillas volcanism (24-10 Ma in Mamani et al., 2010). In adittion, Sempere et al. (2004) reported an age of 20.83 ± 0.06 Ma (Ar-Ar in biotites) from one of the first volcanic ashes at the base of their Camaná "B" Fm. in Quebrada La Chira. This age suggest that the onset of the sedimentary input, likely from Western Cordillera (FT

Gcs), coincide with the deposition of Seq2 of Camaná “A” Fm in Lower Miocene. The marine ingression of Seq2 is thought to continue until ~15-16 Ma (biozones N8a, N8b, Ibaraki 1992), in facies that can be horizontally traced from Cerro Los Cerrillos until La Mina (FA´s S3 and F, in Fig. 3).

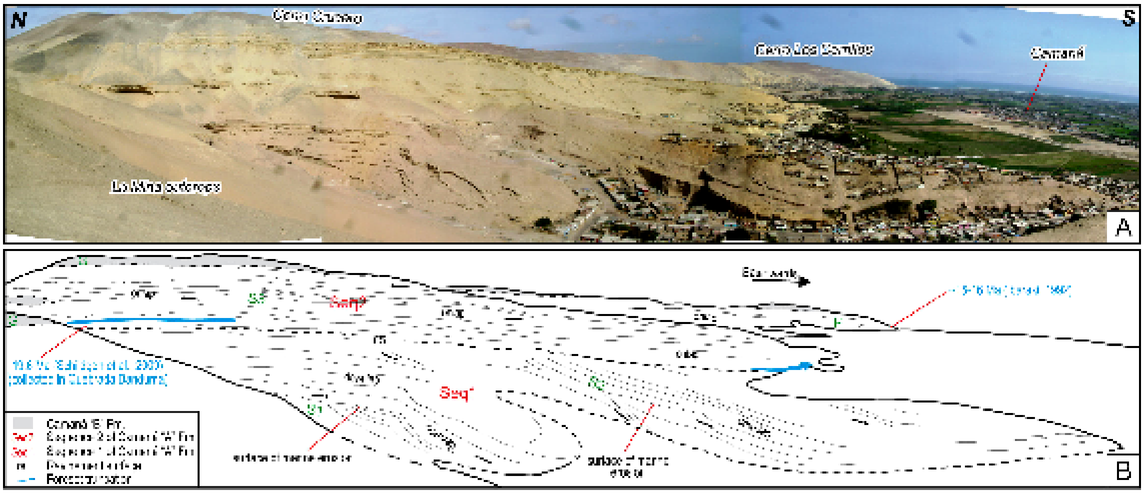

Fig. 3. La Mina outcrops (foreground) and proposed depositional system for Camaná Formation.

2. Tectonics relations between Pisco and Camaná deposits

In order to understand the tectonic regime of this region, Jaillard et al. (2000) suggest that in southern Peru, the Incaic 2 and Aymara tectonic phases, of Upper Eocene and Upper Oligocene age, respectively, caused significant subsidence. In this context, trancurrent stresses dominate in southern forearc, arc and SW Altiplano since at least ~30 Ma (Sempere & Jacay, 2006). In Pisco forearc basin, Bianchi (2004) and León et al. (2005) mentioned grabens formed by transtensive stresses associated to “strike-slip” deformations in Middle Eocene. These grabens occur along the NW-SE striking Cerrillos Fault System (CFS), with roughly perpendicular faults (SW-NE) as secondary structures (León et al., 2005), giving way to some rivers, e.g. Pisco (13°41´S), Santa Ana-Ica (14°26´S) and Caballas (15°00´S). In Camaná, a similar situation is given with the Atico-Ocoña-Camaná Fault System (AOCFS), which lineaments might be traced into the southern CFS, and whose secondary faults could be placed in the valleys of Ocoña (16°26´S), Camaná and Punta del Bombon (17°10´S) rivers.

3. Age of Camaná Formation

The age sedimentation, and for instance, the possible age of uplift of the Coastal Batholith along the Atico-Ocoña-Camaná Fault System is crucial for any interpretation of tectono-sedimentary relations. If the transtension along AOCFS hast started in Eocene, like for the CFS, the onset of the deposition of Camaná Fm. might correspond to Middle or Upper Eocene, similar in age to Caballas Fm. in Pisco basin. Sempere et al. (2004) suggested either Upper Eocene or Upper Oligocene for Camaná “A” Fm., implying a chronological equivalence between lower Camaná “A” Fm. and either MoqB Fm., or MoqC1 unit (Decou et al., 2011). Seq1 of Camaná “A” Fm. can be correlated with a rapid relative sea-level fall that exceeds subsidence (Catuneanu, 2002). However, if sedimentation in Seq1 of Camaná “A” Fm. was prior to ~30 Ma, can be suggested that transcurrent stresses in forearc (Sempere & Jacay, 2006) have influenced in sedimentary accommodation space and sediment input. A transgression is reported in Seq2 of Camaná “A” Fm., where it is assumed that the rate of sea level rise outpaces sediment input, however, a significant sedimentary input (FA: G) likely from the Western Cordillera 20 Ma ago (Sempere et al., 2004) suggest a significant sediment input contemporaneous to that transgression. Finally, the places showing the thickest deltaic stack of Camaná “A” Fm. are located around the actual Camaná river (3, 4, 5) (Fig. 1), and might suggest a significant activity of the shear zone which gave way to the Camaná paleodelta, and after time, the actual valley.

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