Sedimentation model of piggyback basins: Cenozoic examples of San Juan Precordillera, Argentina

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Abstract: Piggyback basins are one of the most important sediment storage systems for foredeep basins within foreland basin systems, so understanding the dynamics of sediment accumulation and allocyclic changes is essential. Three alluvial systems are proposed here to depict sediment movement along the piggyback basin: piedmont, axial and transference systems. We propose differentiation between open continental piggyback basins that include a transference system that is able to deliver sediment to the foredeep and closed piggyback basins that are isolated. Two idealized models of sedimentation in piggyback basins are proposed. For open piggyback basins we identify four stages: (a) the incision stage; (b) the confined low accommodation system tract; (c) the high accommodation system tract; and (d) the unconfined low accommodation system tract. Meanwhile two stages are proposed for closed ones: (a) the high accommodation system tract; and (b) the low accommodation system tract. To test these models, Quaternary deposits and a Miocene unit are analysed. The first one is controlled by climatic changes, and the second is related to tectonic activity in the Precordillera.

Most of the research in foreland basin systems (DeCelles & Giles 1996) has been focused on the evolution of the foredeep region and its relation to the orogenic wedge and the forebulge areas (Jordan 1981, 1995; Beaumont et al. 1988; Flemings & Jordan 1989; Mitrovica et al. 1989; Holt & Stern 1994; Johnson & Beaumont 1995; DeCelles & Giles 1996; Limarino et al. 2001; DeCelles & Horton 2003). These models are useful in understanding the sedimentary patterns in the foredeep as well as in establishing the close relationship between tectonism and sedimentary filling.

Even though they comprise a major storage system of sediments that can feed the foredeep, much less attention has been paid to piggyback basins, developed between thrust sheets, particularly the continental ones. Therefore, understanding the sedimentary dynamics of piggyback areas is important because: (a) piggyback basins are a significant reservoir of sediments exported periodically to the foreland (DeCelles & Giles 1996; Horton & DeCelles 2001; Suriano & Limarino 2006); (b) the volume of exported sediments from piggyback basins may even exceed the volume supplied by the orogenic front to the foredeep; (c) the stratigraphic record gives direct information about the uplifting of the different thrusts sheets and the advance of the clastic wedge; and (d) part of the foreland basin record that is eroded as the orogenic front advances can be preserved in the piggyback basins.

In this contribution the piggyback basins located along the Precordillera in the Argentinian Andes (San Juan Province, 30–31°S, Fig. 1) are analysed. This study intends to characterize the sedimentation patterns and dynamics of piggyback basins as well as to propose a new classification and to establish a sequence stratigraphic model. In order to accomplish these goals, the work is divided in two sections. First, a stratigraphic model based on the changes in the accommodation space is built, taking into account the analysis of piggyback basins, their definition, main sedimentological features, sedimentary environments, stacking patterns and relationship with allocyclic controls. In the second part, the proposed model is tested, analysing two stratigraphic successions (Quaternary deposits and Miocene unit) of the Jáchal River area, controlled by climatic and tectonic changes.

Piggyback basin concept

The piggyback basins were defined by Ori & Friend (1984) as ‘basins that are formed and filled up while

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Fig. 1. Location maps. (a) Morphotectonic units related to the Andean orogen at 30° S; numbers indicate the three major sectors of the Precordillera (1, western; 2, central and 3, eastern), the white frame shows the location of (b). (b) Geological map, where two main domains can be recognized: mainly granitic and volcanic (Cordillera) in the west and a metasedimentary one in the east (Precordillera); the frame shows the location of Figure 7.
being carried on top of thrust sheets’. This term is similar to ‘satellite basins’ proposed by Ricci Lucchi (1986). Thrust-top basins or parched basins (Turner 1990; Butler & Grasso 1993; Butler et al. 1995; Bonini et al. 1999; Doglioni et al. 1999; Hesse et al. 2010) have a related meaning, although they indicate a more specific arrangement associated with basins that are formed and filled up while a portion of the foreland basin is dismantled. According to the above, piggyback and satellite basins are synonymous, and they are related to thrust-top and parched basins. Years later, piggyback basins were included by DeCelles & Giles (1996) in their wedge-top depozone within the foreland system. Gugliotta (2012) divides the wedge-top depozone in inner and outer sequences. In this paper, we follow this terminology, using the term inner-wedge-top depozone for the piggyback area, which designates basins separated from the foreland by thrust sheets or anticlines, while the outer-wedge-top depozone is where blind thrust structures have no superficial expression. This last zone transitionally passes into the foredeep.

Sedimentary dynamics of piggyback basins

To understand the auto and allocyclic factors that could affect sedimentation in piggyback basins, it is essential to inspect the sediment movement pattern all along the basin. Based on the studied examples, the pattern of sediment circulation in continental piggyback basins is here related to three alluvial systems (Fig. 2). The first one corresponds to the piedmont systems, which convey poorly sorted breccias and conglomerates directly from the mountain front to the floor of the basin. This environment includes taluses, different kinds of colluvial fans (Bilker & Nemec 1998), alluvial fans and alluvial slopes. In the case studied here, four piedmont associations related to accommodation space were recognized (Fig. 3; Suriano & Limarino 2009). As the piedmont area has permanent availability of material from the mountain front, the movement of sediment is regulated by axial systems and, if present, by the transference system.

Sediment transport along the elongate axis of the piggyback basins is represented by longitudinal, frequently braided channels (the collector river–conoid systems of Suriano & Limarino 2009). As shown by Suriano & Limarino (2009), these systems are defined as conoids and the associated collector river as axial distributary systems.

Finally, the transference systems (Fig. 2) connect piggyback basins among them and to the foreland basin. These transference systems can be represented by different kinds of rivers or even by open lacustrine arrangements.

Regarding this occurrence, we propose that continental piggyback basins (Type 2 of Wagerich 2001) can be classified into two main types, open and closed (Fig. 4). The open piggyback basins are those including a transference system that connects them and is able to export sediment to the foreland. Closed piggyback basins do not have a transference system, which makes them endorreic. A piggyback basin can shift from open to closed and vice versa owing to allocyclic factors, not only tectonics, directly related to the evolution of the fold and thrust belt, but also climatic

Fig. 2. Schematic distribution of the sedimentary circulation in piggyback basins.
modifications that affect the erosion capability of the transference system.

Open piggyback basins can change from highly efficient to inefficient (or vice versa) according to the efficacy of the major sediment exporter system formed by the fluvial systems inside the piggyback basin and transference system. Highly efficient transference systems are those able to export all the sediment delivered by piggyback basins to the foredeep (Fig. 4). In contrast, a transference system is inefficient if it is not able to transport the material from the piggyback to the foredeep

Fig. 3. Arid piedmont associations for the Precordillera (modified from Suriano & Limarino 2009). Highest energy corresponds to association 1, composed of taluses and colluvial fans with steeper slopes; if there is enough lateral space this association could evolve into association 2. Association 3 is related to gentle slope mountain fronts as much as association 4, which develops in wider valleys and evolved drainages.

Fig. 4. Piggyback basin classification proposed in this work.
(Fig. 4), which leads to the storage of sediment inside the piggyback basin.

Before building a sedimentary model for piggyback basins it is important to examine the factors that control their patterns of sedimentation. They can be local if they affect each basin individually or regional if they have influence over the entire orogenic wedge. Another equally significant aspect to take into account is if those factors affect the accommodation space (A) and/or the sediment supply (S). These factors and their effects are shown in Figure 5.

A local factor that increases the relationship A/S is the upstream thrust movement (Fig. 5a). This factor produces an increase in the accommodation space in the footwall as well a higher sediment supply from the hanging wall. Another way of increasing accommodation space is a local base level rise (Fig. 5b, c). This could be generated by a sediment dam within the basin (Fig. 5b) or by activity of the downstream thrust (Fig. 5c). Efficacy of this last factor is limited as major movements produce narrowing and shallowing of the basins, which decreases the accommodation space (Fig. 5d; Talling et al. 1995). Lower local A/S ratio could also be generated by a downstream river capture (Fig. 5e).

There are also regional factors affecting the A/S relationship. Increase of the A/S ratio owing to subsidence is related to the structural arrangement and dynamics of the orogenic wedge, with regard to tectonic loading and to slab pull (Fig. 5f). Decrease in the accommodation space is instead associated with periods of tectonic quietness and isostatic rebound (Fig. 5h). Fluvial equilibrium profiles, independently of their driving force, could rise (Fig. 5g) or fall (Fig. 5i), causing an increase or decrease in the accommodation space. Finally, dramatic changes in the amount of sediment production, owing to climatic factors or the

### Fig. 5. Allocyclic controls on piggyback sedimentation.
occurrence of explosive volcanism, should be taken into account.

The piggyback sedimentary models presented here are based on the principles of sequence stratigraphy in continental environments (e.g. Shanley & McCabe 1994; Quirk 1996; Dahle et al. 1997; Dalrymple et al. 1998; Blum & Törnqvist 2000; Miall 2002). According to Dahle et al. (1997), two major stages can be recognized in continental basins disconnected of the sea-level: (a) the high accommodation system tract; and (b) the low accommodation system tract. This proposal detaches system tracts from sea-level and relates them to changes in accommodation space (Catuneanu 2006). Following Shanley & McCabe (1994) and Dalrymple et al. (1998), discontinuities generated by fluvial incision are used here as sequence boundaries. Two kinds of erosive bounding surfaces were recognized according to their degree of confinement (confined or unconfined). Finally the existence of sedimentological evidence of the presence of a fluvial transference system can be used to differentiate open from closed piggyback basins, a concept that is also incorporated in the proposed model.

**Model for piggyback basins**

Using the elements mentioned above we constructed a sedimentary model for continental piggyback basins that is based on the temporal variations of accommodation space and sediment supply. These changes are based in four supporting elements: (a) basin subsidence; (b) tectonic activity in the fold and thrust belt; and (c) changes in sediment amount by climatic changes and/or major explosive volcanism.

Subsidence in piggyback basins has been considered short-lived and of much smaller magnitude than that at the associated foredeep (Xie & Heller 2009). In fact, subsidence owing to tectonic loading, a major mechanism in foreland basins (Jordan 1981; Naylor & Sinclair 2008), has lower values in piggyback areas (Zoetemeijer et al. 1993; Xie & Heller 2009). The key factor in the creation of local accommodation space in most piggyback basins is the tectonic activity in the upstream thrust sheet (tectonically induced accommodation, Fig. 5a), which in turn produces migration of the depocentre (Bonini et al. 1999; Zoetemeijer et al. 1993). In this sense, migration of the depocentres in piggyback basins has been associated with passive rotation of the internal thrusts owing to the successive external thrust activation (Bonini et al. 1999; Roure 2008) or active thrusting. In this last case, migration of the depocentre towards the foredeep has been interpreted as in-phase thrusting sequences while hinterland-directed depocentre migration seems to be related to out-of-phase thrusting (Zoetemeijer et al. 1993). In the same way Bonini et al. (1999) showed that the depocentre migration is controlled by the thrust having the highest displacement rate.

Sequence deposition is essentially ruled by the above factors, which affect the A/S relationship. On this basis we propose a sequence stratigraphy model for open piggyback basins involving: (a) the incision stage; (b) the confined low accommodation system tract; (c) the high accommodation system tract; and (d) the unconfined low accommodation system tract or overfill stage (Fig. 6).

The first stage or incision stage begins with an important drop in the equilibrium profile (a in Fig. 6) that produces incision in the transference system and generates the entrenchment of the piedmont system and the development of an incision surface across the basin (incision stage, a in Fig. 6). As Shanley & McCabe (1994) pointed out, even in high-incision events some remnant deposits can be found in the sides of the valley owing to short moments of stabilization during this mainly erosive phase.

The confined low accommodation system tract can be separated into two substages. The first one takes place following the incision stage when there is a time of relative instability during which the river profile is close to equilibrium, generating the infilling of incised transference system deposits (b in Fig. 6). In this stage deposition of a coarsening-up incised channel complex can be observed (Catuneanu 2006). The amount of sediment involved during this stage relates to the time span of this unstable situation and therefore it is not always recognized. The next stage occurs when the river profile reaches or is slightly above the equilibrium profile. At that point slow aggradation takes place in the previously eroded piggyback area (c in Fig. 6). This stage is denoted by the presence of amalgamated high-energy braided channels, generated by the transference system and also by limited aggradation in the piggyback area.

If the rise of the equilibrium profile continues, the transference system produces high aggradation in its alluvial plain, promoting high equilibrium profiles in the axial and piedmont systems and the consequent filling of the piggyback basins (high accommodation system tract, d in Fig. 6). As the sediment supply from the mountain front is more or less continuous, if no new accommodation space is created, the basin tends to fill up, reaching the unconfined low accommodation system tract (or overfill stage, e in Fig. 6).

For closed piggyback basins, only two stages are proposed. Initially, when the basin is created, the A/S ratio is high, so there is also high
Fig. 6. Proposed model for piggyback basin evolution. (a) Schematic sedimentary section. (b) Transference system profile and its equilibrium profile through time. Numbers relate to time.
accommodation space. This stage is dominated by fine-grained playa lake deposits (f in Fig. 6) with an external ring of coarse piedmont facies. Again, if there is no newly created accommodation space, the basin tends to fill up, and the overfill stage is developed. This stage is represented by the progradation of low-energy piedmont associations (2 in Fig. 3) like alluvial slopes and fluid flow-dominated colluvial fans and a marked decrease in the area previously occupied by playa lake deposits. The late stage of this system tract is characterized by a decrease in sediment supply associated with an extensive aeolian reworking and development of a desert pavement.

**Stratigraphic context**

Between 30° and 31°S, the Andean orogen is made up of five morphotectonic units (Fig. 1a): (a) western and higher Cordillera de los Andes; (b) the wide intermontane Rodeo–Iglesia Basin; (c) the fold and fault thrust belt of Precordillera; (d) the Bermejo Basin; and (e) the Pampean Ranges. In this area the Cordillera Frontal (part of (a)) is composed of a Carboniferous metasedimentary rocks (Cerro de Agua Negra Formation), Triassic batholiths (Llambíás & Sato 1990) and Triassic to Miocene volcanic rocks (Ramos 1999). To the east, the wide Rodeo-Iglesia Basin is developed, where Cenozoic volcaniclastic rocks are exposed.

The Precordillera belt is divided into three structural provinces (Fig. 1a): western, central and eastern (Ortiz & Zambrano 1981). The studied area is located within the western Precordillera (Fig. 1b), which has been built since the Early Miocene (Jordan et al. 1993, 2001; Cardozo & Jordan 2001; Alonso et al. 2011) by eastward migration of the orogenic front. The thin-skinned fold and thrust belt of the western Precordillera expose Early Palaeozoic rock sheets that contain the Miocene to Holocene piggyback sedimentation. In particular, we studied the Quaternary piggyback basins along the Jáchal River (Figs 1b & 7) and the Cuesta del Viento Formation, a Miocene unit deposited within the same stratigraphic context (Fig. 7). The western Precordillera is characterized by its west vergence of thick-skinned structures (Zapata & Allmendinger 1996). Finally, Bermejo Basin separates the Precordillera from the basement uplifted blocks of Pampean Ranges.

**Depositional sequences**

**Sequence 1: pediment.** The base of this unit is formed by a low-relief erosive pedimentation surface on Miocene and Palaeozoic deformed rocks. Over this unconformity a relatively thin layer (up to 10 m thick) of Quaternary deposits is found (Fig. 8). These deposits are dominated by monomictic breccias of piedmont accumulations with minor participation of lenses of polimictic conglomerates.

The monomictic breccias are fine-grained and occur mainly as clast-supported tabular, massive or horizontally stratified beds. Lenticular bodies of massive mud-supported breccias interbedded with clast-supported breccias are scarce. The latter show planar cross-bedding or clast imbrications, and it is worth mentioning that their scarcity does not allow a statistical measurement of palaeocurrents. Clasts are pebbles, mainly slates (more than 95%) and basic volcanic rocks derived from the Yerba Loca Formation, which indicates local provenance as it is the sole unit outcropping in the Precordillera in the area. Deposits are interpreted as having formed in alluvial slopes (Smith 2000) with minor participation of colluvial fans (Bilkra & Nemec 1998), so they can be interpreted as a low-energy piedmont association (2 in Fig. 3).

The infrequent polimictic conglomerates are coarse, well-rounded and clast-supported. They show imbrication, horizontal and planar cross-bedding. They appear as lenticular to lentiform beds and are interpreted as gravel bars in a multichannelized fluvial system. Cobbles are dominated by granites and acid volcanics fragments. These lithologies are widely present at the Colángüi Cordillera located to the west (Fig. 1b), indicating an external provenance. An ancient transference system (ancient Jáchal River) draining the Precordillera from west (Cordillera de los Andes) to east basins was analysed in detail. Taking into account the presence of incision surfaces, resulting in decametric- to metric-scale relief, the sedimentary infill of the four Jáchal River piggyback basins (La Tranca, Caracol, Zanja Honda and Pachimoco) was divided into four depositional sequences (Fig. 8). The Pleistocene–Holocene sequences studied here do not show evidence of significant tectonic disturbance. This suggests that tectonic uplift of thrust sheets was not a main mechanism to produce changes in the accommodation space during Pleistocene–Holocene times. Moreover, the lack of evidence of volcanic activity (Kay et al. 1988) sets climate change as a major allocyclic control for sedimentation in these basins. In addition, the sequence’s age fits with regional climate changes (Iriondo 1999).

**Dynamics of the Quaternary piggyback basins of Jáchal River area**

In order to apply the models described to the Jáchal River area, the Quaternary filling of the piggyback
(present day foredeep) can be interpreted from the clast composition of this conglomerate unit.

Sequence II: Quaternary incised valley. The lower boundary of Sequence II is a high relief surface carved on Quaternary deposits of Sequence I, Miocene or Palaeozoic rocks (Figs 8 & 9a). Deposits are few and scattered, with relatively small thicknesses (up to 25 m). This unit is dominated by polimictic conglomerates with scarce intercalations of gravelly sandstones.

The polimictic conglomerates are coarse to very coarse and clast-supported, with erosive base, and occur as massive or planar cross-bedded beds.
The clasts (sized up to boulders) are rounded to well-rounded, compositions are granite and acid-volcanic (reflecting external provenance), with little participation of greenish grey and yellow sandstones, quartz and greenish slates. The gravelly sandstones have planar or trough cross-bedding. The described facies are interpreted as ancient Jáchal River deposits, as they are similar to the present Jáchal River, sharing the provenance, lithology and sedimentary structures. Occasionally, breccias associated with taluses, coluvial fans and collector rivers (piedmont and axial systems) are interbedded within the fluvial conglomerate.

We correlate this sequence with an important erosive event responsible for the generation of the lowest Quaternary valley floor, which can be traced up to Llano del Médano, an upstream site (Fig. 1b), where the incision is evidenced by several hundred metres of relief between the oldest Quaternary deposits and the valley floor (Suriano & Limarino 2006). The eroded material was probably exported from the piggyback area and formed two megafans (Damanti 1993; Horton & DeCelles 2001) that can currently be seen at the mouth of Huaco and Jáchal Rivers in the Bermejo Valley (Fig. 10).

**Sequence III: sedimentary dams.** The lower boundary of this sequence largely fits the incision marking the base of Sequence II (Fig. 8). Above this surface, there is one of the thickest and best preserved Quaternary units in the area, characterized by the presence of conspicuous intermontane shallow lacustrine sediments (Colombo et al. 2000, 2005, 2009; Suriano & Limarino 2005, 2008, 2009). Deposits of these natural dams can be found in Rodeo, La Tranca, Caracol and Zanja Honda basins, all of them with similar characteristics. Three main facies associations could be recognized in the lacustrine system: (a) siltstones and fine sandstones; (b) monomictic roughly stratified breccias; and (c) polymictic conglomerates.

The fine-grained association is dominant and is formed mainly by muddy and sandy lithofacies (1 in Fig. 11a, c) with scarce breccias. Tabular beds of whitish grey mudstones with horizontal lamination or massive are abundant. Mudstones commonly show root marks and mudcracks and there are also some levels with shells of freshwater gastropods (Colombo et al. 2005) and others with plant remains. Brown shales with high contents of organic matter are present, though scarce. Gypsum levels are present towards the top. Light brown sandstones are massive or with ripple lamination, and some planar cross-bedded structures are also found.

Fine-grained lithofacies are interpreted as produced by both decantation and underflows, which according to May et al. (1999) can take place in shallow lacustrine environments. The ephemeral nature of the lake system is inferred by the root marks, mudcracks and evaporite deposits at the top of the association (May et al. 1999; Colombo et al. 2009). Massive sandstones represent rapid deposition from sheet floods. Horizontally laminated sandy lithofacies record the migration of subaqueous micro- and mesoforms and represent the coastal zone of the lake when dominant.

The palynological assemblage of these lacustrine deposits has been studied by Colombo et al. (2009), who proposed periods of heavy rain, alternating with episodes of extreme aridity in a warm climate for the base of the section, turning arid towards the top. Colombo et al. (2005) dated gastropods shells and organic matter by $^{14}$C technique obtaining ages from 8930 ± 50 (near the base of the lacustrine deposits) to 6497 ± 45 years BP (in the upper part). These ages indicate that the lacustrine system persisted for at least 2700 years.
This fine-grained association alternates with breccia levels. Roughly stratified matrix- and clast-supported monomictic breccias appear as tabular massive beds. Some of them also show imbricated clasts, normal gradation or planar cross-beded stratification. Massive and laminated mudstones occur to the top of some bodies.

Breccias are clearly dominant downstream (2 in Fig. 11c), and are interpreted as conoids (axial distributaries systems). As they always occur downstream from the lacustrine deposits, these breccias are interpreted as resulting from the dam closure (Fig. 11d, Colombo et al. 2000, 2009 Suriano & Limarino 2005).
While downstream the muddy lacustrine association pinches out into conoid facies, upstream intercalations of polimictic conglomerates become frequent (at left in Fig. 11c), forming the last facies association. The beds of polimictic conglomerate form biconvex beds from 2 to 7 m in thickness. They show horizontal, planar cross-bedded or massive structures. Between the conglomeratic beds, sandy facies are common, forming beds up to 1 m with a coarsening upward arrangement (3 in Fig. 11b).

The interpretation of these deposits and their lateral variations is shown in Figure 12. Fine-grained sediments are found at the centre zone of the lake (Fig. 11a). In the upstream area, the transference system (ancient Jáchal River) flowing into the lake generated a microdeltaic arrangement (Fig. 11b). Figure 11c shows the natural dam deposits represented by the light grey fine lacustrine sediments that laterally pinch out to the downstream conoid breccias (dark grey) responsible for the dam closure. The above-described arrangement is related to a high equilibrium profile in the transference system owing to the damming that also caused a local level rise in the whole piggyback basin, so that aggradation was favoured. This led to the deposition of thick units in conoids and collector rivers (axial systems) as well as in the piedmont areas.

Sequence IV Jáchal River. This stage is developed over an important incision surface that corresponds to the present Jáchal River Valley (Fig. 8) and includes two subsequences. The first subsequence (IVa) involves the highest terraced levels dated by Colombo et al. (2005) in La Tranca area between $978 \pm 20$ and $525 \pm 32$ years BP. This unit is composed of two types of deposits, the first characterized by clast-supported conglomerates and sandstones with lenticular to lentiform geometry, which represents channel facies, and the second corresponding to tabular mudstones floodplain beds.

The conglomerates of the channel facies have clasts of granite and acid volcanic rocks, indicating a foreign provenance similar to those of the Stage II,
but clasts have a smaller mean diameter (minor to 30 cm). There are two types of channel arrangements according to their hierarchy; the first one is dominated by polimictic clast-supported conglomerates. Some of the beds begin with massive or imbricate conglomerates, but overlying clast-supported conglomerates are a conspicuous lithofacies, with planar cross-bedding and horizontal stratification. On top of beds, gravelly sandstones and sandstones with planar cross-bedded and horizontal lamination are found. This arrangement corresponds to migrating transversal and longitudinal gravelly bars (Hein & Walker 1977). Considering the geometry of the beds, they are interpreted as migrating in a conglomeratic channel of low to medium sinuosity.

The second type of channel facies (Fig. 9b) comprises gravelly sandstone or sandstone lenticular beds. Massive or horizontally laminated fine-grained conglomerates or gravelly sandstones are found at the base. Above them, sandstones with planar and trough cross-bedded stratification occur. This association is interpreted as having been deposited by sinuous channels in which longitudinal gravel bars and 2D and 3D sand dunes migrated.

Fig. 11. Scheme and pictures from the Quaternary lacustrine arrangement. (a) Dam–lacustrine fine-grained association. (b) Coarsening-up cycles from a micodeltaic system. (c) Closure of a dam represented by conoid facies, laterally related to fine dam–lacustrine facies. (d) Scheme of the dam facies; numbers in the scheme correspond to those shown in the photos.
Floodplain beds are the dominant facies of the Subsequence IVa. They are formed by mudstones and subordinated sandstones. Mudstones show horizontal lamination, ripple cross lamination or massive structures. They are greenish or light brown and have intense root bioturbation. Sporadic beds of planar cross-bedded, horizontally laminated or massive sandstones are intercalated within

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Fig. 12. Schematic section of the Quaternary sequences, with system tract interpretation and geological events that caused them (right column).
mudstones. The fine-grained lithofacies were formed by decantation or low-energy fluid flows in the waning of floods. These floodplains (Fig. 9b) show different degrees of maturity (according to Reinfelds & Nanson 1993), which range from incipient to well evolved, this last one with important development of palaeosols. During the flood events, the sandstones reach these areas with the migration of megaripples, plane bed or sudden deposition by competence loss.

In summary, this association is characterized by different hierarchy channels with low to intermediate sinuosity and extensive development of confined floodplains (Nanson & Croke 1992). Therefore we interpret the subsequence IVa as an anastomosed fluvial system (Smith & Smith 1980; Nadon 1994), which represents the Early Holocene dynamics of the Jáchal River.

Subsequence IVa is best developed in Pachimoco area (Fig. 2), where a wider piggyback basin allowed for the deposition of large amounts of fine-grained deposits (Pachimoco Formation after Furque 1979) of ancient Jáchal River. Subsequence IVb includes the recent and present deposits of the Jáchal River, younger than 525 ± 32 years BP. Its lower limit is marked by a low relief surface (up to 5 m high) carved into the Subsequence IVa deposits (Fig. 8). Above this surface, the youngest terraces and active channels with scarce floodplains of the Jáchal River are found. In addition to the incision surface between them, the difference among Subsequences IVa and b is the minor participation of fine-grained floodplain deposits in Subsequence IVb that could be described as a bed load-dominated system intermediate between braided and wandering (Miall 1996).

**Accommodation stages in the Quaternary Precordillera’s piggyback basins**

In this section, we present the evolution of the Quaternary sequences in the context of temporal changes in relative accommodation space and sediment supply. The scenario before the deposition of Sequence I is a regional-scale erosive surface (pediment) carved into Palaeozoic to Miocene rocks (Figs 9a, 12 & 13). This low-relief surface indicates a long erosive period. Its origin cannot be stated unequivocally but may be associated with a period of relative tectonic quiescence of the fold and fault thrust belt. Tectonic quiescence could have been related to an isostatic rebound phase owing to erosion, during which a slow but continuous fall in the equilibrium profile (Fig. 13) led to an important erosive event throughout the entire orogenic wedge, generating a pedimentation surface all over the piggyback area. That situation was followed by a small rise in the equilibrium profile that produced a relatively thin layer of breccias and conglomerates of Sequence I deposited in...
an unconfined low accommodation system tract (overfill stage; Fig. 12).

Then, long-term degradation in the piggyback area, which generated the present valley of the Jáchal River, took place. This phase had probably begun in late Pleistocene and involved an intensive erosion period, with a low degree of discontinuous stages of deposition in isolated patches which were gathered within Sequence II (incision stage; Figs 12–14a).

The origin of Sequence II is related to deglaciation times that took place after the late glacial maximum (isotopic stage 2; Iriondo & Kröling 1996; Iriondo 1999), when the Cordillera de los Andes was glaciated (above 3500 m). During the deglaciation (between 15 500 and 16 500 years BP; Iriondo & Kröling 1996) melted ice generated high discharge in rivers that drained the Andes, including the transference systems across the Pre-cordillera (i.e. Huaco and Jáchal Rivers), all of them with catchment areas including large portions of glaciated regions. The climate amelioration caused a higher flow of the transference fluvial systems that increased its efficiency and produced the fall of the equilibrium profile (Fig. 13). As a result of this, huge volumes of sediments eroded, promoting the deposition of large megafans (DeCelles & Cavazza 1999; Horton & DeCelles 2001) in the foredeep. According to Damanti (1993), the megafans of Huaco and Jáchal reach areas of 700 and 1400 km² with catchment areas of 7100 and 27 700 km², respectively. Owing to the huge amount of sediment delivered to the foredeep, Bermejo River had to divert its course next to the Pampean range.

Sequence III deposits represent the end of the deglaciation phase little before 8930 ± 50 to beyond 6.497 ± 45 years BP (Colombo et al. 2005), when a dramatic fall in the flow rates of the transference rivers occurred. This situation favoured high rates of aggradation (up to 150 m thickness) and the occurrence of the high accommodation system tract (Figs 12 & 13) in the piggyback basins. Note that these ages, according to our interpretation, are related to climatic amelioration proposed by Iriondo & Kröling (1996). During this period, the loss of efficiency of the transference system together with an increase in sediment supply from piggyback basins could have produced the advance of these axial systems (conoid-collector

![Fig. 14. Block diagrams of the Jáchal River-related basins. C2 = sediment transport efficiency of the longitudinal fluvial system; C3 = sediment transport efficiency of the transference system. (a) Sequence II deposition arrangement scheme (mainly erosive phase, few related isolated deposits). (b) Sequence III deposition scheme.](http://sp.lyellcollection.org/)
rivers) over the transference system valley. In addition, it would have led to the formation of the numerous sedimentary dams (La Tranca, Caracol and Zanja Honda), recorded at the margins of the present Jáchal River Valley (Figs 11c & 14b). The increase of sediment supply can be related to the humid period associated with the deglaciation proposed by García et al. (1999) for the southern Precordillera. It is also consistent with the pollen record of the base of the lacustrine sediments in the area studied by Colombo et al. (2009). Although thick monomictic breccias, from piedmont and axial systems, were deposited in the piggyback area, it is important to point out that, despite the local high sediment supply and the low efficiency of the transference system, the overfill stage was never reached. This was probably due to the large accommodation space created during the previous stage (deglaciation; Figs 12 & 13).

A new incision surface, which contains terraces and the present day alluvial belt of the Jáchal River, was carved into the lacustrine deposits of the Sequence III, which form the lower boundary of Sequence Vla. The origin of the change in the accommodation space between sequences III and IVa is not clear, but it may have resulted from the adjustment of the transference system to its regional base-level fall (the Bermejo River). This was associated with the end of lacustrine system sedimentation (the local-base level of the piggyback basins in Sequence III), which could be related to the breaking of dams by connection with the foredeep (regional-base level) and/or the readjustment to the new base level (probably falling by a continued subsidence in the foredeep). For this reason the Jáchal River produced an incision in its valley in order to catch up with its new base level (degradation stage in the base of Sequence IV; Figs 8, 12 & 13). This period of degradation, with very limited or no aggradation, also reached the piggyback area. From 978 ± 20 to 525 ± 32 years BP (Colombo et al. 2005) the Jáchal River had a short aggradation period recorded by Sequence IVa, corresponding to a high accommodation system tract (Fig. 12). A minor incision surface (Figs 8 & 12) separates Sequence IVa from the present-day fluvial deposits of the Jáchal River, only interrupted by short episodes of aggradation limited to the transference system that form Sequence IVb.

Ancient record of piggyback basin sedimentation in La Tranca

The proposed model for piggyback sedimentation can also be applied to ancient settings. As an example, we analysed the Cuesta del Viento Formation, a Miocene unit, described and proposed by Suriano et al. (2011), located within the same geographic context as the previous Quaternary basins. These are the oldest synorogenic strata in the area and record the transition from outer-wedge-top to inner-wedge-top (piggyback basin) sedimentation. The upper section was dated as Lower Miocene (19.5 ± 1.1 and 19.1 ± 1.3 Ma) by Jordan et al. (1993).

Sedimentary environments

This unit was studied in detail by Suriano et al. (2011), who have defined six facies association that are summarized here.

Facies association 1 (chaotic breccias). This facies association comprises monomictic breccias, with metamorphic clasts from the Yerba Loca Formation. They are dominated by coarse-grained chaotic matrix-supported massive breccias (Fig. 9c) in beds up to 60 cm thick. Massive and imbricated clast-supported breccias in lenticular amalgamated beds also appear. This is interpreted as a high energy piedmont arrangement composed of hyperconcentrated flow-dominated colluvial fans, with some participation of taluses (1 in Fig. 3).

Facies association 2 (breccias). This facies association is composed of breccias with the same provenance as facies association 1, sandstones and mudstones (Fig. 15). It is dominated by clast-supported massive and imbricated breccias. Matrix-supported breccias appear as tabular bodies with massive or strong parallel fabric deposited by hyperconcentrated flows (Bilkra & Nemec 1998). Sandstones and gravelly sandstones locally appear with massive, planar cross-bedded or horizontal lamination. These lithofacies are more common to the top of the section (Fig. 15). Massive and laminated mudstones also appear as milimetric mud drapes or as continuous centimetre-thick levels.

This facies association is interpreted as braided river deposits, in particular a transitional system between gravel-bed braided with sediment-gravity-flow and shallow gravel-bed braided types of Miaill (1996). The full interpretation of this facies association depends upon its geomorphic context (Suriano et al. 2011). At both the bottom and the top of the section (Fig. 15) it appears as braided channels developed in piedmonts, colluvial fans and alluvial slopes, associated with proximal facies. In contrast, in the middle part of the unit an alternation of transference and dam facies occurs, allowing their interpretation as collector river deposits (axial systems). These interpretations are supported by the scarce clast imbrications observed (Fig. 15), which are not abundant enough to make a statistical analysis.
Fig. 15. Sedimentary section of Cuesta del Viento Formation and summary of its facies associations, characteristics and interpretation.
Sedimentation model of piggyback basins

Facies association 3 (polimictic conglomerates). This unit comprises lenses of coarse- to fine-grained clast-supported conglomerates and sandstones. The conglomerates bearing granites, mudstones, slates, acid and ultrabasic volcanic clasts record a mixture of local and foreign provenance (Suriano et al. 2011). The conglomeratic lenses occur as massive beds or with imbricated or horizontally stratified structures, thus indicating the deposition of transversal gravel bars (Hein & Walker 1977). Subordinately massive or horizontally laminated sandstones appear as bar tops. Tabular beds of sandstones and mudstones, massive or laminated, deposited in a floodplain environment are also present.

This facies association is interpreted as a low-sinuosity river with channels of multiple hierarchies, similar to the deep gravel-bed braided river of Miall (1996) or the Donjek type of Williams & Rust (1969). Owing to its lithology and environmental interpretation, this association is envisaged as a transference system, which represents the ancient Jáchal River.

Facies association 4 (mudstones with polimictic conglomerates). Two fine-grained facies associations were recognized in this formation. The facies association 4; Fig. 9d) is formed from coarsening-up cycles up to 20 m thick. The cycles are dominated by massive or slightly laminated light brown mudstones, intercalated with fine-grained sandstones. Deposition took place owing to alternating processes of sheetfloods (Davis 1938) and decantation. These facies are overlaid by sandstones with ripple cross-lamination and planar cross-bedded, which are covered in turn by lenses of polimictic conglomerates. Conglomerate composition is similar to that described in the facies association 2, highlighting a mixing of local and external provenance. Conglomerate beds have an erosive base and appear as massive or planar cross stratification, deposited by channelized fluid flows.

In summary, facies association 4 is interpreted as the occurrence of clastic ephemeral lake (natural damming) associated with microdeltaic bars facies related to ancient Jáchal River. The fine-grained tabular facies are related to lacustrine deposits and the sandstones and conglomerates in coarsening arrangements are interpreted as microdeltaic bars facies in the ancient Jáchal channel mouths.

Facies association 5 (mudstones with monomictic breccias). This facies association (Fig. 9e, f) is formed from thick tabular beds of light greenish mudstones, dominantly laminated. Coarsening-up arrangements of laminated sands and massive and trough cross-bedded breccias, with local provenance, appear in a minor proportion. This association is interpreted as closed ephemeral clastic lacustrine system deposits, dominated by decantation processes and the prograding lobes of sandstone sheetfloods or thin monomictic gravel bars with local provenance (microdeltaic facies with local provenance).

Facies association 6 (stratified breccias). This is made up of tabular beds of 10–20 cm of thickness composed of fine to medium clast-supported breccias, imbricated or massive. Locally, some lenses of planar cross-bedded stratification are found. Some palaeocurrent measurements indicate east to west direction of flow. This unit is interpreted as shallow channels with broad interchannel areas dominated by gravel sheetfloods, corresponding to alluvial slopes (Smith 2000) developed in a low-energy piedmont environment (2 in Fig. 5).

Basin evolution

The Cuesta del Viento Formation records the earliest stages of the Bermejo Foreland Basin (Jordan et al. 1993, 2001; Alonso et al. 2011; Suriano et al. 2011), related to the uplift of the Sierra de La Tranca. The base of the unit (Figs 15 & 16, facies association 1 and 2) corresponds to wedge-top deposition in the inner wedge-top depocentre, represented by the development of high-energy and local provenance piedmont (Figs 16 & 17a). Overlying this basal unit, lower-energy piedmont facies were deposited, represented by braided channels of colluvial fans. Finally, the last facies associations deposited in this basin correspond to the ancient Jáchal River, interbedded with colluvial fans (Fig. 16, facies associations 3 and 2).

As the Andean deformation advanced to the east, the uplift of the Caracol Range started. This phase represents the onset of the La Tranca area as a piggyback basin configuration, and the deposition of lacustrine and microdeltaic facies recording this change (Fig. 16, facies association 4). The dam was, in this case, related to an increase in the local accommodation space owing to the Caracol range uplift (Fig. 17b). Afterwards, the base level was readjusted to the foreland, probably because the damming was broken, an incision surface was carved (incision stage, Fig. 16) and axial systems prograded in response to a low equilibrium profile on the transference system (confined low accommodation system tract; Fig. 17c). Finally, the major uplift of the Caracol range took place. La Tranca area was isolated, forming a closed piggyback basin (Figs 16 & 17d), recording a high accommodation system tract, registered by muddy lacustrine deposits and a high-energy piedmont association (Fig. 16). In the latter phase, low-energy piedmont systems (facies association 3) prograded onto playa lake facies, producing the filling of
**Fig. 16.** Schematic section of the Cuesta del Viento Formation, with system tract interpretation and geological events that caused them (right column).
the basin (unconfined low accommodation system tract, Fig. 16).

Conclusions

The movement of sediments within continental piggyback basins can be sketched as driven by three different types of alluvial–fluvial systems: (a) piedmont accumulations (talus, different types of colluvial fans and, in wide enough basins, alluvial fans) forming alluvial aprons during mountain denudation; (b) axial fluvial systems which collect sediments derived from the piedmont area and transport them to transversal rivers; and (c) transfer-ence systems formed by large rivers draining the fold and thrust belt and transferring sediments from the piggyback basins to the foredeep region.

Despite the fact that this model is a simplification of the alluvial–fluvial systems in the Precordillera, it is useful to explain the transference of sediments not only within the piggyback basins but also from the piggyback area to the foreland. In addition, the existence of transference fluvial systems (in our case the Ja´chal River) enables the recognition of two different types of piggyback: open and closed piggyback basins (when the lack of transference fluvial systems prevents the trans-port of sediments from the piggyback to the foreland, turning the piggyback into an endorheic isolated basin). The evidence obtained from Ceno-zoic deposits as analysed in this paper clearly shows that open piggyback basins can undergo temporary closures and, in the same way, closed piggyback areas can be open when a new transference fluvial system develops in the thrust and fold belt.

The stratigraphic record of open piggyback basins has been divided in this paper into four major theoretical stages: (a) the incision stage; (b) a confined low accommodation system tract; (c) a high accommodation system tract; and (d) an unconfined low accommodation system tract or overfill stage. The incision stage is reached when long-lived periods of erosion within the piggyback allow/produce a massive transference of sediments to the foreland. Degradation stages are recorded by incision surfaces. These surfaces can be related not only to changes in subsidence or tectonism in the foreland or in the fold and thrust belt, but also to climatic fluctuations significant enough to pro-duce an increase in the sediment transport capacity of the third-order fluvial systems. The high accom-modation system tract is characterized by strong aggradation in the piggyback basins mainly related to either low rates of subsidence in the foredeep or inefficiency of the transference fluvial systems. Low-accommodation stages reflect limited capacity of the piggyback to store sediments. The confined stage occurs in subsequent periods of erosion and transference of sediments towards the foreland, recorded as the first fill over the incision surface. Finally, the unconfined stage is associated with basin overfill.

The deposits of close piggyback basins have been divided in two end members stages: (a) high accommodation system tracks; and (b) low accommodation system tracts. In order to examine the
utility of the proposed model, two case studies in the Precordillera of San Juan province, Argentina were analysed: the Pleistocene–Holocene deposits of the Jáchal River piggyback basins and the Oligocene–Miocene Cuesta del Viento Formation.

The first example associated with relative relatively quiescent tectonic shows that changes in subsidence rates along the foreland under these conditions can exert a strong control in the equilibrium profiles of the transference systems, thus promoting periods of aggradation and degradation of the piggyback. A good example of this situation appears in Sequence I, which illustrates how the isostatic rebound in the thrust and fold belt controlled the enhancement of aggradation phases. On the other hand, changes in climatic conditions should not be overlooked, in fact, the widespread development of intermontane lakes (Sequence III) and the large progradation of megafans (Sequence II) into the foreland are linked to postglacial conditions and result in good examples of how climate plays an important role in the accumulation patterns in both piggyback and foreland basins.

The second case study records the transition between the outer-wedge-top depozone and piggyback basin as well as different types of piggyback basin (open to close). We conclude that the model proposed here is useful to analyse the sediments of the Jáchal River area deposited during limited or absent tectonic activity with climatic controls, as well as the Cuesta del Viento Formation deposited in an active fold and thrust belt. In both cases, the model provides a framework in which piggyback basin evolution can be described and related to the factors that control the dynamics of sedimentation.

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MORPHOGENETIC MODELS OF PIGGYBACK BASINS


