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Vallecito Formation (Miocene): The evolution of an eolian system in an Andean foreland basin (northwestern Argentina)

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Abstract

The Vallecito Formation, a red bed sequence deposited during the Lower Miocene in the Andean foreland basins of the Precordillera (Argentina), has been studied to enable an analysis of the characteristics and temporal evolution of its facies and the major extrinsic factors that control its development. The unit is composed mainly of eolian sandstones and thin intercalations of fine-grained conglomerates and mudstones. The lithology, eolian stratification style, bounding surface type, cross-bedded set geometry, and depositional unit scale indicate six facies associations. Facies association I represents an eolian sand sheet; facies associations II, III, IV, and VI correspond to dunes and draas; and facies association V constitutes fluvial–eolian interaction deposits. With regard to sandstone composition, the Vallecito Formation is formed of feldlithic and lithic arenites with variable proportions of quartz and abundant volcanic rock fragments. The Vallecito Formation represents a large dune field developed in arid to semiarid climates during the first stages of the Andean orogeny. Its formation and development were controlled by climatic and tectonic factors. Concepts about eolian sediment states enable the establishment of a three-phase model of eolian evolution: (1) constructional, (2) maximum development, and (3) destructional. Contemporaneous influx in the constructional phase was limited by low sand availability in the marginal eolian sand sheets and the transport capacity of the wind in the main dune field. During the maximum development phase, dunes and draas grew under contemporaneous influxes limited by the transport capacity. The destructional phase corresponds to alluvial system progradation, which in some localities formed a fluvial–eolian interaction system where contemporaneous and lagged sediment influx was limited by sand availability. Eolian successions such as the ones represented by the Vallecito Formation are interpreted as foredeep deposits of continental foreland basins. In this depozone, the eolian facies correspond to very thick deposits characterized by thick cross-bedded sets, limited fluvial intercalations, a lack of paleosols, and high subsidence rates.

Keywords: Argentina; Eolian dunes and draas; Eolian sediment state; Miocene Andean basins; Vallecito formation

1. Introduction

Eolian sediments are an important component of many ancient and present-day foreland basins located in arid and semiarid regions (Brookfield, 1980; Andrews, 1981; Clemmensen and Abrahamsen, 1983; Limarino and Spalletti, 1986; Limarino and Martinez, 1992). They comprise thin levels intercalated in fluvial sequences, which sometimes results in fluvial–eolian interaction deposits (Langford and Chan, 1989), as well as thick, monotonous successions dominated by large- and giant-scale cross-bedded sandstones sedimented in large dune fields.

In the case of the Andean foreland basins from western and northwestern Argentina, arid and semiarid climates promoted the formation of large dune fields during the Miocene. As a result, and favored by the high rates of subsidence that characterize foreland basins, regionally extensive and thick eolian sequences were formed and preserved. For example, eolian deposits occur in Miocene Andean sequences such as the Mariño (Chiotti, 1946), Pachaco (Milana et al., 1993), Vallecito (Bracaccini, 1946), and Vinchina Formations. These units, which represent the initial stage of foreland basin infilling, are composed essentially of three genetic desert environment types: (1) dune fields and sand sheets, (2) fluvial–eolian interaction systems, and (3) ephemeral fluvial systems.

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Important eolian sedimentation in Argentinean Andean basins was not limited to the Miocene; dune field deposits have also been recognized in Pliocene, Pleistocene, and even modern deposits. With regard to the latter, intermontane dune fields, sand sheets, and fluvial–eolian interaction systems have been described by Iriondo (1990), Iriondo and García (1993), Tripaldi et al. (1998), Muruaga et al. (1999), Tripaldi and Limarino (2000), and Tripaldi et al. (2003) among others.

Although eolian sedimentation leads to one of the basic components in the evolution of many Andean foreland basins from western and northwestern Argentina, it has not been studied in detail yet and frequently has been considered only an accessory constituent of basin sedimentary infilling. Nevertheless, the characterization and analysis of these eolian intervals has become critical for not only reconstructing the depositional area history but also understanding the interplay among subsidence, climate, and sediment supply in Andean foreland basins.

Herein, we examine the Vallecito Formation (Bracaccini, 1946; Borello and Cuerda, 1968; Furque, 1979; Milana, 1993), which is composed mainly of eolian sandstones with relatively thin intercalations of fluvial and lacustrine

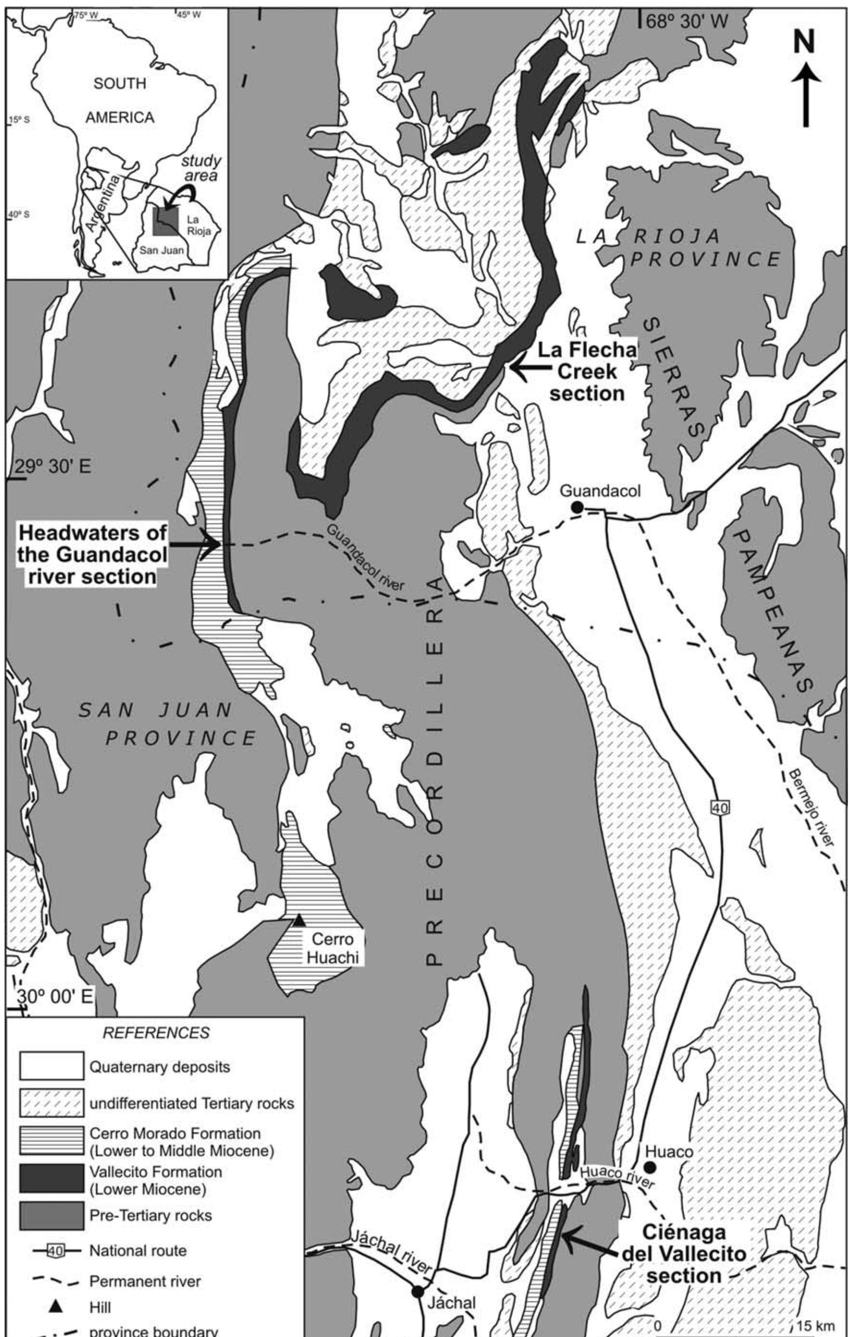

Fig. 1. Geologic sketch map of the study area showing the distribution of the Vallecito and Cerro Morado Formations.

deposits (Tripaldi, 2002). This unit represents a complete record of the eolian sedimentation that took place at the beginning of the evolution of the Andean foreland basins (northwest Argentina, Fig. 1). The aim of this study is to describe the Vallecito Formation sequence together with the temporal evolution of its facies associations and to analyze the major extrinsic factors that controlled eolian sedimentation.

2. Stratigraphic setting

The Vallecito Formation is a red bed sequence that was deposited during the Lower Miocene in the Andean foreland basins of the Precordillera. The unit forms a thick (up to 1200 m) succession composed mainly of eolian sandstones that crop out along the eastern margin of the Precordillera (29°–30°30′ lat. S) to form a narrow, more than 150 km long belt (Fig. 1).

The Vallecito Formation rests on Oligocene–Early Miocene sandstones and mudstones that belong to the Puesto La Flecha Formation (Caselli et al., 2002). In the north (La Flecha creek area, Fig. 1), the unit is unconformably covered by conglomerates and sandstones included in the Vinchina Formation, and to the south (headwaters of the Guandacol River and Ciénaga del Vallecito areas, Fig. 1), volcanic rocks, agglomerates, and sandstones (Cerro Morado Formation, Furque, 1979) overlie the eolian sandstones. No fossil remains or other evidence have been found in the Vallecito Formation to establish the age of the sequence. However, an Early Miocene age can be postulated on the basis of the stratigraphic relations and radiometric dates of the underlying and overlying units. The upper part of the underlying Puesto La Flecha Formation contains tuff levels dated at 21.6 ± 0.8 Ma (Jordan et al., 1993), and the overlying Cerro Morado Formation has been assigned to the Lower–Middle Miocene on the basis of the radiometric ages of volcanic rocks (13.4 ± 1.6, 18.3 ± 0.7 Ma; Jordan et al., 1993; Limarino et al., 2002).

For this investigation, three detailed sections of the Vallecito Formation were studied in different localities. The southernmost Ciénaga del Vallecito area is located in the San Juan province and comprises the type section of the unit (265 m thick). To the north, a second locality is located in the headwaters of the Guandacol River (La Rioja province), where the sequence is 234 m thick. Finally, the northernmost section occurs in the La Flecha creek area, where the eolian sandstones form the thickest succession (1200 m).

The Vallecito Formation is almost entirely formed by eolian sandstones, mainly fine- to medium-grained and cross-bedded. However, in some localities (i.e. Cienaga del Vallecito and La Flecha creek), fluvial and lacustrine intercalations appear, especially in the upper half of the unit. The fluvial deposits constitute no more than 5% of the sequence and are composed of pebbly to medium-grained, massive or cross-bedded sandstones and, in some cases, thin beds of massive conglomerates. Even less frequent, lacustrine intercalations of mudstones and fine-grained sandstones also occur at La Flecha creek.

3. Facies associations

On the basis of the lithology, sedimentary structures, type of bounding surfaces, geometry of the cross-bedded sets, and scale of the depositional units, six facies associations have been recognized in the Vallecito Formation. Facies associations I, II, III, IV, and VI are interpreted as eolian deposits (eolian sand sheets, interdunes, and different kinds of dunes and draas), whereas facies association V corresponds to fluvial–eolian interaction and lacustrine environments. Eolian stratification styles can be distinguished and described using the criteria established by Hunter (1977a,b) and Kocurek and Dott (1981). Likewise, the hierarchy of eolian bounding surfaces defined by Brookfield (1977) and then revisited and renamed by Kocurek (1988) are applied to the eolian successions.

3.1. Facies association I

Facies association I is almost entirely composed of coarse- to very fine-grained sandstones that form stacked tabular bodies (up to 3 m thick) of horizontally laminated, low-angle, cross-laminated beds (Fig. 2a). Intralamina inverse grading is a very common feature in the sandstones (Fig. 2b), and some isolated ripple foresets appear in the sets, especially in the medium- to coarse-grained sandstones. In addition, fine- to medium-grained sandstone layers are intercalated with coarse- to very coarse-grained sandstone layers, yielding bimodal sandstones.

The horizontal beds are interpreted as formed by vertical accretion due to eolian ripple migration (Hunter, 1977a,b). However, where inverse grading is not recognized, deposition by an upper flow regime should not be dismissed (Clemmensen and Abrahamsen, 1983). Ripple-form laminated levels and bimodal sandstones are better interpreted as the migration of eolian granule ripples (Fryberger et al., 1992).

Although horizontal and low-angle cross-laminated sandstones predominate in this facies association, isolated tabular sets (up to 1 m thick) of cross-bedded, fine- to medium-grained sandstones are not uncommon. The sets correspond to solitary, small, straight-crest crescentic dunes.

Small-relief erosive surfaces that point to deflationary processes are another feature of these rocks. Commonly marked by few, coarse-grained, thick lag horizons, these surfaces form from roughly horizontal planes to irregular surfaces that bound small blowout hollows (Fig. 2c).

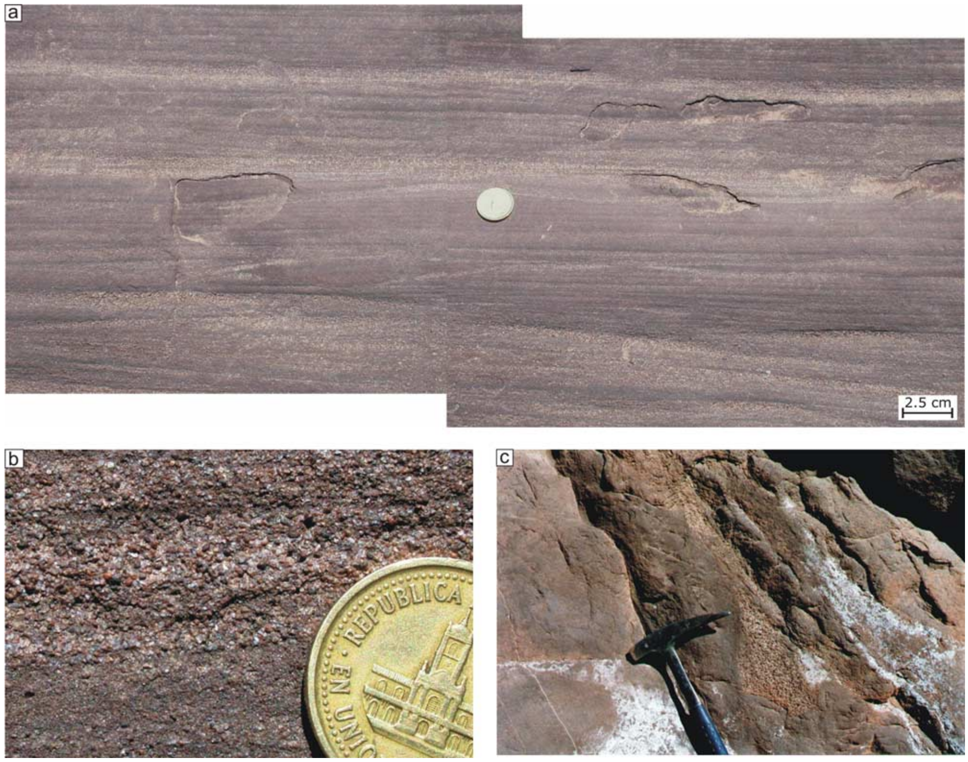

Fig. 2. Facies association I (eolian sand sheet): (a) General view of horizontal and low-angle cross-laminated sandstones; (b) detail of laminated sandstones with the typical eolian inverse-graded lamina; and (c) blowout hollows filled with coarse- to very coarse-grained sandstones indicating deflationary processes.

The latter are filled with massive, bimodal, fine- to very coarse-grained sandstones.

As a whole, facies association I represents an eolian sand sheet, similar to that described by Fryberger et al. (1979) and Kocurek and Nielson (1986) as a low-relief surface of irregular topography covered by eolian ripples and some isolated small dunes (Fig. 3a). Although this unit has a similar morphology to that of interdune deposits, sand sheet sequences are distinguished by their greater thickness (in this case, 15–60 m) and common position at the base or top of sections.

3.2. Facies association II

This unit is made up of large- (5–20 m thick, Fig. 4a) to medium-scale (up to 5 m thick), planar, cross-bedded sets of medium- to very fine-grained sandstones. Cross-bedded units are organized into two different arrangements: large-scale sets that appear stacked and limited by low-angle, planar, and regionally extensive surfaces (first-order surfaces of Brookfield, 1977; interdune bounding surfaces of Kocurek, 1988; Fig. 5a) and interstratifications of large-scale sets with thinner cross-bedded units, which form laterally discontinuous cosets that are also limited at their bases by interdune bounding surfaces (Fig. 5b).

Cross-bedded sets are formed by alternating thick (up to 5 cm) foresets of medium- to coarse-grained sandstones and thinner lamina (less than 1 cm) of fine- to very fine-grained sandstones in an even lamination. The former correspond to grainflow deposits, whereas the thinner lamina are due to grainfall processes (Hunter, 1977a). Foresets have mainly a tangential relationship with the underlying bounding surfaces and show inverse-graded lamina at their toes, which points to sand reworking by wind ripple migration, probably due to secondary reverse winds (Kocurek, 1996). Similarly, the sporadic outgrowth of slides on a partially wet, steep lee slope is indicated by the presence of deformed cross-laminated sandstones and fine breccias in cross-bedded sets.

The geometry of the described sets clearly suggests this facies association was deposited through the migration of straight-crest crescentic dunes. Moreover, large-scale sets and interdune bounding surfaces indicate the presence of draas. As demonstrated by Havholm and Kocurek (1988), the lee face of draas may have superposed smaller dunes or a free slope, depending on the area. Therefore, the draa migration could create the two types of set arrangements. Stacked, large-scale, cross-bedded sets correspond to draas with dune-free lee faces, whereas the intercalation of large-scale sets and cosets of medium-scale, cross-bedded units suggests that superposed dunes covered the draa lee faces (Fig. 3b; Chrintz and Clemmensen, 1993; Scherer, 2000; Mountney and Howell, 2000).

At La Flecha creek, the sequence shows the thickest development, reaching almost 400 m, whereas at the headwaters of the Guandacol River it is 94 m thick, and in Ciénaga del Vallecito, it reaches 150 m.

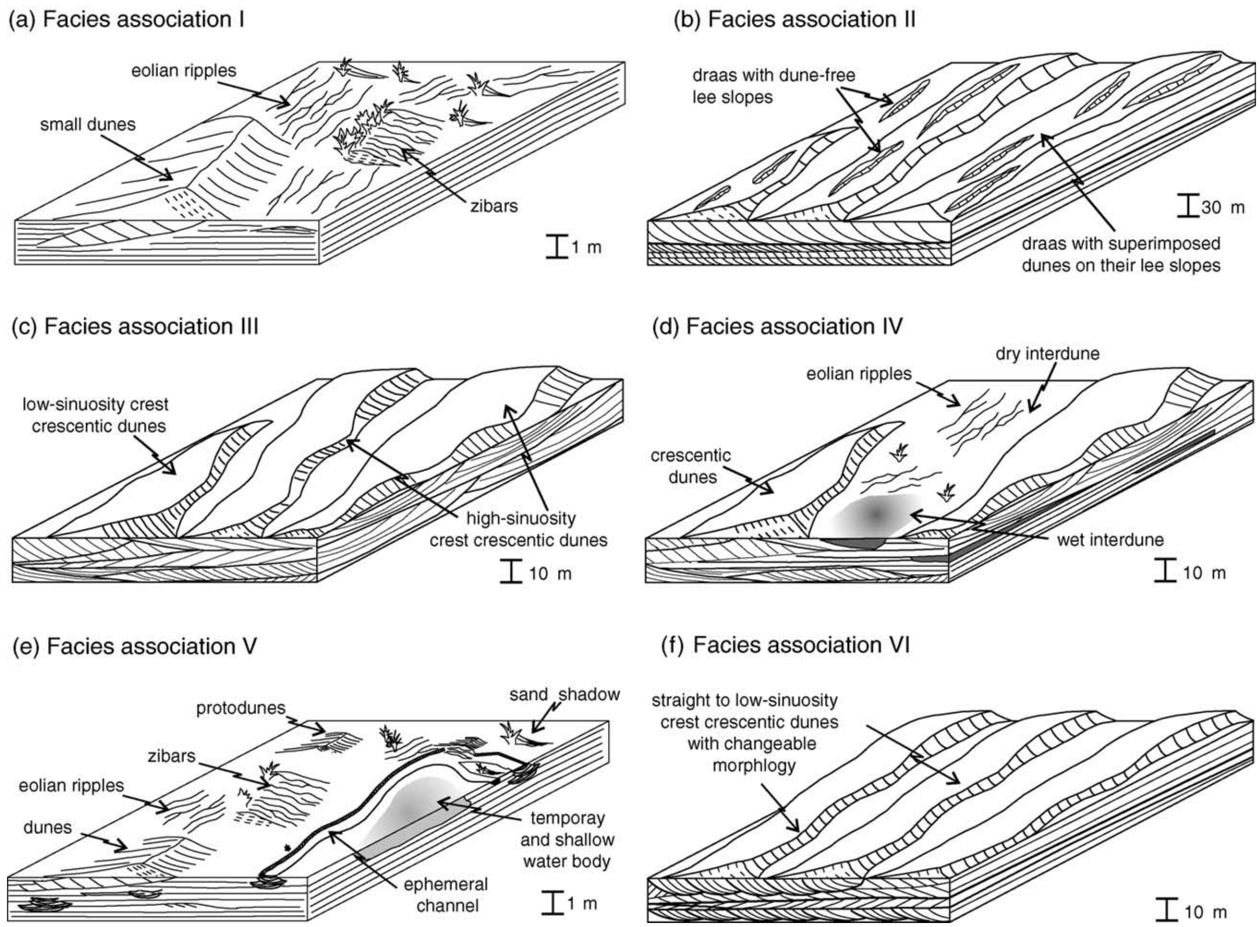

Fig. 3. Conceptual schemes for different facies associations recognized in the Vallecito Formation.

Finally, foreset orientations in large-scale, cross-bedded sets show a unimodal paleocurrent pattern of dune migration, with a mean trend to the north (Az 0.6°, data dispersion of 82.2°, Fig. 4a).

3.3. Facies association III

This facies association is formed by fine- to coarse-grained sandstones that constitute two types of medium- to large-scale (up to 7 m thick), cross-bedded units: wedge-shaped sets limited by planar or slightly concave upward bounding surfaces (second-order surfaces of Brookfield, 1977; superposition surfaces of Kocurek, 1988) and very well-developed trough cross-bedded strata, up to 20 m wide, bound by distinctive concave upward superposition surfaces (Kocurek, 1988; Fig. 4b). Both types consist mostly of alternating fine- to very fine-grained and medium- to coarse-grained, internally massive sandstone lamina. The coarser sandstones typically appear in lens-shaped layers, up to 8 cm thick and 2 m wide, because they are thin lamina whose inverse grading rarely is distinguished.

Facies association III suggests an important change in dune morphology compared with facies association II. Wedge-shaped sets may represent crescentic dunes with moderate to low sinuosity crests, whereas trough cross-bedded sandstones may be high sinuosity-crest crescentic dunes (Fig. 3c). Moreover, the smaller thickness of the sets and the absence of interdune bounding surfaces suggest that different dune types formed this facies association; draas are scarce or absent. According to the grain size, geometry, and arrangement of the foresets, grainfall and grainflow processes dominated in these dunes, and wind ripple migration was less important.

Although there are significant changes in the cross-bedding geometry, the contact between facies associations III and II is almost transitional. At La Flecha creek, the unit is 400 m thick, whereas in the headwaters of the Guandacol River and Ciénaga del Vallecito, it reaches only 125 and 60 m, respectively.

Cross-bedding paleocurrent data reveal a mean foreset dip to the WSW (242.8°, data dispersion of 72.8°, Fig. 4b).

3.4. Facies association IV

This unit constitutes very thin intercalations of fine- to very fine-grained sandstones that appear mostly between the cross-bedded sets of facies associations II and III. Despite

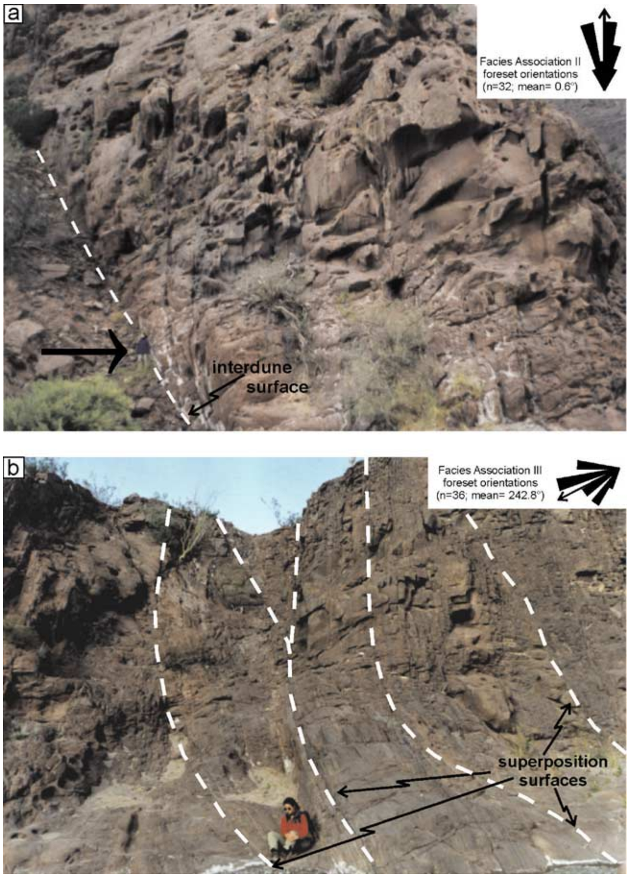

Fig. 4. (a) Very large cross-bedded set (person for scale) limited by an extensive interdune surface, corresponding to facies association II. (b) Trough cross-bedded sets, limited by superposition surfaces, representing facies association III. The paleocurrent patterns of the units appear at the top right corners of each picture.

their low proportion, thin beds of massive and laminated mudstones, sometimes with desiccation cracks and epichnia and endichnia bioturbation, were observed.

At La Flecha creek, the unit appears at least four times within facies association III, always less than 1 m thick and mostly as lens-shaped beds. Fig. 6 shows a detail of this unit divided into three parts. The lower one (A in Fig. 6a) is made up of silty to very fine-grained sandstones, massive or with horizontal lamination. Division B (Fig. 6a) is composed of massive and laminated mudstones that pass gradually upward to thin levels of massive and horizontal laminated sandstones. Some of the latter have internally inverse grading (C in Fig. 6a).

Although similar characteristics are observed in the headwaters of the Guandacol River and Ciénaga del Vallecito, in these localities, facies association IV is mainly dominated by coarser-grained sandstones. They show horizontal lamination and low-angle cross-lamination, often with inverse-graded lamina. Isolated ripple-form laminated sandstones and thin mudstone lamina with desiccation cracks and tracks are also present. In both areas, facies association IV forms a unique, thin interval (50–1.5 m thick).

Facies association IV is interpreted as an interdune deposit (Fig. 3d; Ahlbrandt and Fryberger, 1981; Kocurek, 1981) on the basis of (1) the massive and horizontally laminated fine-grained sandstones, sometimes with inverse grading; (2) the lens-shaped form of the bodies; (3) their comparative thinness with regard to facies association I; and (4) the presence of mudstone levels.

Although subaqueous current ripples were not observed in La Flecha creek outcrops, these deposits probably correspond to the wet interdunes described by Ahlbrandt and Fryberger (1981), according to the presence of mudstones. Thus, the basal division in Fig. 6a represents wind ripple migration over a dry surface. The mudstone levels indicate the development of small water bodies, because silts and clays are easily trapped by standing ponds. Finally, the uppermost division (Fig. 6a) records renewed eolian deposition on a dry surface, supporting the temporary character of these ponds.

In contrast, in the other two sections, the characteristics of the interdune deposits indicate that facies association IV

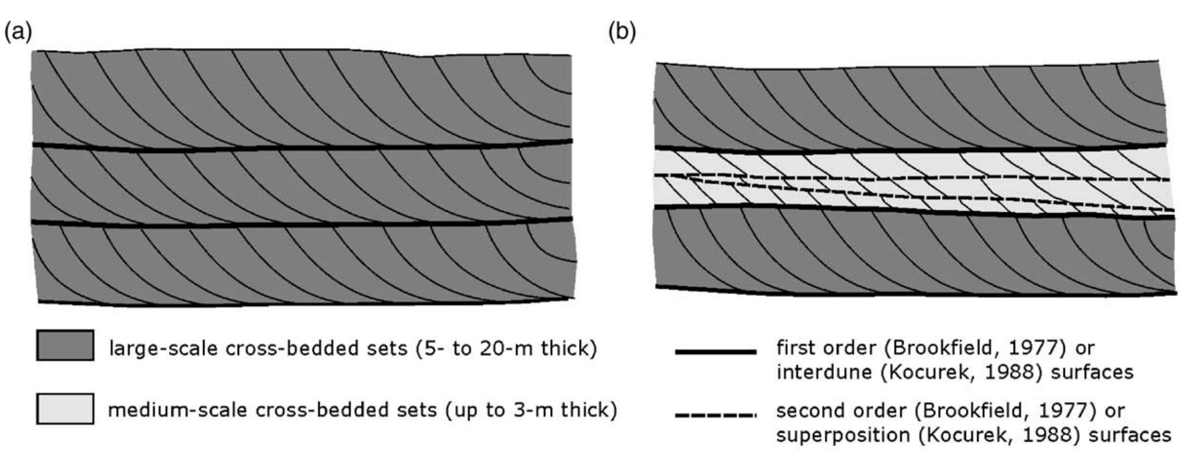

Fig. 5. Schematic drawing of two different arrangements of cross-bedding that form facies association II: (a) stacked, large-scale sets limited by a low angle, indicating draas with dune-free avalanching lee faces and (b) interstratifications of large-scale sets with thinner cross-bedded units indicating draas with dune-free lee faces and superposed dunes, respectively.

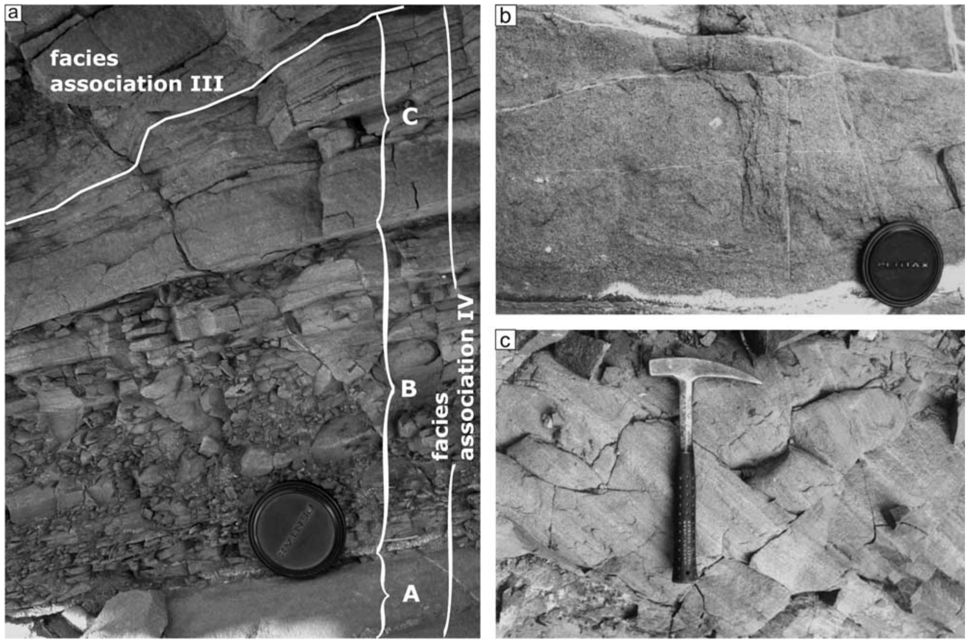

Fig. 6. (a) Close-up of facies association IV (interdunes), formed by massive and horizontally laminated, silty to very fine-grained sandstones and massive and laminated mudstones. See the text for the description of the different divisions (A, B and C). (b) Fluvial-deposited massive gravelly sandstones of facies association V. (c) Eolian-deposited thin, cross-laminated, fine-grained sandstones of facies association V.

is a dry interdune (Fig. 3d; Ahlbrandt and Fryberger, 1981; Kocurek, 1981) in which sedimentation was essentially eolian.

3.5. Facies association V

This facies association shows significant lithological changes in relation to the previously described facies. Closely associated to eolian sandstones, fine-grained conglomerate and gravelly to fine-grained sandstone bodies occur together with thick beds of laminated and massive mudstones. This unit, with its characteristic greenish-grey color, crops out twice in La Flecha creek and reaches a total thickness of 150 m. In Cienaga del Vallecito, it is located at the top and has minimal thickness (15 m).

The lower part of facies association V corresponds to gravelly to coarse-grained sandstones (Fig. 6b) and fine-grained conglomerates that form up to 3 m thick lenticular beds with erosive bases. Beds are massive and, in some cases, pass upward to horizontally laminated or planar cross-bedded, coarse-grained sandstones. The upper part is made up of purple mudstones, generally laminated and interlayered with very fine-grained sandstones that display horizontal lamination, ripple cross-lamination, and wavy bedding.

Massive and thin laminated, well-sorted, matrix-free sandstones appear interstratified with the previous beds. They show horizontal lamination and low-angle cross-lamination with inverse-graded lamina. Up to 2 m thick, isolated sets of planar cross-bedding are also present (Fig. 6c). In some cases, bimodal sandstones are common, with a principal mode in fine sand and a secondary one in coarse sand, and exhibit horizontal lamination, low-angle cross-lamination, or massive beds.

Facies association V has a complex origin due to the interplay of fluvial, eolian, and lacustrine processes (Fig. 3e). The participation of erosive-based channeled beds of conglomerates and coarse-grained sandstones suggests fluvial deposits. Channel sedimentation would have been dominated by lag deposits that formed the described massive levels, followed by the sporadic growth of small sandy bars, as evidenced by the cross-bedded gravelly sandstones. However, the mudstones were deposited in ephemeral and shallow water bodies. During desiccation periods, small current ripples migrated and produced the intervals of very fine-grained, cross-laminated sandstones.

The bimodal sandstones, massive or with horizontal or low-angle cross-lamination and inverse grading, are interpreted as eolian deposits. The former beds probably were formed through eolian deflation, whereas the latter correspond to wind ripple migration, most likely eolian granule ripples (Fryberger et al., 1992). In reference to the tabular, planar cross-bedded sandstones, their fine to very fine grain size, good sorting, and very fine lamination suggest they were formed by the migration of isolated straight-crest crescentic dunes over alluvial plains.

The close relation between eolian and fluvial processes, together with the settling of silt and clay, suggests that this facies association is comparable to the fluvial–eolian interaction system described by Langford (1989) and Langford and Chan (1989). These depositional environments can thus be described as a dune field partially degraded by successive flooding. At the beginning, a series of braided channels was established in the lower part of the unit, and interchannel areas were dominated by eolian sedimentation, mainly as wind ripples and solitary small dunes. The deposits can be correlated with three depositional elements described by Langford and Chan (1989): fluvial channels, eolian dunes, and sand sheets. The overbank-interdunes element (Langford and Chan, 1989) is represented by mudstones and sandstones of the upper part of the unit. This subenvironment is characterized by mud that settles with the deposition of sand eroded from the dunes.

3.6. Facies association VI

This unit is formed of medium- to very fine-grained sandstones that composed up to 5 m thick (mean value 2 m) planar cross-bedded sets. Although this unit roughly resembles facies association II, the common occurrence of several successive reactivation surfaces within the sets (Fig. 7), which resulted in scalloped cross-bedded sandstones (Rubin and Hunter, 1983), is a diagnostic feature. Moreover, neither large-scale, cross-bedded sets nor interdune bounding surfaces (Kocurek, 1988) have been identified in this interval.

Scalloped cross-bedded sets, bounded by planar or slightly concave upward surfaces (second-order surfaces of Brookfield, 1977), internally show several concave-upward reactivation surfaces that bind intrasets (third-order surfaces of Brookfield, 1977). Closely associated with facies association V, planar cross-bedded sandstones appear, usually arranged as simple sets limited by planar surfaces.

The internal arrangement of cross-bedded sets consists of thin foresets in which fine- to very fine-grained sandstone lamina interlayer with medium-grained ones. In most cases, foresets are tangential to the underlying bounding surfaces and display inverse-graded lamina at their toes.

Planar cross-bedded strata indicate that the unit was built by the migration of straight-crest crescentic dunes (Fig. 3f). Moreover, the absence of large-scale sets or regionally extensive interdune bounding surfaces suggests that draas were not developed during the growth of this facies association.

As noted by Rubin (1987), the regular presence of reactivation surfaces can be explained by fluctuation in the bedform asymmetry (height and spacing) or migration velocity of the dunes. Regarding scalloped cross-bedding, two different processes have been proposed for their formation by Rubin and Hunter (1983): (1) flow condition variations result in the development of surfaces that dip in the same direction as the foresets or (2) scour pit migration in the dune lee facies produces surfaces that dip in a direction opposite that of the foresets. The geometry of the scalloped cross-bedded units herein indicates that reactivation surfaces were controlled by flow condition changes that produced variations in the bedform asymmetry or migration velocity. These characteristics point to a changeable morphology for the dunes represented by facies association VI.

Foresets of this unit are dominated by fine- to very fine-grained sandstone lamina that stem from grainfall processes and medium-grained ones formed by avalanches. Furthermore, wind-ripple migration was a common process in the lower portions of the dune leefaces, as revealed by the inverse-graded lamina.

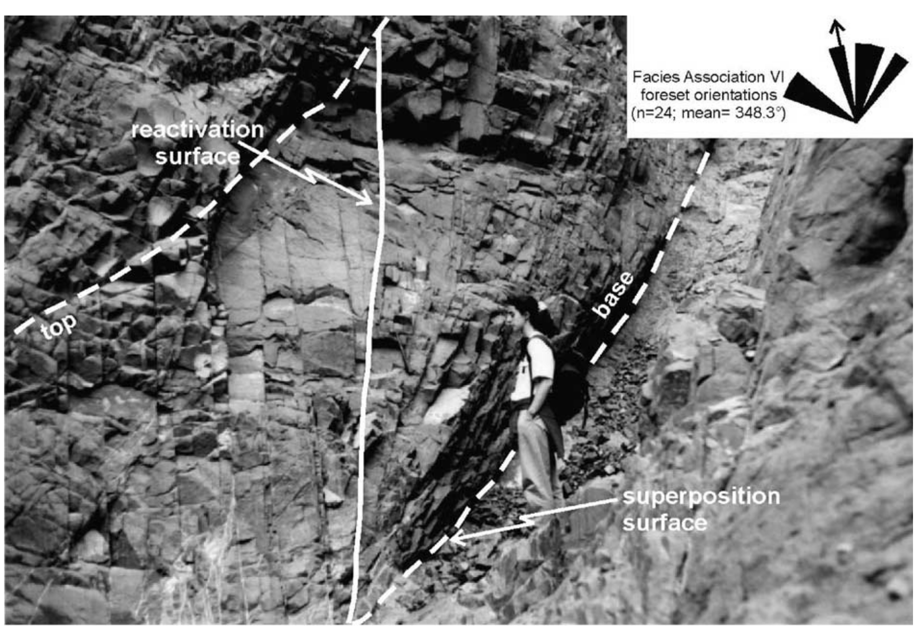

Fig. 7. Detail of a planar, cross-bedded set characterized by successive reactivation surfaces, noting straight-crest crescentic dunes with changeable morphology represented by facies association VI. Paleocurrent pattern is shown at the top right corner.

This facies association has been recognized only at the top of the La Flecha creek section, with a thickness of 150 m. Finally, paleocurrent measurements show a general trend of dune migration to the NNW (348.3°, data dispersion of 87.2°, Fig. 7).

4. Sandstone composition

The sandstone detrital modes of the different facies associations have been analyzed as a control of paleocurrent measurements and to characterize the Vallecito Formation source areas. Although feldlithic and lithic arenites dominate in the whole sequence, two petrofacies can be identified according to the quartz abundance, type of feldspars, and amount of volcanic lithic fragments. Facies associations I, II, III, and VI arenites are composed of up to 30% monocrystalline quartz grains. K-feldspars, mostly orthoclase and microcline (15%), are more abundant than plagioclase (9%). Lithic fragments (46%) are composed of acid and mesosilicic volcanic rocks, metamorphic clasts (mostly slates and schists), and some fragments of sedimentary rocks (fine sandstones and mudstones).

Facies association V arenites are mainly formed by volcanic fragments of andesites, dacites, and riolites (58%). In these rocks, plagioclase (24%) dominates over K-feldspar (8%), mostly orthoclase. Quartz appears in very low proportions ($<10\%$); metamorphic and sedimentary clasts are uncommon.

Arenites with moderate quartz and K-feldspar proportions form the major part of the eolian deposits, whereas sandstones with high amounts of volcanic fragments, scarce quartz, and abundant plagioclase are restricted to the fluvial–eolian interaction sediments of facies association V. This composition change reflects the different sandstone provenance for eolian and fluvial intervals. In eolian sandstones, paleocurrent data show paleowinds from the east, where granitic, metamorphic, and sedimentary rocks from the Sierras Pampeanas range predominate (Fig. 1). The presence of metamorphic clasts, microcline, and high quantities of quartz and the predominance of K-feldspar over plagioclase suggests an eastern provenance. In contrast, the fluvial incursion represented by facies association V reveals a western provenance in which volcanic rocks that correspond to the Miocene volcanic arc of the Precordillera (Cerro Morado Formation) prevail (Fig. 1; Limarino et al., 2002).

5. Evolution of the Vallecito eolian system

The Vallecito Formation represents a large eolian system developed in arid to semiarid climates during the beginning of the Andean orogeny. These eolian sandstones were considered by Jordan et al. (1993) to be the first syntectonic filling of the Andean Foreland basins related to thrusting that raised the Precordillera during the Miocene.

The formation and development of the Vallecito eolian system was controlled by climate and tectonism. The arid climate promoted the creation of dune fields by increasing the sediment availability and transport capacity of the winds. Moreover, arid conditions cause less efficient transport of sediments by rivers. These features made eolian processes more important than fluvial ones in most of the basin, thus favoring eolian sedimentation. Regarding tectonism, the thickness of mostly eolian sandstones (234–1200 m) and up to 20 m thick cross-bedded sets reflect the high availability of accommodation space during the evolution of the Vallecito eolian system. This large accommodation space agrees with the high subsidence rates that characterize most evolution of foreland basins.

We analyze the evolution of the Vallecito eolian system on the basis of Kocurek and Lancaster's (1999) concepts about the construction and evolution of eolian systems. These authors distinguish three factors that define the eolian sediment state (or sediment budget) that controls the creation and development of a dune field: (1) sediment supply, (2) sediment availability, and (3) transport capacity of the wind.

In the case of the Vallecito Formation, its paleogeographic distribution as a narrow belt attached to the Precordillera's eastern margin clearly suggests topographic control in the formation of the dune field (Fig. 1). Thus, winds blowing from the southeast and east would have found a topographic barrier (Fryberger and Ahlbrandt, 1979) in the highlands formed by Andean thrusting and the Miocene volcanic arc (Ramos, 1999; Limarino et al., 2002; Fig. 8). This proposed control is reinforced by data given by Furque (1979) and Jordan et al. (1993), who show that the Vallecito Formation crops out to the east of the Jáchal–Huachi area (where Miocene volcanic rocks have their maximum development; Limarino et al., 2002) but suddenly disappears to the west.

Because no unconformity was recognized between the Vallecito Formation and the underlying alluvial and lacustrine deposits (Puesto La Flecha Formation), a change to more arid conditions, along with the previously mentioned paleogeographic changes, promoted the passage from alluvial- to eolian-dominated sedimentation and, consequently, to the formation of the eolian belt.

A conceptual model for the Vallecito eolian system evolution includes three phases: (1) constructional, (2) maximum development, and (3) destructional. The evolution of the dune field was slightly different for the three analyzed localities (Figs. 9 and 10) because of their different paleogeographic positions with respect to the highland barrier, as is partially represented by the Miocene volcanic arc (Cerro Morado Formation, Fig. 1).

During the constructional phase, the La Flecha creek area was a dune field marginal zone dominated by an eolian sand sheet environment (facies association I). The sediment state of the eolian system could be defined as a contemporaneous

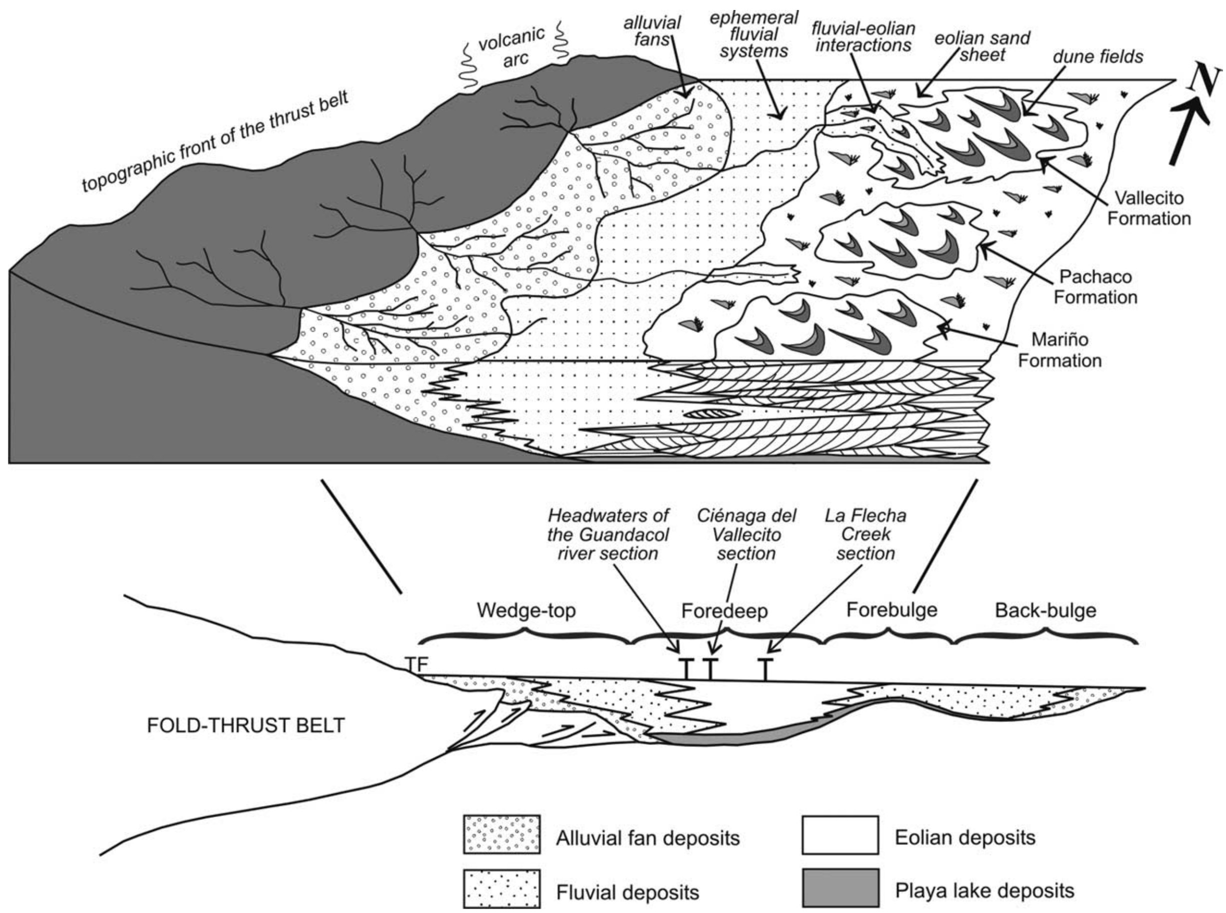

Fig. 8. Conceptual model for the eolian system that characterized the first stages of Andean foreland basins, showing depositional environments and location of the eolian deposits within the foredeep depozone of the foreland basin system (De Celles and Giles, 1996).

sediment influx partially limited by the presence of coarse-grained lags and scarce vegetation (availability-limited contemporaneous influx, CI_{AL} in Fig. 9). Near more proximal areas (Ciénaga del Vallecito and Guandacol River, Fig. 1), a larger sand supply, obtained from the associated alluvial plains and marginal sand sheet areas, promoted a constructional phase dominated by large eolian bedforms. As a result, Oligocene deposits were covered directly by deposits of large dunes and draas (facies association II). In these areas, contemporaneous sediment influx was limited only by the transport capacity of the wind (CI_{TL} in Fig. 10).

The maximum development phase corresponds to eolian field growth due to the migration of large dunes and draas (facies association II), which then evolved to low and high sinuosity-crest crescentic dunes (facies association III, Figs. 9 and 10). During this phase, sand influx was contemporaneous and mostly derived from the laterally associated alluvial plains (CI_{TL} in Figs. 9 and 10). Well-developed bedforms suggest that sediment availability was limited only by the transport capacity of the wind.

The destructional phase corresponds to the progradation of alluvial systems (including alluvial fans and braided river deposits) from the volcanic arc located west of the dune field (Figs. 8 and 10). The factors controlling the alluvial system advance are uncertain but probably relate to tectonic movements or increased volcanic activity (the syneruptive phase of Limarino et al., 2002).

In the headwaters of the Guandacol River area, eolian field degradation started with a sand sheet environment (facies association I) dominated by intense deflation. The sand sheet sediment state was dominated by contemporaneous and lagged sediment influxes, which came from the laterally associated alluvial plains and the deflation of previous eolian deposits, respectively. However, both were limited by low sand availability due to the presence of armored covers (CI_{AL} in Fig. 10). Subsequently, eolian sedimentation was sharply terminated by fluvial progradation followed by fine-grained deposition (Barreda et al., 2002).

In Ciénaga del Vallecito, a short interval of fluvial sedimentation coupled with eolian processes produced a fluvial–eolian interaction environment (facies association V) during the destructional phase. The sediment state of this phase, characterized by a lower sediment supply, corresponds to a contemporaneous sand influx (from overbank channel areas) and a lagged one (from the reworking of prior eolian deposits), both of which were limited by low sediment availability (CLI_{AL} in Fig. 10). After a brief

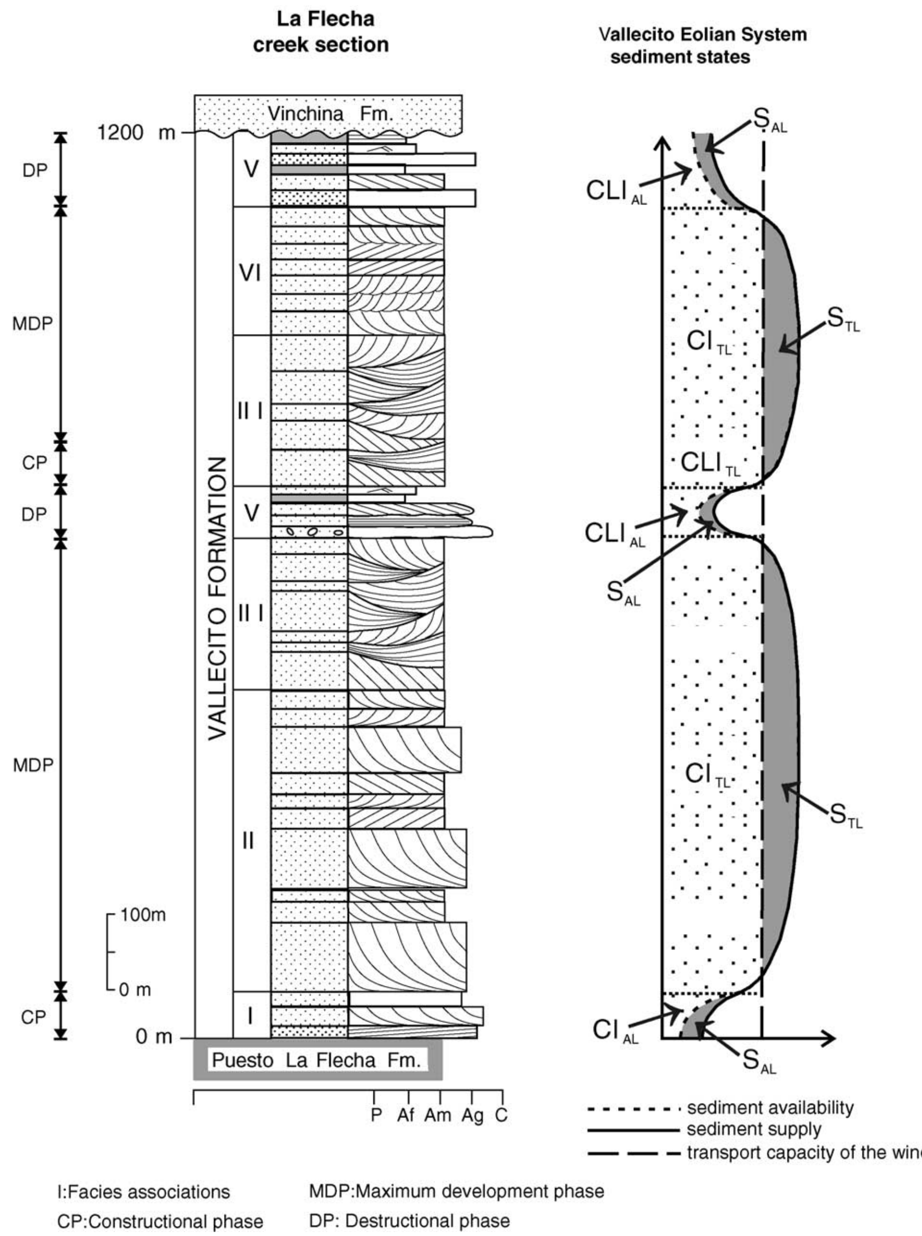

Fig. 9. Schematic log for the Vallecito Formation at La Flecha creek (for location, see Fig. 1) and sediment state diagram. S_{AL}: stored sediment (availability limited), S_{TL}: stored sediment (transport limited), CI_{AL}: contemporaneous influx (availability limited), CI_{TL}: contemporaneous influx (transport limited), CLI_{AL}: contemporaneous and lagged influx (availability limited), CLI_{TL}: contemporaneous and lagged influx (transport limited).

period of eolian sedimentation (facies association II), the progradation of volcanic breccias, agglomerates, and conglomerates, derived from the western volcanic arc (Limarino et al., 2002), covered the dune deposits (Fig. 10).

In more distal areas, the situation was very different, and eolian sedimentation was only temporarily interrupted by the progradation of braided channels (Fig. 9). In the La Flecha creek section, dune sandstones passed upward to an fluvial–eolian interaction and lacustrine deposits (facies association V). During this briefly destructional phase, and similar to the Ciénaga del Vallecito area, the lower sediment supply came from the contemporaneous alluvial deposits and the sand lagged in previously formed dunes. On the basis of the presence of a high water table level, coarse-grained lags, and mud surfaces, we interpret a limited sediment availability (CLI_{AL} in Fig. 9). Moreover, the stored sediment supply, limited by low availability (S_{AL} in Fig. 9), was generated by sand accumulation in temporary water bodies and alluvial plains.

A new eolian field succession of constructional, maximum development, and destructional phases took place at La Flecha creek (Fig. 9). The constructional phase was controlled by the progress of drier conditions coupled with a higher sediment supply from the coeval uplifted areas (Fig. 9). This high sand supply gave rise to the formation of low to high sinuosity-crest crescentic dunes

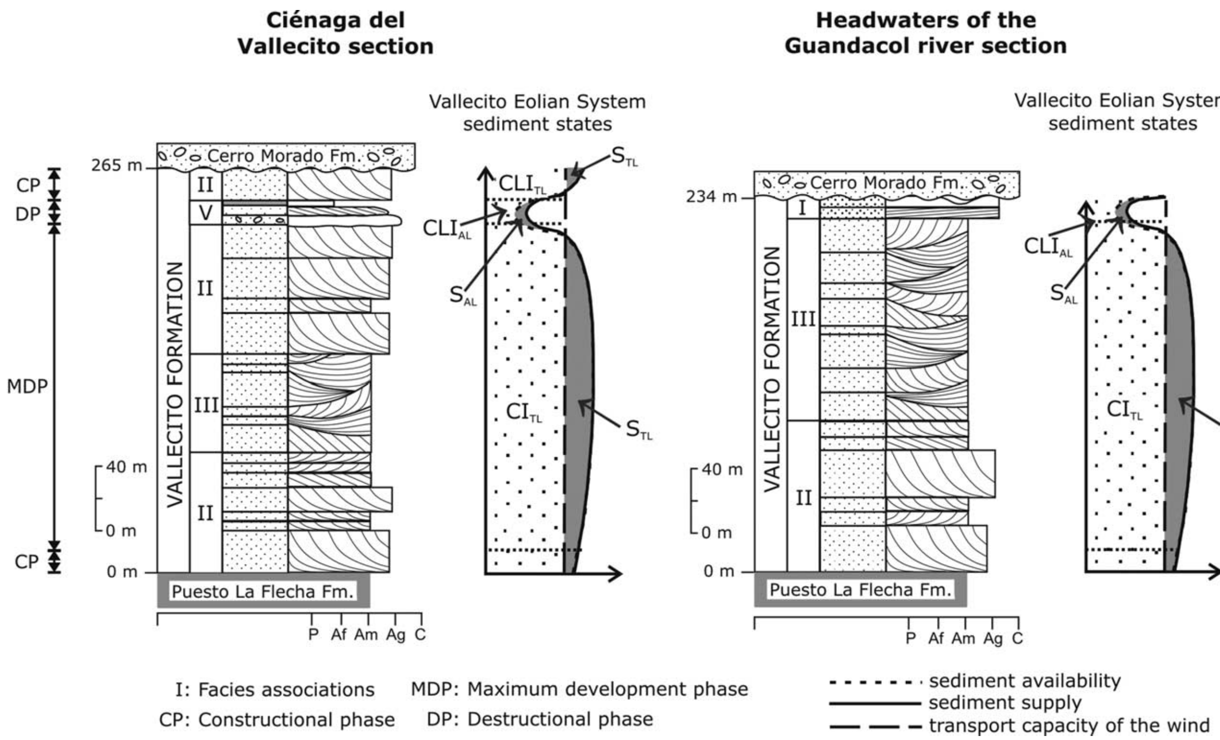

Fig. 10. Schematic log for the Vallecito Formation at Ciénaga del Vallecito and headwater of Guandacol River (for locations, see Fig. 1) and sediment state diagram (for key, see Fig. 9).

(facies association III). These bedforms shifted to straight-crest crescentic bedforms, in some cases with changeable morphology (facies association VI). Constructional and maximum development phases had a contemporaneous sediment influx limited by the wind transport capacity (CI_{TL} in Fig. 9). Finally, a new fluvial incursion promoted the destruction of the dune field and formed a fluvial–eolian interaction setting (facies association V) that evolved to an alluvial environment (Vinchina Formation, Fig. 9).

The Vallecito Formation clearly shows the importance of eolian sedimentation during the first stages of foreland basin development dominated by continental infilling. In this sense, a similar stratigraphic framework of thick eolian rocks at the bottom of the foreland successions appears in the Precordillera of Mendoza (Mariño Formation, Chiotti, 1946) and the southern part of the Precordillera of San Juan (Pachacó Formation, Cevallos and Milana, 1992).

De Celles and Giles (1996) mention the presence of thin flaps of highly condensed fluvial and eolian deposits in the forebulge depozone of foreland basins. In this depositional area, eolian deposits show low thicknesses, frequent fluvial intercalations, an abundance of well-developed paleosols, and low subsidence rates. However, the great thickness of the Vallecito Formation, as well as its occurrence as a narrow, long belt along the axis of the thrust belt, enable us to establish these eolian rocks in a foredeep depozone (Fig. 8). Moreover, the limited presence of fluvial intercalations, the lack of paleosols, and higher subsidence rates clearly reinforce the location of eolian fields in the foredeep depozone. Although we cannot rule out a climatic control, we believe that the significant eolian sedimentation in foredeep depozones was possible because the deposits occurred during the first stages of the Andean orogeny, when alluvial sedimentation was mostly constrained to proximal areas of the thrust belt topographic front (Fig. 8). However, the progress of the thrust belt to the foreland probably resulted in the migration of eolian fields to the forebulge depozone. In this location, eolian deposits show lower thicknesses, frequent fluvial intercalations, and other characteristics of forebulge sequences mentioned by De Celles and Giles (1996).

6. Summary and conclusions

The Vallecito Formation represents an excellent example of a large eolian system developed in an active foreland basin. During dune field evolution, eolian bedform migration and sand sheet aggradation produced thick strata of mostly fine- to medium-grained sandstones with varied structures and geometries. In addition, brief fluvial floodings produced fluvial–eolian interaction deposits.

This unit can be constrained to the Lower Miocene on the basis of its stratigraphic relationship with the underlying and overlying sedimentary sequences, the Puesto La Flecha and Cerro Morado Formations, respectively. The upper part of the former unit has been dated at 21.6 ± 0.8 Ma by Jordan et al. (1993), and the latter provides radiometric dates of volcanic rocks of 13.4±1.6 and 18.3±0.7 Ma (Jordan et al., 1993; Limarino et al., 2002).

On the basis of lithological and eolian architectural element analysis, the Vallecito Formation can be divided into six facies associations. Facies association I, mostly formed by horizontal and low-angle, cross-laminated, coarse- to very fine-grained sandstones, corresponds to an eolian sand sheet environment that grew through ripple vertical accretion (Fig. 3a). Isolated small dunes, deflationary surfaces, and blowout hollows are also recognized. Facies association II is composed of planar cross-bedded, medium- to very fine-grained sandstones that represent straight-crest crescentic dunes. Up to 20 m thick, stacked, cross-bedded sets and cosets, both limited by interdune bounding surfaces, indicate the existence of draas in this facies association (Fig. 3b). Facies association III consists of medium- to fine-grained sandstones with wedge-shaped and trough cross-bedded sets. This unit formed through the migration of low to high sinuosity-crest crescentic dunes (Fig. 3c). Intercalated with facies associations II and III, up to 1.5 m thick, fine- to very fine-grained sandstones and mudstones appear. These rocks, included in facies association IV, are interpreted as interdune deposits (Fig. 3d). Fine-grained conglomerates and gravelly to medium-grained sandstones, together with mudstones and fine-grained sandstones, constitute facies association V, which was deposited by a compound environment in which an interaction among fluvial, eolian, and lacustrine processes took place (Fig. 3e). Finally, facies association VI is formed by medium- to very fine-grained sandstones arranged in planar cross-bedded sets, in some cases with several successive reactivation surfaces. The rocks indicate the migration of straight-crest crescentic dunes that suffered periodic changes in the bedform asymmetry (height, spacing) or migration velocity (Fig. 3f).

The Vallecito Formation sandstones correspond to feldlithic and lithic arenites, as is indicated by their detrital modes. Moreover, according to the quartz abundance, type of feldspars, and amount of volcanic lithic fragments, two different petrofacies can be identified. Arenites in facies associations I, II, III, and VI have up to 30% monocrystalline quartz grains, K-feldspar (15%) is more abundant than plagioclase (9%), and lithic fragments (46%) correspond to acid and mesosilicic volcanic clasts, metamorphic clasts, and a few fragments of sedimentary rocks. In contrast, arenites of facies association V are formed mainly by volcanic fragments of andesites, dacites, and riolites (58%); plagioclase (24%) dominates over K-feldspar (8%); and quartz is very scarce (<10%).

Each facies association characterizes a different stage of the Vallecito eolian system evolution and can be correlated with a particular sediment state (Kocurek and Lancaster, 1999). Thus, Vallecito eolian system evolution can be divided into three main phases: (1) constructional, (2) maximum development, and (3) destructional. The constructional phase corresponds to an eolian sand sheet environment (facies association I) in distal areas and large dunes and draas (facies association II) in proximal ones. In both cases, the sediment state was dominated by a contemporaneous sand influx, limited by the availability and transport capacity of the wind, respectively (CI_{AL} and CI_{TL} in Figs. 9 and 10). The maximum development phase is characterized by draas (facies associations II) and straight- to high sinuosity-crest crescentic dunes (facies associations III, IV, and VI), for which the sediment state had a contemporaneous sediment influx limited by the transport capacity of the wind (CI_{TL} in Figs. 9 and 10). Finally, the destructional phase results from the progradation of alluvial systems into the dune field. In some localities, the fluvial sedimentation, coupled with eolian processes, produced a fluvial–eolian interaction environment (facies association V) characterized by a sediment state with contemporaneous and lagged sand influxes limited by low sediment availability (CLI_{AL} in Figs. 9 and 10). In other areas, eolian field degradation started with an extremely deflated sand sheet environment (facies association I) dominated by contemporaneous and lagged sediment influxes limited by sand availability (CLI_{AL} in Fig. 10).

Important eolian successions such as those represented by the Vallecito Formation are interpreted as deposited in the foredeep depozone of continental foreland basins (Fig. 8). The great thickness of the unit and the cross-bedded sets, the limited occurrence of fluvial intercalations, the lack of paleosols, and the high subsidence rates can be used to distinguish eolian foredeep sequences from eolian forebulge ones. Eolian sedimentation and preservation in the foredeep depozone may be favored by a distal, low topographic front of the thrust belt during the first stages of orogen evolution.

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