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The Upper Jurassic (Kimmeridgian) fluvial–aeolian systems of the southern Neuquén Basin, Argentina

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Abstract

The Kimmeridgian Quebrada del Sapo Formation in the southernmost Neuquén Basin in Argentina represents a succession up to 40 m thick of coarse- to fine-grained fluvial deposits overlain by aeolian deposits. These fluvial–aeolian deposits reflect a significant palaeogeographic change in the basin and are related to a major, tectonically enhanced, relative sea-level fall. The fluvial section is dominated by braided-channel, fine-grained ephemeral, and sheetflood deposits. Aeolian facies are dominated by dune deposits, with minor sandsheet and interdune units. Changes in the nature of both fluvial and aeolian sedimentation within the studied area suggest a regional variability of accommodation/sediment supply conditions. The regional changes of the aeolian succession likely reflect different relative positions within a major erg. In the upwind margin of the erg, a shallow water table promoted water-lain sedimentation in interdune areas, whereas in the central parts of the erg, dry sediment accumulation took place above the regional water-table level. The vertical transition observed in the Quebrada del Sapo Formation, from fluvial to aeolian deposits, may be the result of a local climatic change to drier conditions due to the development of a climatic barrier imposed by growth of a magmatic arc to the west. Alternatively, the vertical transition could be related to a lowering of the water table associated with the compartmentalization of the basin during a period of low sea level.

Keywords: Argentina; Neuquén Basin; Kimmeridgian; Fluvial; Aeolian

1. Introduction

Interaction between fluvial and aeolian depositional systems is very common in many arid environments. The relationship between these systems and associated sedimentation processes has been studied not only in modern systems (Langford, 1989; Bullard and Livingstone, 2002), but also in the ancient sedimentary rock record (e.g. Langford and Chan, 1989; Mountney and Howell, 2000; Veiga et al., 2002). Detailed studies of the lateral variability of facies architecture and inferred interaction of processes have made it possible to define climatic and palaeogeographic variations during the development of these continental depositional sequences.

Both the regional variability of these depositional systems and the temporal transition from fluvial to aeolian systems (and vice versa) within the geological record have been studied in detail (e.g. George and Berry, 1993; Herries, 1993; Howell and Mountney, 1997; Sweet, 1999; Mountney and Jagger, 2004). Although most of these models suggest a climatic influence in the development of these transitions, detailed sedimentological studies are required to fully understand the evolution of these fluvial–aeolian systems.

In the Neuquén Basin of Argentina, low sea-level stand periods are often exclusively characterized by the deposition of both fluvial and aeolian deposits (Howell et al., 2005). Therefore, the detailed identification and characterization of relationships between deposits and the definition of controlling mechanisms are vital for the understanding of these stages of basin evolution. Previous studies in the region have considered aeolian–fluvial environments within low-stand successions in the Lower Cretaceous units of the Neuquén Basin (Veiga et al., 2002; Veiga et al., 2005), but aeolian–fluvial systems in Jurassic (Kimmeridgian) sedimentary successions in the Neuquén Basin have never been considered in detail.

The main objectives of this study are threefold: (a) to define the sedimentological characteristics of fluvial and aeolian successions of the Kimmeridgian Quebrada del Sapo Formation

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in the southern Neuquén Basin, (b) to assess the main controls on sequence development, as well as on the vertical and lateral variations, and (c) to compare these new results with those from other low-stand deposits within the basin in order to define a comprehensive Mesozoic evolution of the Neuquén Basin.

2. Geological setting and stratigraphy

The Neuquén Basin, located in west-central Argentina and Chile (Fig. 1), is a large triangular-shaped basin that was active between the Late Triassic and early Tertiary (Legarreta and Gulisano, 1989). It has a complex history, but it mostly evolved as an ensialic backarc basin along the southwestern margin of Gondwana, between a volcanic arc to the west and two major uplifted cratonic areas to the northeast and southwest (Fig. 1) (Legarreta and Uliana, 1991).

The sedimentary fill of the Neuquén Basin is characterized by the superimposition of at least six (2nd to 3rd order) transgressive–regressive cycles associated both with eustatic oscillations (Legarreta and Gulisano, 1989; Legarreta and Uliana, 1991, 1996) and a complex tectonic history that includes several episodes of inversion (Vergani et al., 1995; Veiga et al., 2001). These tectonic inversions caused and/or enhanced relative sea-level falls and resulted in the accumulation of six wedges that sharply overlie deep-marine deposits. These low-stand wedges are generally continental deposits and are spatially restricted to the central part of the basin (Legarreta,

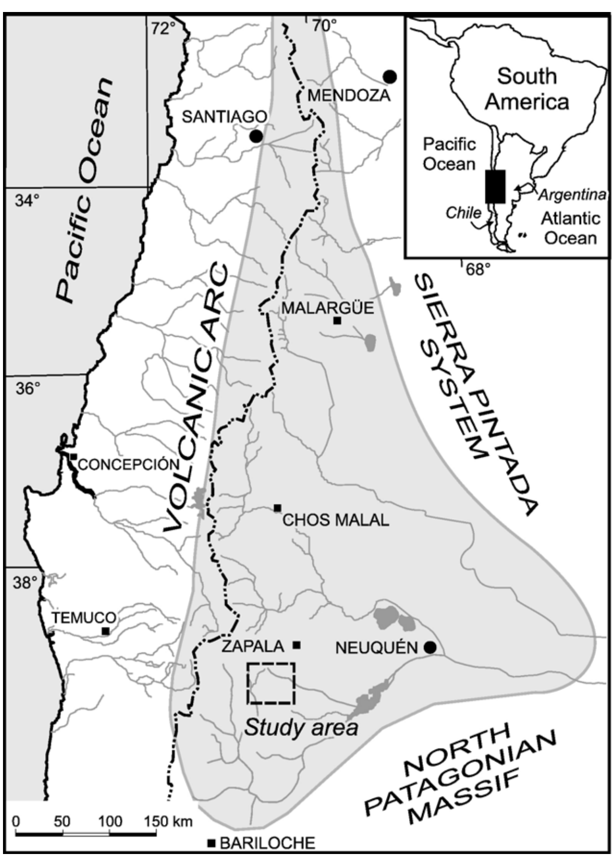

Fig. 1. Location and boundaries of the Neuquén Basin, and location of the studied area.

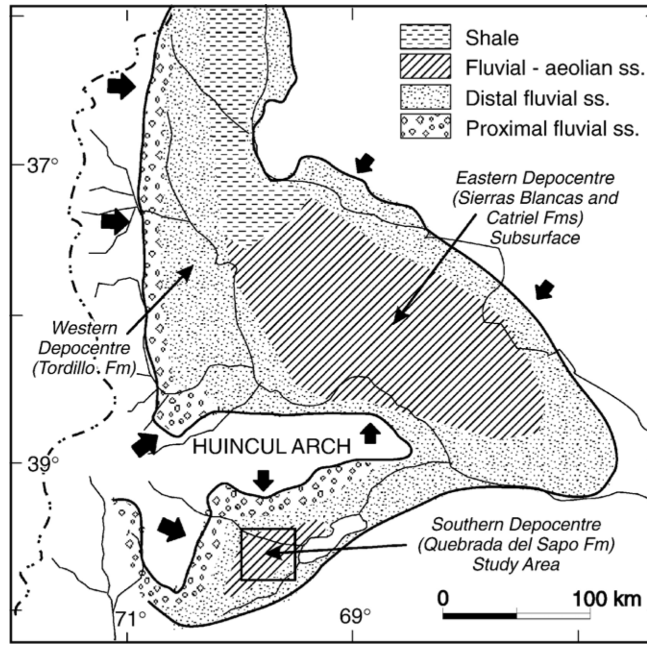

Fig. 2. Palaeogeographic sketch of Kimmeridgian sedimentation in the Neuquén Basin (modified from Vergani et al., 1995).

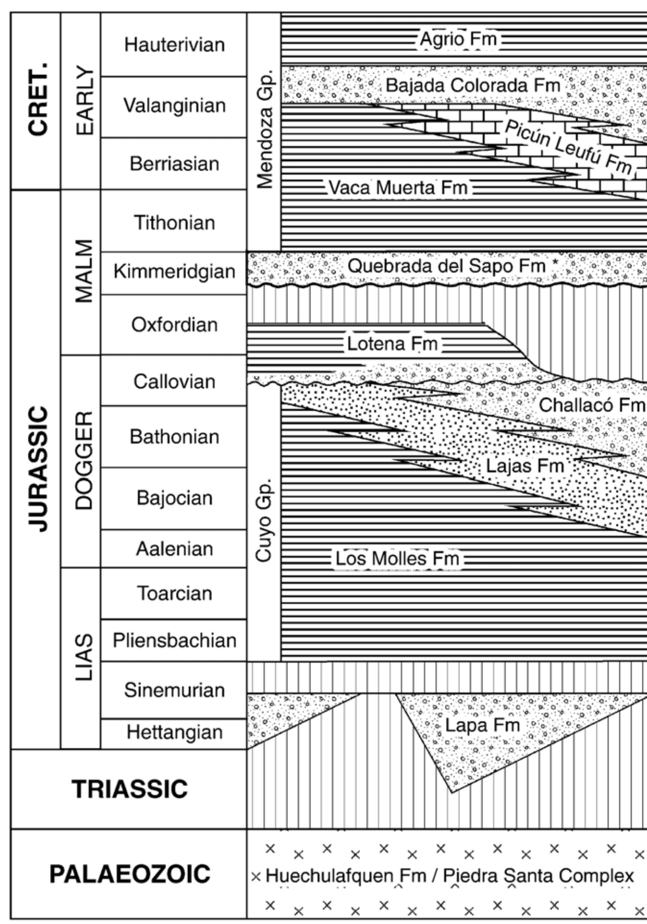

Fig. 3. Chronostratigraphic chart for the Triassic–Early Cretaceous in the southern Neuquén Basin (modified from Legarreta and Gulisano, 1989 after Veiga, 2002). *Note that the Quebrada del Sapo Formation is equivalent to the Tordillo Formation in the northwestern part of the basin and to the Sierras Blancas and Catriel Formations in the eastern Neuquén Embayment.

2002). In the marginal areas of the basin, the tectonic inversions are often represented by angular unconformities between sedimentary units as important hiatal surfaces.

During late Oxfordian to Kimmeridgian time (Late Jurassic) one of the most important of these inversion events occurred and was due to a change in the subduction regime along the active margin of the basin (Vergani et al., 1995). Reconfiguration of the basin at this time was produced mainly by the inversion of a major tectonic element of the basin, the Huincul Arch. After the inversion of the Huincul Arch, the wide embayment of the Neuquén Basin became divided by this east–west trending feature. Additionally, the development of other structures allowed the definition of at least three individual depocentres for the accumulation of Kimmeridgian sediments (Vergani et al., 1995; Spalletti and Colombo Piñol, 2005) (Fig. 2). Kimmeridgian strata in the northwestern part of the Neuquén Basin are known as the Tordillo Formation (Groeber, 1946). This unit is composed of as much as 400 m of fluvial sediments deposited in an alluvial fan to playa environment (Marchese, 1971; Spalletti and Colombo Piñol, 2005). Towards the eastern part of the basin, in the subsurface of the Neuquén Embayment, these deposits constitute a ≤250-m-thick succession composed of the Sierras Blancas and Catriel Formations. The Sierras Blancas Formation is dominated at the base by fluvial deposits that grade upwards into a dry aeolian system, and these are overlain by sediments of a wet aeolian system of the Catriel Formation (Maretto and Lara, 2002). In the southern part of the basin, south of the Huincul Arch, Kimmeridgian deposits of the Quebrada del Sapo Formation (Digregorio, 1972) are composed of ≤40-m-thick coarse- to fine-grained fluvial deposits that grade to aeolian deposits. In every part of the basin, the upper contact of the Kimmeridgian strata is sharp and abrupt, and is characterized by a major transgressive event that led to the accumulation of Tithonian shales and marls of the Vaca Muerta Formation (Fig. 3).

3. Study area and methods

The study area is located in the southern part of the Neuquén Basin, where rocks of the Quebrada del Sapo Formation crop out along the main structures that were active during the Neogene Andean inversion. The studied unit lies unconformably either on top of the Middle Jurassic continental deposits of the upper Cuyo Group (Challacó Fm) or on the marine shales of the Lotena Formation, which bears microfossils of Callovian to early Oxfordian age (Simeoni, 1995) (Fig. 3). The Quebrada del Sapo Formation is overlain by black shales of the Vaca Muerta Formation across a sharp surface on top of which, a marker bed with distinctive Tithonian ammonites (*Virgatosphinctes* sp.) is present. No diagnostic fossils have been recovered from the Quebrada del

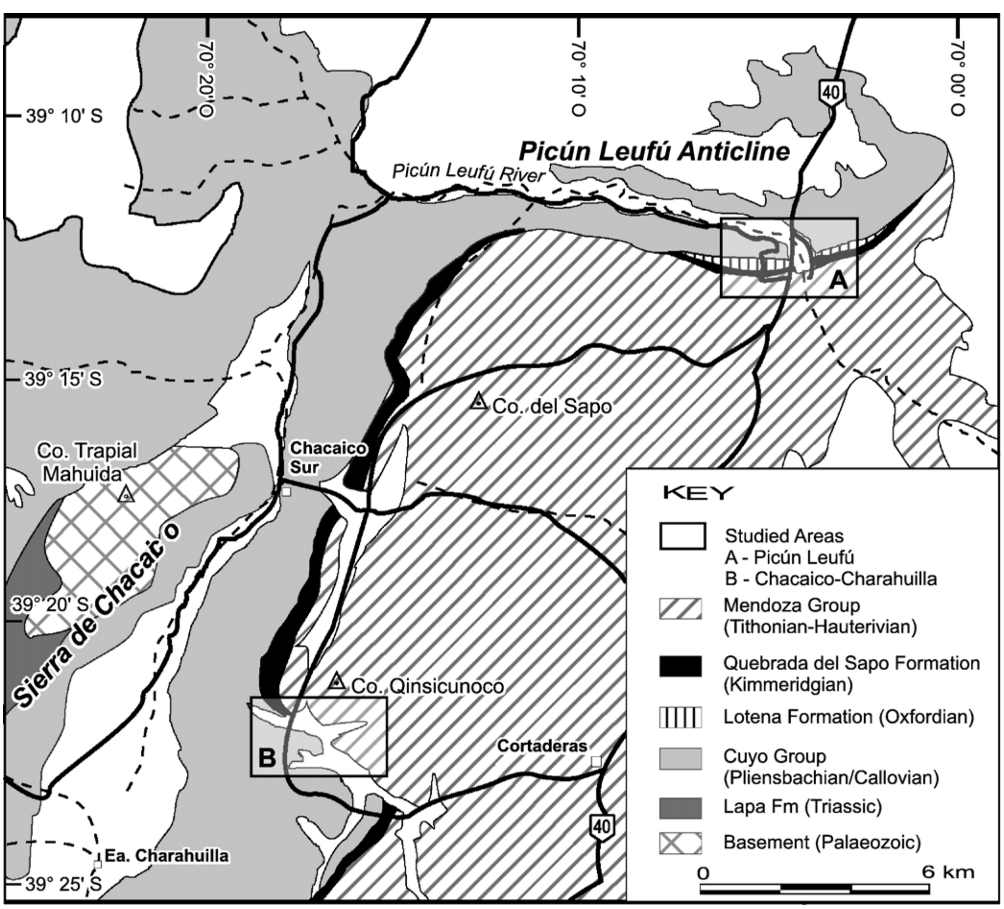

Fig. 4. Geologic map of part of the southern Neuquén Basin (after Leanza, 1990) showing location of the two studied areas (A: Picún Leufú, B: Chacaico-Charahuilla).

Sapo Fm. It is considered Kimmeridgian because of its stratigraphic position and lithostratigraphic correlation with the Tordillo Formation in the northern part of the basin. Therefore, the absolute age and time span represented in the Quebrada del Sapo Formation and chronostratigraphic correlations with other Kimmeridgian deposits are uncertain.

The Quebrada del Sapo Formation has been studied in two areas of the southern Neuquén Basin (Fig. 4). These areas are located to the east of the NNE–SSW oriented Sierra de Chacaico range, a major physiographic element of the area, and its continuation to the north as the E–W-oriented Picún Leufú Anticline. The northern area (Picún Leufú, area A in Fig. 4) is

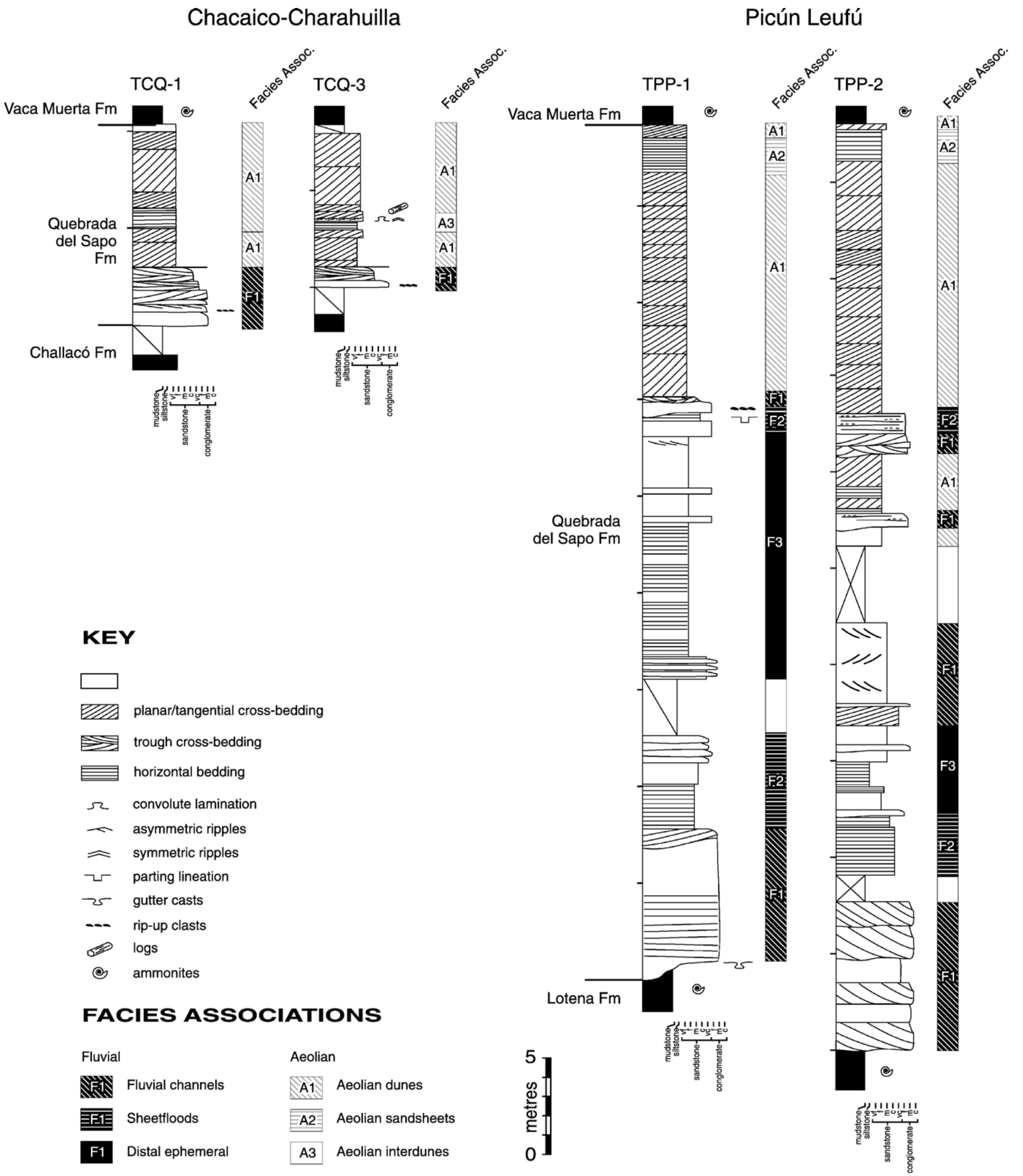

Fig. 5. Selected vertical logs and facies associations from the Quebrada del Sapo Formation in the southern Neuquén Basin.

located near where Route 40 crosses the Picún Leufú River, which is approximately 50 km south of the city of Zapala in central Neuquén province. The southern area (Chacaico-Charahuilla, area B in Fig. 4) is located approximately 15 km to the southwest of the Picún Leufú area, to the east of the Sierra de Chacaico, and 6 km west of the town of Cortaderas. In this area, extensive outcrops that reveal important lateral continuity are present; however, the basal portion of the formation is poorly exposed.

The Quebrada del Sapo Formation was studied using classic sedimentological techniques. High-resolution sedimentary logs were measured in order to define the main sedimentary elements of the studied interval. Facies were defined mainly on the basis of grain-size and sedimentary structures. Palaeocurrent orientations were measured from cross-stratified beds and pebble imbrication. Important discontinuities within the outcrops and the general geometry of distinctive rock bodies were analysed continuously along 5 two-dimensional panels where suitable outcrops were present. Also, the main characteristics of the lower and upper boundaries of the studied interval were analysed in detail across the outcrop areas.

4. Facies associations

4.1. Fluvial facies association

Fluvial deposits within the Quebrada del Sapo Formation are characterized by a wide variety of grain sizes. They range from coarse-grained conglomerates to very fine-grained sandstones and mudstones. They are present in the lower part of the formation in both study areas and are as much as 35 m thick in the Picún Lufú sector (Fig. 5). Where not well exposed in the more southern study area, fluvial deposits are <10 m thick and fine-grained facies are completely absent.

Coarser-grained deposits of the Quebrada del Sapo Formation constitute tabular, and less frequent lenticular, bodies with an erosive lower boundary, where gutter casts and grooves are present, although erosional relief does not exceed 1 m. These lenticular bodies are composed of medium- to coarse-grained polymictic conglomerates with abundant sub-rounded to rounded volcanic fragments. These deposits typically show an upward-fining trend, grading from conglomerates to coarse-grained sandstones, and with isolated granules and pebbles towards the top. Internally, they show predominantly planar and minor trough cross-bedding in sets that are 0.3 to 0.5 m thick (Fig. 6a). These deposits are thought to represent accumulation within coarse-grained, bedload-dominated fluvial channels (F1) caused by the migration of in-channel and marginal bars (Miall, 1996) and minor channel (chutes) fills.

However, not all the coarse-grained deposits within the Quebrada del Sapo Formation are related to in-channel deposition. In the Picún Leufú area, the intercalation of 5- to 15-cm-thick conglomerates and coarse-grained sandstones with horizontal bedding, in couplets as thick as 20 cm, is common (Fig. 6b). These deposits, particularly the conglomerate part of the couplet, show a discontinuous sheet-like geometry and are only rarely concave with erosive bases. They are present as

Fig. 6. Fluvial facies associations. (a) FU sequences in lenticular bodies. Arrows indicate the basal scouring surface of channel deposits. D: aeolian dune deposits. (b) Thin layers of fine-grained conglomerates and coarse-grained sandstones interpreted as sheetflood deposits. D: aeolian dune deposits.

lenticular bodies ≤15 cm thick and <1 m wide. They are composed of angular to sub-rounded clasts that are as much as 8 cm in diameter, and which may be as large as individual conglomerate beds (Fig. 6b). Sandstone layers are more continuous and are characterized by horizontal bedding, occasionally with parting lineation, although they may show low angle cross-bedding. These layers form composite sequences up to 3 m thick that are located above an erosive, but flat, lower boundary. They are also vertically associated with fluvial channels and may represent sedimentation due to short-lived, high-energy sheetfloods (F2) (Wells and Harvey, 1987; Nemec and Postma, 1993; Blair and McPherson, 1994).

Fine-grained deposits of the fluvial facies association are only present in the Picún Leufú area (Fig. 5). They are characterized by red siltstones and mudstones that are intercalated with very thin, medium- to coarse-grained sandstones. Fine-grained beds are mainly massive, with a characteristic mottling and a weak blocky structure. Intercalated sandstone layers, 5 to 15 cm thick, are mainly massive, but also show less common horizontal lamination. Some isolated fining-upward sandstone beds, as thick as 10 cm, are intercalated as well. These beds may show an erosive, horizontal lower boundary and, in places, are transitional to mudstones towards the top. These fine-grained deposits are interpreted as products of subaqueous accumulation in a relatively low-energy environment. Their association with other fluvial facies favors their assignment to a distal ephemeral fluvial setting, particularly an ephemeral mud plain (F3) environment with the development of semi-permanent water bodies. Intercalated sandstone layers may represent the low-density (distal) portions of short-lived sheetfloods (F2) that characterize the more proximal fluvial environment. The massive nature of these facies may be related to post-depositional modifications caused by both bioturbation and incipient pedogenesis.

4.2. Aeolian facies association

Aeolian deposits of the Quebrada del Sapo Formation are well represented in both studied areas and characterize the upper part of the formation. The aeolian interval is 20 m thick in the Picún Leufú area and decreases to 7 m in thickness in the Chacaico-Charahilla sector (Fig. 5). The lateral continuity of the outcrops allowed the identification of at least three different aeolian associations for the studied interval.

Most of the aeolian sandstones are characterized by fine- to medium-grained, bimodally sorted sandstones, in beds up to 2 m thick and with large-scale, planar to tangential cross-bedding. Lenticular sets with trough cross-bedding are less common. These deposits are also characterized by alternating medium- to coarse-grained, massive to inversely graded laminae in the bottom part of the foresets (Fig. 7a). The geometry of these sandstones is mainly tabular, with sharp and horizontal lower boundaries, although some of them are wedge-shaped. Internally, these sets show steeply-inclined bounding surfaces (dipping in the same direction as the inclined foresets) and, therefore, can be regarded as compound sets (Kocurek, 1996). These internal bounding surfaces truncate the underlying foresets and are parallel to overlying cross-laminae. The presence of thinly laminated deposits, interpreted as wind-ripple laminae (Hunter, 1977), in large-scale compound sets with planar- and trough cross-bedding suggests that these represent the accumulation of aeolian dunes (A1). Massive and inversely graded medium-grained sandstones, which are intercalated in the foresets, suggest deposition by grainfall and grainflow processes (Hunter, 1977) in the lee face of slipfaced aeolian dunes. Internal bounding surfaces within the sets were interpreted as reactivation surfaces and are thought to represent slight changes in wind direction or in the rate of dune migration (Kocurek, 1988; Mountney and Jagger, 2004).

Intercalated within the dune deposits are 20- to 40-cm-thick, tabular beds of fine- to medium-grained, bimodally sorted sandstones in which horizontal lamination is present. These sandstones are characterized by sharp and near-horizontal boundaries (Fig. 7b). As no lateral relationships with dune deposits have been observed for these units, they are interpreted as aeolian sandsheets (A2). They are probably related to periods of reduced upwind sand supply or periods when the water table was relatively shallow, locally reducing sand availability and inhibiting dune migration (Kocurek and Nielson, 1986).

Finally, fine- to medium-grained sandstones and red mudstones (15 to 30 cm thick) are also intercalated with the

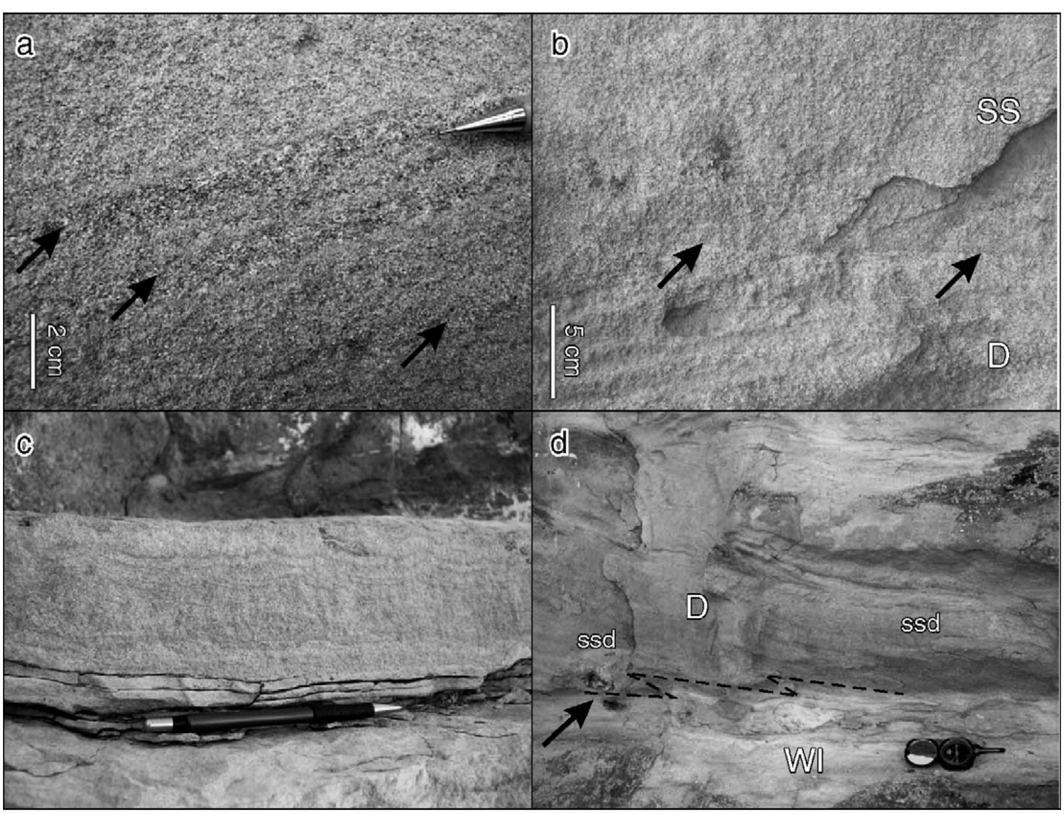

Fig. 7. Aeolian facies association. (a) Millimeter-thick, inversely-graded laminae that are a product of grainfall processes in the slipface of aeolian dunes. (b) Sharp surface (arrows) between dune (D) and sandsheet (SS) deposits. (c) Slightly deformed aggradational symmetric ripples in wet interdune deposits. (d) Interfingering between dune (D) and wet interdune (WI) deposits. Note the important degree of soft-sediment deformation (ssd) and the presence of silicified logs (arrow).

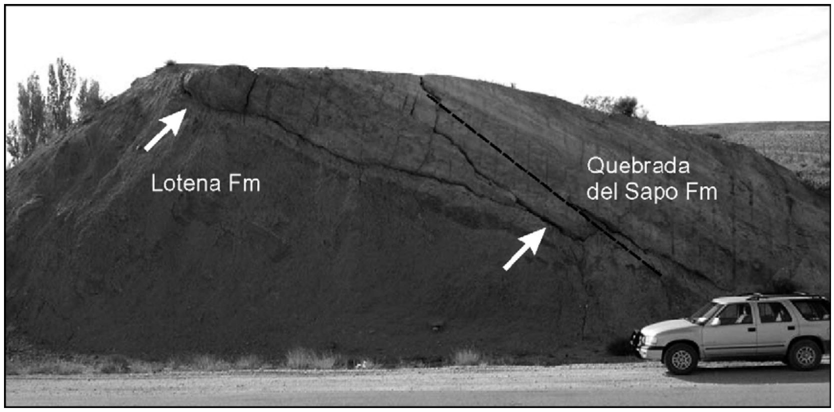

Fig. 8. Lower boundary of the Quebrada del Sapo Formation in the Picún Leufú area. Note the erosive nature of the boundary (with a relief of approximately 2 m, arrows) over Oxfordian marine shales of the Lotena Formation.

aeolian dune deposits. Sandstones resemble aeolian sandsheet deposits, with bimodal sorting and horizontal lamination, but some beds show symmetric and asymmetric, subaqueous ripples (Fig. 7c). Mudstones are usually massive, but they may show a subtle horizontal lamination. Highly compacted, silicified wood fragments are commonly observed in these deposits. Externally, these units are characterized by a sharp and near-horizontal lower boundary. Towards the top, these deposits interfinger with the bottom parts of the foresets of the dune deposits (Fig. 7d), suggesting that their accumulation was at least partly contemporaneous with aeolian dune migration. Therefore, interstratified sandstones and mudstones are interpreted as aeolian interdune deposits (A3) accumulated laterally to active dunes and associated with a shallow water table (wet interdunes, *sensu* Kocurek, 1981) that locally intersected the interdune areas. The presence of wind-lain deposits intercalated with subaqueous facies suggests that water-table oscillations may have produced the intercalation of wet and dry facies units within these interdune environments. Laterally, these deposits may be replaced by horizontally laminated sandstones with no mudstone present, suggesting that the wet interdunes may pass laterally to exclusively wind-lain deposits deposited above the influence of the water table (dry interdunes, *sensu*Kocurek, 1981).

5. Sedimentary architecture

Sedimentary architecture of the Quebrada del Sapo Formation is described here for two localities that are thought to represent different palaeogeographic positions within a continental setting. Although facies and vertical stacking of

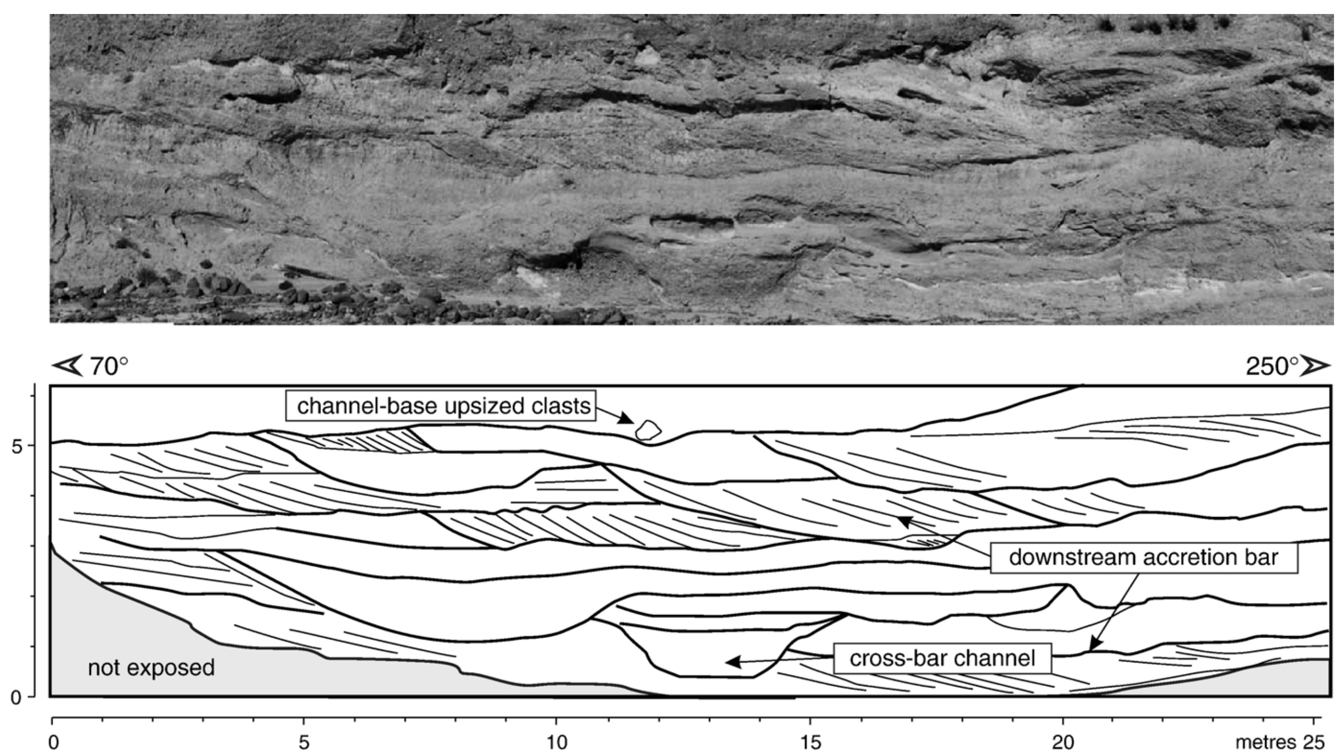

Fig. 9. Architectural Element Analysis of the basal fluvial deposits of the Quebrada del Sapo Formation in the Picún Leufú area.

sedimentary units are similar in both areas, sedimentary architecture differs considerably, particularly in terms of thickness and lateral facies relationships.

5.1. Site 1—Picún Leufú area

The Quebrada del Sapo Formation in the Picún Leufú area is thicker than in any other part of the southern Neuquén Basin. Both fluvial and aeolian sections are well-developed, with the fluvial section as thick as 30 m and the aeolian section about 20 m thick. Fluvial deposits are characterized by a wide range of grain sizes and a conspicuous vertical trend, with an overall upward fining section overlain by an upward coarsening succession. The basal 7 to 8 m are dominated by the coarsest sediments, with conglomerates containing clasts as much as 10 cm in diameter. These conglomerates overlie an erosive surface that truncates the underlying deposits and that locally shows some important erosional relief (Fig. 8). These coarse-grained deposits constitute tabular to wedge-shaped bodies with erosive lower boundaries and abundant cross-bedding (Fig. 9).

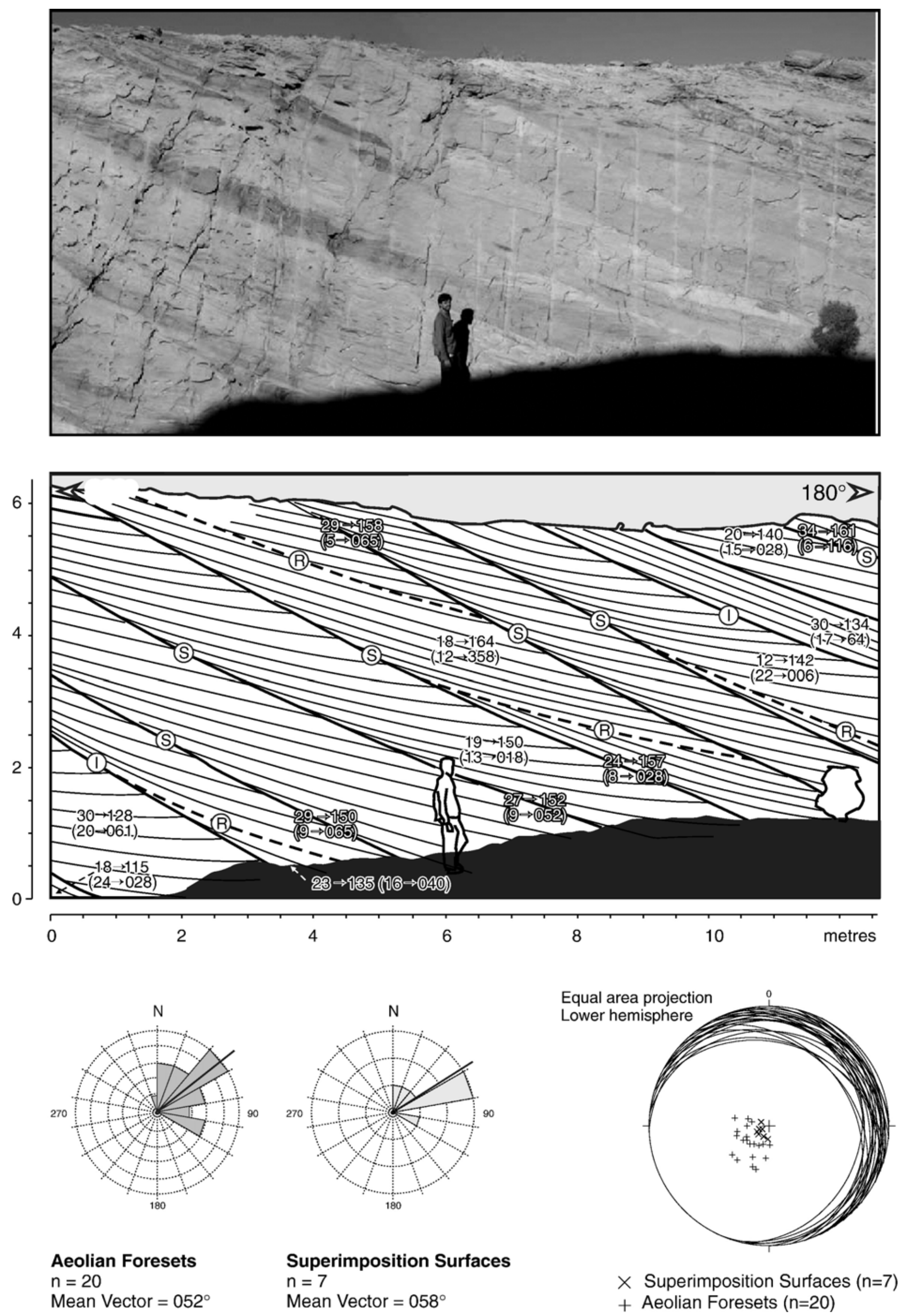

Fig. 10. Architectural Element Analysis of aeolian deposits of the Quebrada del Sapo Formation in the Picún Leufú area. I: interdune surface, S: superimposition surface, R: reactivation surface. Black labels show amount and direction of dip of cross-strata. White labels show amount and direction of dip of bounding surfaces. Values in brackets represent rotated values considering the tectonic tilt of the outcrop that dips 30° towards 170°.

Fig. 11. Large-scale, soft-sediment deformation structures within aeolian deposits of the Quebrada del Sapo Formation in the Picún Leufú area towards the top of the unit.

Grain size decreases considerably in higher parts of the succession, and fine-grained conglomerates and coarse-grained sandstones are dominant (Fig. 5). This interval is characterized by the absence of channel features and by the predominance of horizontal bedding. Fine-grained sandstones and horizontally laminated or massive mudstones are also present, and these suggest deposition in a more distal ephemeral fluvial system. Towards the top of the fluvial succession, an increase in grain size is again recorded. Abundant fine-grained conglomerates and coarse-grained sandstones, occurring as 5- to 30-cm-thick, tabular intercalations, dominate the upper 5 m of the succession.

Although there is a conspicuous vertical change from fluvial to aeolian facies in this area, this change is not abrupt. In fact, approximately 30 m above the lower boundary, aeolian dune deposits are intercalated with sandstones and conglomerates deposited by sheetfloods and minor channelised flows (Fig. 5).

The upper part of the Quebrada del Sapo Formation is dominated by fine- to medium-grained sandstones associated with the preservation of aeolian dunes (A1). Sedimentary architecture of these deposits is rather uniform, and it is exclusively composed of ≤1-m-thick, tabular to wedge-shaped, tangential cross-bedded sets (Fig. 10). Grainflow and grainfall laminae are frequent in the foresets of cross-sets, and reactivation surfaces within the sets are also present. The palaeocurrent trend for cross-laminae is strongly unimodal (circular standard deviation 33°), with a mean transport direction towards the northeast (048°). Bounding surfaces within sets (reactivation surfaces) have a similar orientation to the foresets. However, bounding surfaces between sets truncate the foresets and reactivation surfaces, and dip in a similar direction as cross-bedding (042°), but with a lower angle (<10°) (Fig. 10). A few of the bounding surfaces between sets are, however, near-horizontal.

Within the upper third of the aeolian sequence, cross-strata associated with the development of slipfaced dunes are replaced by fine- to medium-grained sandstones with horizontal lamination, which suggests the development of aeolian sandsheets. Also in the upper part of the unit, just below its contact with black shales of the overlying Vaca Muerta Formation, soft sediment deformation features, including convolute lamination

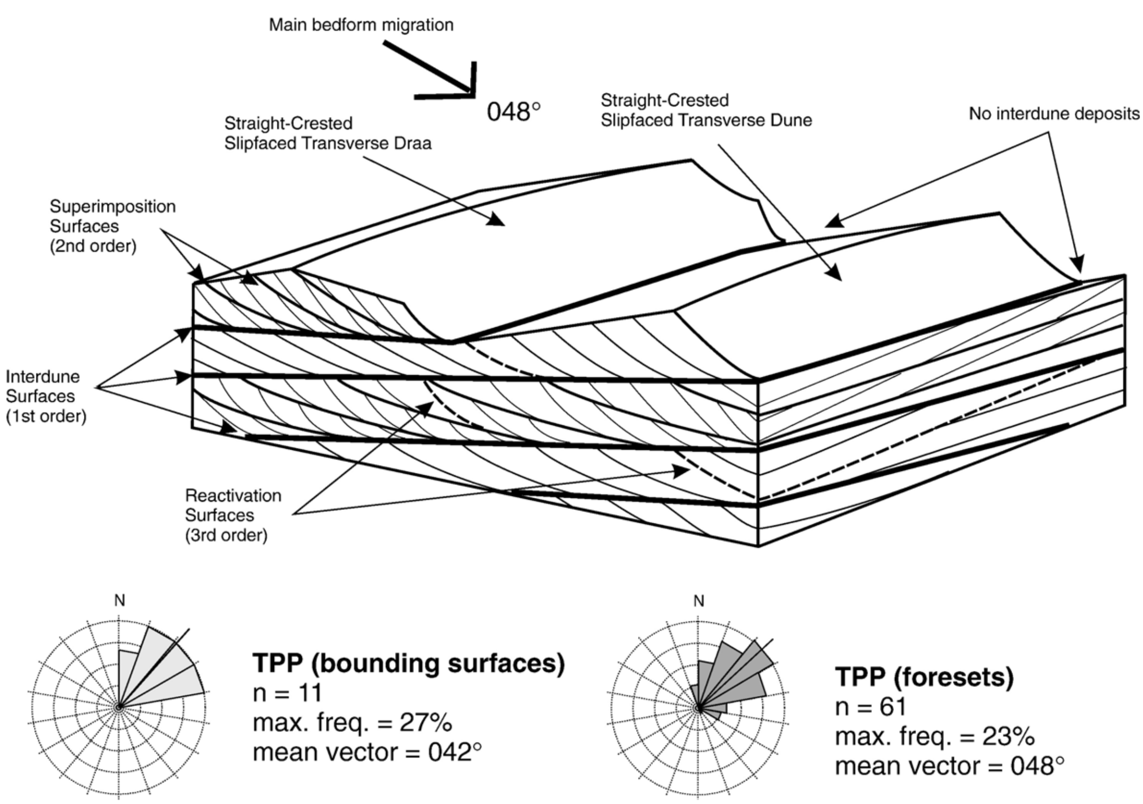

Fig. 12. Reconstruction of the aeolian systems of the Quebrada del Sapo Formation in the Picún Leufú area.

and large-scale folds, are present laterally adjacent to relatively undeformed aeolian dune deposits (Fig. 11).

5.2. Interpretation

The basal fluvial part of the Quebrada del Sapo Formation in the Picun Leufu area shows a clear grain size trend. The lowest units are conglomeratic deposits associated with the development of a bedload-dominated fluvial system with multiple channels and cross-channel bars. These deposits are replaced higher in the sequence by fine-grained sandstones and mudstones associated with an ephemeral low-energy fluvial system. Only towards the top, in contact with the aeolian section, does grain size increase again with the presence of pebble- to cobble-size conglomerates associated with sheet-floods and minor fluvial channels.

In contrast, the aeolian succession in the Picun Leufú area is relatively simple and uniform. The presence of amalgamated tabular cross-sets, with abundant grainfall and grainflow laminae in the bottom of the foresets, and a strongly unimodal palaeocurrent direction, suggest the development of slipfaced, relatively straight-crested transverse dunes. However, the fact that most of these cross-bedded sets are bounded by low-angle, downwind-dipping surfaces, with a much lower angle than foresets or reactivation surfaces (and therefore truncating these), suggests that these surfaces may be superimposition surfaces. This implies the development of composite draa, which is characterized by the migration of superimposed aeolian dunes over the lee face of major bedforms (Fig. 12). Although the discrimination between reactivation and superimposition surfaces can be problematic (Rubin, 1987, Mountney and Thompson, 2002), the former are more steeply inclined and are always overlain by concordant cross-strata, in contrast to superimposition surfaces that are more gently inclined and overlain by downlapping foresets. As cross-bedded sets and superimposition surfaces dip roughly in the same direction (Fig. 10), it can be concluded that superimposed bedforms migrated in a similar direction as the primary bedforms (Rubin and Hunter, 1983) and, therefore, their relative migration is almost downslope of the main, large-scale, features located towards the northeast. The similar orientation of primary and superimposed bedforms might indicate a low relief of the major primary bedform because it did not interfere with the primary flow direction (Sweet and Kocurek, 1990; Sweet, 1992).

Near-horizontal surfaces within the aeolian succession may represent interdune surfaces (Fig. 12) and important dune coverage is indicated by the amalgamation of dune deposits with no participation of coeval interdunes. This may reflect the development of a sand-saturated environment with enough supply and availability for dunes to grow laterally until interdune flats disappeared.

Towards the top of the studied unit, the aeolian accumulation seems to change slightly, with the presence of horizontally laminated deposits associated with the development of aeolian sandsheets. The presence of these deposits, in contrast to the accumulation of aeolian dunes, suggests a limited sand supply or a decrease in sand availability. These are due to the development of stabilising factors (surface cementation, vegetation, etc.) or the presence of a relatively shallow water table that considerably decreases sand availability, inhibiting dune development (Kocurek and Nielson, 1986).

The presence of soft-sediment deformation structures in the aeolian deposits towards the top of the unit could be also associated with water saturation of previously wind-lain deposits. However, the development of large-scale folds and the modification of original dune profiles may also be related to the sudden flooding of the dune field, rather than to water saturation of dune deposits by a water table rise (Glennie and Buller, 1983; Ahmed Benan and Kocurek, 2000; Strömbäck et al., 2005).

5.3. Site 2—Chacaico-Charahuilla area

Towards the southeast of the studied area, in the Chacaico-Charahilla sector, the Quebrada del Sapo Formation never exceeds 15 m in thickness. As in the Picún Leufú locality, the lower part of the studied unit is dominated by fluvial deposits, whereas aeolian deposits prevail towards the top.

The basal fluvial interval is characterized by medium- to coarse-grained conglomerates and sandstones in lenticular, cross-bedded bodies as much as 1 m thick (Fig. 13a). There is a

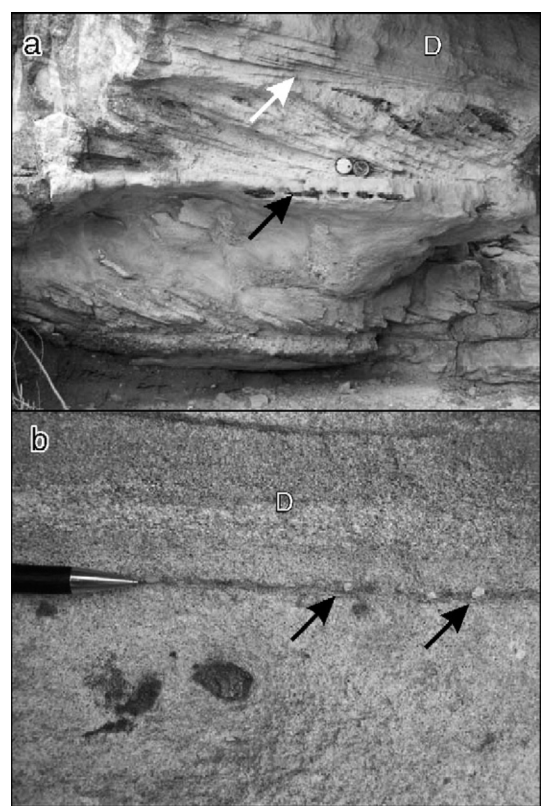

Fig. 13. Details of the aeolian facies association in the Chacaico-Cahrahuilla area. (a) Cross-bedded, coarse-grained sandstones and fine-grained conglomerates with abundant rip-up clasts at the base (black arrow). Note the sharp contact between these and the overlying aeolian dune deposits (white arrow). (b) Detail of the boundary between fluvial and aeolian deposits (black arrows). Note the concentration of pebbles in the boundary that suggests aeolian deflation.

fining-upward trend in these fluvial deposits, with conglomerates present at the base that pass upward into coarse-grained sandstones with abundant rip-up clasts. No fine-grained deposits have been identified within these basal fluvial deposits, although the presence of abundant rip-up clasts suggests the accumulation and subsequent reworking of fine-grained deposits (Fig. 13a).

The fluvial-to-aeolian transition in this area is characterized by an abrupt shift, with no intercalation between these deposits as observed in the Picún Leufú area. In fact, the top of the fluvial section in this area is marked by the presence of a distinctive, 1- to 2-cm-thick horizon, characterized by a greater concentration of rounded pebbles that are similar in shape and size to those found intercalated within the upper fluvial sandstones (Fig. 13b). On top of this horizon, only aeolian deposits were identified, suggesting a sudden change from fluvial to aeolian deposition.

Aeolian deposits in the Chacaico-Charahuilla area are thinner than in the Picún Leufú area, with a uniform thickness of approximately 7 m. They are characterized by the presence of relatively thin (≤1-m-thick), trough-shaped, cross-bedded sets. Troughs are <10 m in lateral extent and are also oriented towards the northeast (average 023°), but with a greater spread (standard deviation 54°) than in the Picún Leufú area. However, the main difference between the aeolian sections is that in the Chacaico-Charahuilla area, interdune deposits are present, intertongued with the toe-sets of overlying aeolian dunes (Fig. 7d). These interdune facies show evidence of both subaerial and subaqueous accumulation, and the presence of abundant soft-sediment deformation structures including convolute lamination and dish structures. The lateral extension of these wet interdune deposits does not exceed 200 m, being laterally replaced by dry-surface deposits (dry interdunes) or by a bounding surface between aeolian dune deposits (Fig. 14).

The upper boundary of the unit in the Chacaico-Charahuilla area is also with the marine shales of the Vaca Muerta Formation. This boundary is sharp and lacks evidence of large-scale soft-sediment deformation as is common in the Picún Leufú area.

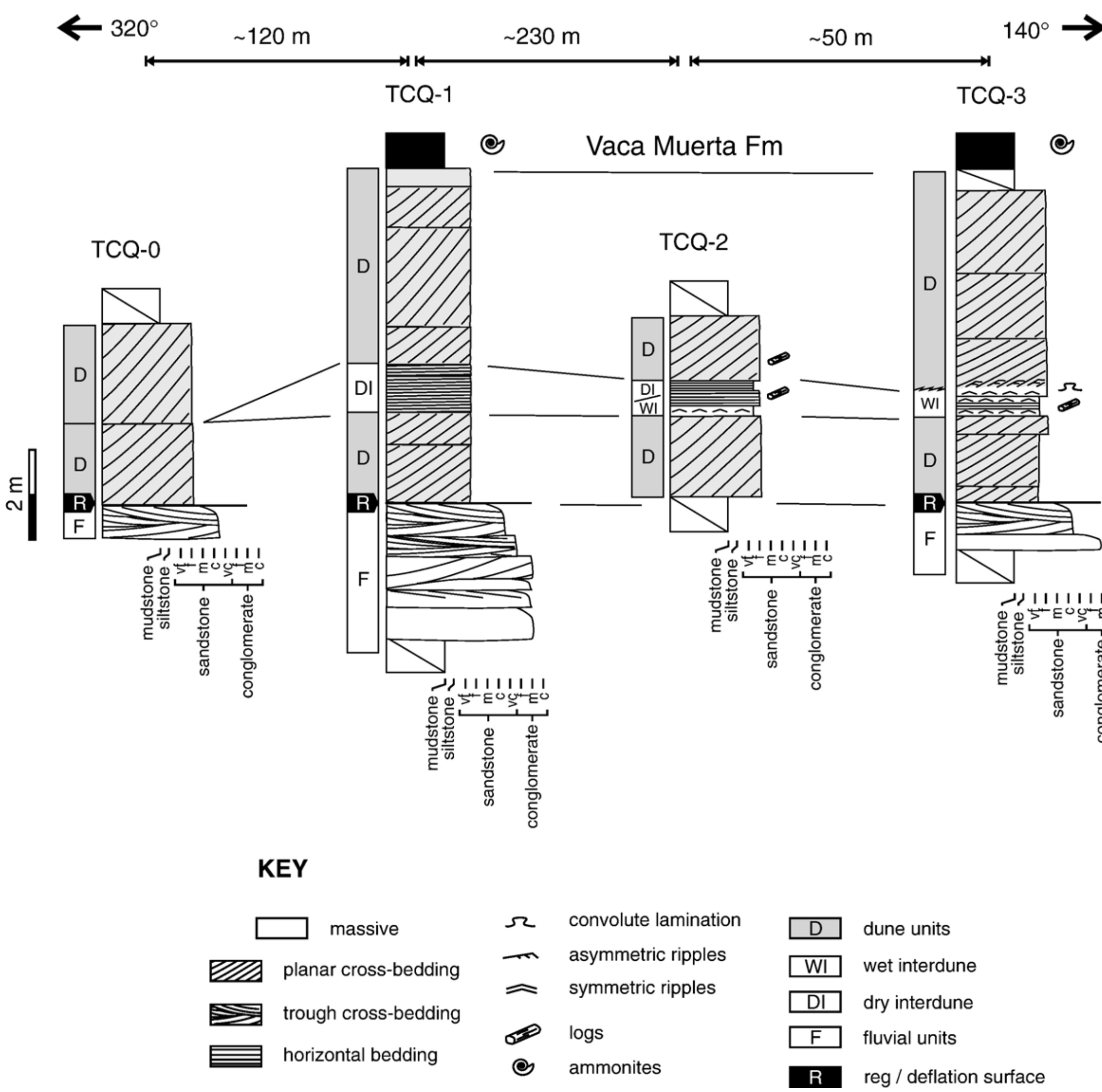

Fig. 14. Detailed vertical logs showing the lateral variability of aeolian facies in the Chacaico-Charahuilla area.

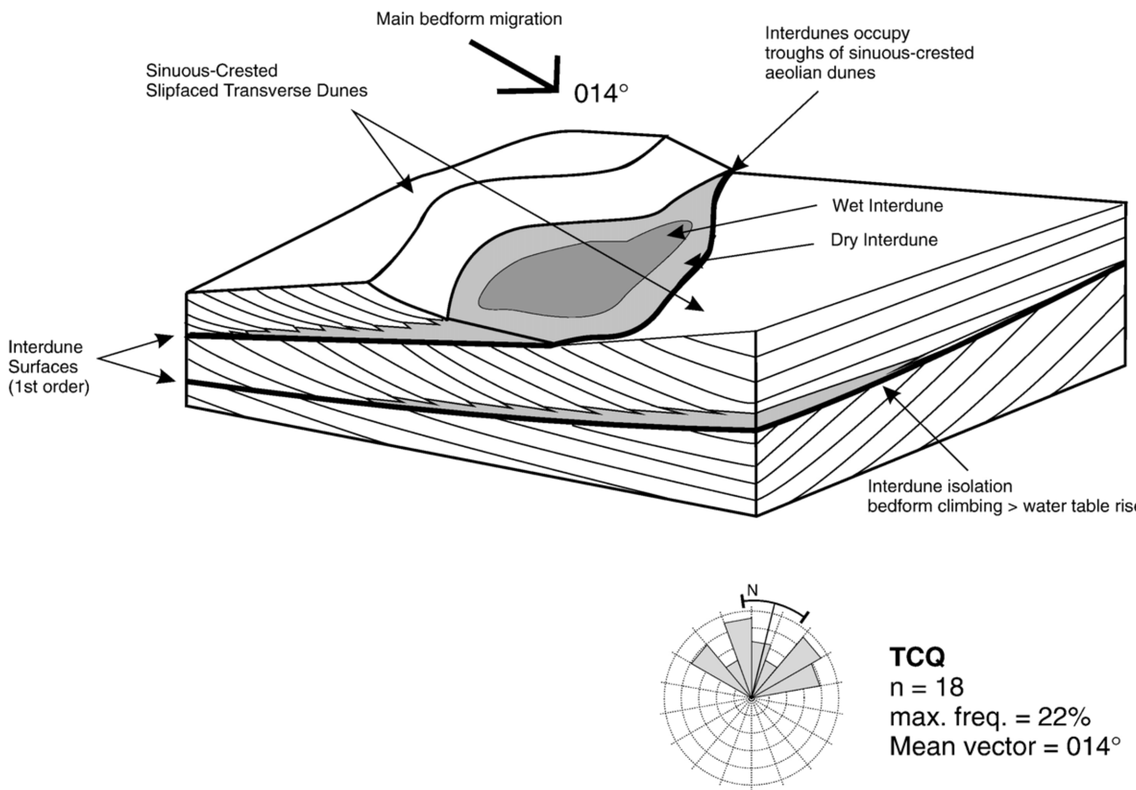

Fig. 15. Reconstruction of the aeolian systems of the Quebrada del Sapo Formation in the Chacaico-Charahuilla area.

5.4. Interpretation

Although a similar vertical trend in facies as in the Picún Leufú area is observed in the Chacaico-Charahuilla area, important changes in sedimentary architecture and facies associations occur, and suggest different depositional conditions. First, the thinner Quebrada del Sapo Formation in this area indicates either reduced sediment supply (or availability) in an under-filled, non-marine basin or reduced accommodation creation in this area. This is also marked by an absence of fine-grained deposits, which suggests no vertical evolution to more distal fluvial settings as is recorded in the stratigraphy of the Picún Leufú area. Fluvial deposits are exclusively characterized by channelised bedforms, suggesting a bedload-dominated, braided fluvial system, with multiple unstable channels. Abundant, large rip-up clasts suggest the reworking of fine-grained deposits that previously accumulated laterally to active channels.

The vertical transition from fluvial to aeolian deposits in this area is sharp, and characterized by a deflation surface (or reg) suggestive of a period of wind erosion and/or sediment by-pass. This implies an abrupt cessation of fluvial sedimentation in the area and the dominance of sediment-undersaturated winds under relatively low water-table conditions that allowed the deflation of fluvial deposits accumulated at the initial phase.

Aeolian accumulation in the Chacaico-Charahilla area is characterized by a relatively wet, climbing aeolian system. This system is dominated by sinuous-crested, transverse dunes that climbed in association with discontinuous wet interdunes. Dunes were probably simple forms, as no superimposition surfaces were observed in this area (Fig. 15).

The limited lateral extent of interdunes suggests that subaqueous accumulation, contemporaneous with dune migration within interdune areas, was controlled by a shallow water table. However, the fact that these water-lain deposits have a limited lateral extent of 200 m, and that they laterally pass into wind-lain deposits and into a bounding surface within dune facies (interdune surface) (Fig. 14), suggest: (a) they might have accumulated in the erosive, frontal troughs of the sinuous-crested dunes, and (b) the water table was not high enough to cover all the interdune areas, but rather the more depressed erosional troughs, grading laterally to damp and even dry depositional conditions in the interdune areas.

6. Discussion

Two main conclusions can be drawn from the description and interpretation of the Quebrada del Sapo Formation in the southern part of the Neuquén Basin. First, it is clear that the vertical transition from fluvial to aeolian facies is consistent across the study area, suggesting that the same overall pattern in the evolution of the sedimentary systems in this part of the basin. Second, and despite the same vertical trend, facies associations and depositional environments show important variations between the two studied areas in this part to the basin. This suggests that, although influenced by the same regional factors, sedimentation proceeded in somewhat variable patterns on a local scale.

6.1. Lateral variability

The main difference between the two studied areas lies in the thickness of the Quebrada del Sapo Formation, with the unit in the northern area (Picún Leufú) being almost three times thicker than in the southern area. This thickness difference occurs both in the fluvial and aeolian parts of the formation, which suggests the relationship between sediment supply and accommodation creation differed between these two areas throughout the sedimentary evolution of this unit. Accommodation creation rate exceeding the rate of sediment supply in the Picún Leufú area is suggested by a relatively constant retrogradational stacking of the fluvial deposits and their evolution to distal, low-energy ephemeral deposits. Also the preservation of these thick sequences of fine-grained deposits suggests a reduced sediment supply compared to the rate at which accommodation was being created. By contrast, in the southern area, the reworking of any previously deposited fine-grained material implies a high degree of lateral shifting of fluvial channels and a low aggradation of the fluvial plain under low accommodation conditions.

The main features of the aeolian depositional systems that develop towards the top of the Quebrada del Sapo Formation differ from one locality to the other. In the southern part of the study area, a relatively thin wet aeolian system is developed. Although laterally restricted to erosional troughs, wet accumulation in interdune areas is recorded laterally to simple, sinuous-crested, transverse dunes. As proposed in other models (e.g. Mountney and Jagger, 2004), lateral facies transitions occur in a rather predictable succession within the interdune deposits (Fig. 14), with the transition from wet to dry deposits in the interdunes. The northern sector, in contrast, is characterized by the deposits from a dry aeolian system. No record of wet interdune deposits was found in this area, and in fact, no interdune deposits are present at all, suggesting a dry depositional environment with complete dune coverage and dune deposition well above any influence from the water table.

The fact that the transition between fluvial and aeolian deposits is different between the two localities gives further evidence of a contrast in sedimentation conditions. In the northern area, there is a gradual intercalation of fluvial and aeolian deposits before the gradation to completely aeolian conditions. In the southern sector, however, there is a sharp deflation surface that forms the boundary between the fluvial system and the younger aeolian system. This may represent an important deflation event under low aggradation of the depositional systems.

Considering the reduced thickness of the aeolian section of the Quebrada del Sapo Formation in the south, and that in each locality the characteristics of the aeolian deposits remained essentially constant, it is difficult to attribute these differences to the temporal evolution of the aeolian depositional system. Taking into account that dune coverage and sand availability increase towards the centre of an erg (Mountney and Jagger, 2004), and that in the central parts dunes can climb above the regional depositional surface, it is likely that these differences reflect different locations within an erg (Fig. 16). In fact, the northeast transport direction indicates that the southern sector was in an upwind position relative to the northern sector. It may, therefore, represent a location closer to the upwind erg margin, with reduced dune coverage. A relatively shallow water table resulted in interactions with the depositional surface in the interdune areas. In contrast, the northern sector might represent a more central part of the aeolian depositional environment, with maximum dune coverage. Aeolian accumulation in the central part of the erg was thus independent from the regional water table because of the vertical growth of transverse draa.

Although it is not possible to physically trace the lateral relationship between the studied locations and the aeolian deposits in the subsurface of the Neuquén Basin towards the northeast, the above interpretation may also explain the presence of a thicker and better developed aeolian record towards that area (following the same lateral pattern) (Fig. 16). Whether or not the southern sector of the basin was connected with the eastern sector, these two areas seem to nonetheless have been controlled by the same regional processes. The main differences between them arise from the subsidence pattern and from the potential to generate a stratigraphic record during the late stage of aeolian sedimentation.

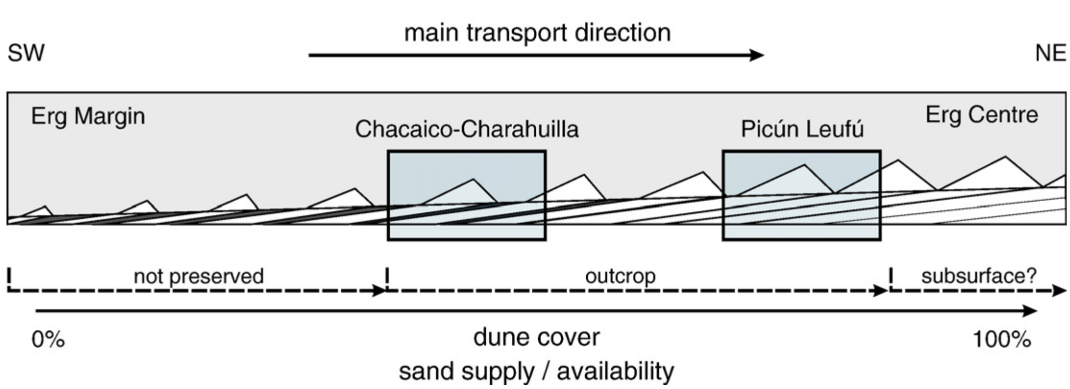

Fig. 16. Reconstruction of the relative position of the studied localities within a major erg system with possible correlation with subsurface deposits (modified from Mountney and Jagger, 2004).

6.2. Vertical facies evolution

Despite the observed lateral differences, the main characteristic of the Quebrada del Sapo Formation in the southern part of the Neuquén Basin is its internal transition from fluvial to aeolian deposits. Many mechanisms have been proposed to explain this transition in the rock record, the most commonly cited being the gradual change in climate towards drier conditions (Howell and Mountney, 1997; Mountney et al., 1999). This change includes reduced fluvial discharge and an overall lowering of the water table that increases sand availability for winds to transport and accumulate dunes (Kocurek, 1999; Kocurek and Lancaster, 1999). The consistent change to aeolian conditions in the whole southern sector of the basin (and also in the subsurface towards the east), and the presence of a regional deflation surface in the southern area between the fluvial and aeolian depositional systems, suggest that this was possible. However, there is evidence that challenges the application of a simple climatic model to explain the vertical transition observed in the stratigraphy of the Quebrada del Sapo Formation.

The contrasting characteristics of the Kimmeridgian low-stand wedge deposits in the northwestern part of the Neuquén Basin (Tordillo Formation) can be used to explain the application of a local, rather than a basin-scale, climate change model to explain the fluvial to aeolian transition observed in the south. In the northern Neuquén Basin, the Tordillo Formation is over 450 m thick and consists of exclusively fluvial sediments. Furthermore, there is a clear trend towards increasing accommodation conditions that could be associated with a local subsidence pattern or even with an overall transgressive trend (Spalletti and Colombo Piñol, 2005). As no climate change is recorded in the stratigraphic record of this northern area, the gradual change to deposition of aeolian sediments (e.g. more arid conditions) within the Quebrada del Sapo Formation must be explained by a relatively restricted, local climate change. This also suggests that the local fluvial–aeolian transition observed in the Quebrada del Sapo Formation seems to have developed independently of the sedimentary evolution of time-equivalent successions in other parts of the basin. In the Late Jurassic southwestern margin of Gondwana, this transition could be a response to growth of a magmatic arc towards the west (Sanguinetti and Ramos, 1993), which acted as a topographic barrier between the southern part of the basin and the palaeo-Pacific. Wind transport direction along this margin would have been mainly towards the NNE–NE and, therefore, storm systems would have been controlled by the topographic evolution of the western margin of the basin (Fig. 17).

However, despite evidence for an important topographic barrier to the west and of a coarse-grained sediment supply directly from the western arc also in the northwestern part of the basin (Spalletti and Colombo Piñol, 2005), no climatic change is recorded in that part of the basin. Considering the varied evolution of this low-stand wedge in different parts of the basin, and that it developed after tectonic inversion and palaeogeographic reconfiguration of the basin (Vergani et al., 1995), it is possible that different depocentres developed and evolved in rather independent ways. This would explain not only the accommodation differences, but also the different evolution of fluvial and/or aeolian sedimentation systems within each depocentre. Thus, whereas in the south of the basin the Kimmeridgian low-stand wedge is characterized by a clear transition from fluvial to aeolian systems, sedimentation in the northwestern sector proceeded under solely fluvial conditions with an overall transgressive pattern (Spalletti and Colombo Piñol, 2005). However, if this compartmentalization occurred, then it would have only affected the distribution of low-stand deposits (and early transgressive deposits) because, except for the basal part, the distribution of the overlying deep-marine sediments of the Vaca Muerta Formation does not follow this same pattern and, in contrast, shows a uniform facies distribution throughout the basin (Spalletti et al., 2000).

Aeolian sedimentation during low-stand periods was common in the Neuquén Basin after Late Jurassic (Hauterivian, Veiga et al., 2002; Barremian/Aptian, Veiga et al., 2005), with similar facies to those recorded in the Kimmeridgian deposits and suggesting that conditions favorable for aeolian accumulation (wind distribution and orientation) were frequent (if not ubiquitous) in the basin. However, aeolian deposits are commonly associated with low accommodation settings and generally not laterally related to fluvial systems (Veiga et al., 2005), suggesting that they could have occurred in association with locally favorable conditions in particular parts of the basin. If no climatic variation took place, then the aeolian deposits are more likely products of local sediment supply and availability conditions rather that of global (or local) climatic fluctuations

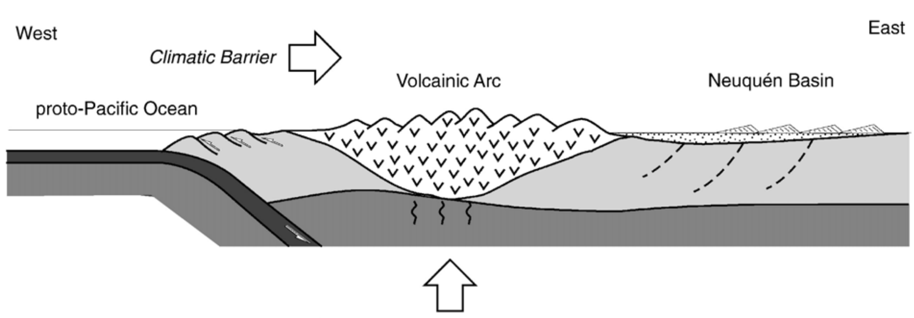

Fig. 17. Reconstruction of the Kimmeridgian southwestern margin of Gondwana and implications for local climatic variations on the accumulation of sediments forming the Quebrada del Sapo Formation.

(wind moisture and orientation). Therefore, and also considering that sedimentation in the southern part of the basin was independent of that to the northwest, sediment accumulation could have been controlled by a lowering of the water table (related to the tectonically-enhanced relative sea level fall) and thus sand supply not being limited by a relatively shallow water table.

The development of a wet aeolian system in the southernmost area, however, suggests that, at least during final sedimentation of the Quebrada del Sapo Formation, a relatively shallow water table was present in this marginal area of the erg. The presence of a climbing wet aeolian system implies a rising water table (Mountney and Jagger, 2004). This could be correlated with the overall transgressive trend observed in the northwestern part of the basin that could have also been recorded in the uppermost part of the Quebrada del Sapo Formation. However, their effects are also observed in the marginal portions of the erg, as in the central area accumulation proceeded above the water table throughout the entire Quebrada del Sapo Formation.

Extensive soft-sediment deformation of the aeolian deposits in the uppermost Quebrada del Sapo Formation could be associated with the final transgression of the Kimmeridgian erg. Unfortunately, discontinuous outcrops prevent detailed definition of the extent of these deformation features and their lateral relationship with aeolian dune deposits. However, a sudden transgression of these continental deposits has been recorded in other ergs of the Neuquén Basin (Huitrín Formation, Strömbäck et al., 2005). The presence of ammonite-bearing, deep-marine black shales of the Vaca Muerta Formation lying sharply on top of the aeolian deposits, without any transitional facies or cementation layers, suggests that the transgression was rapid and occurred when aeolian deposits were still unconsolidated. Such an interpretation has been applied to the Huitrín Formation in the Neuquén Basin (Strömbäck et al., 2005) and to many other aeolian systems (Glennie and Buller, 1983; Ahmed Benan and Kocurek, 2000). However, no absolute time constraints are available and the period between aeolian accumulation and marine transgression is uncertain.

7. Conclusions

Deposition of the Quebrada del Sapo Formation in the southern part of the Neuquén Basin resulted in a thin succession (compared to other parts of the basin) of fluvial and aeolian deposits. Fluvial deposits dominate the lower part of the unit. They are characterized by coarse-grained deposits (conglomerates and coarse-grained sandstones) associated with a braided river system, fine-grained conglomerates and sandstones related to sheetfloods, and fine-grained sandstones and mudstones representing an ephemeral low-energy fluvial environment. Aeolian deposits characterize the upper part of the Quebrada del Sapo Formation in the study area. They are dominated by cross-bedded, fine- to medium-grained sandstones related to aeolian dunes, horizontally stratified sandstones interpreted as sand-sheets and fine-grained sandstones, and mudstones interpreted as aeolian interdunes.

In the northern part of the study area, the Quebrada del Sapo Formation is thicker and dominated by a retrogradational pattern in the basal fluvial deposits. A transition to a dry aeolian system, dominated by straight-crested slipfaceless draa with no interdune deposits, is gradual and is represented by the interstratification of aeolian dune and sheetflood deposits. In the more southerly area, the unit is thinner and fluvial facies are only represented by conglomerates and sandstones of a braided fluvial system. There is a sharp transition to the aeolian deposits at the top of the unit, which is characterized by a deflation surface. The aeolian deposits are dominated by sinuous-crested dunes that interfinger with wet to damp interdunes.

The different characteristics of the upper aeolian section of the Quebrada del Sapo Formation may be the result of different palaeogeographic positions within a major aeolian depositional system (erg). In this context, and considering the main transport direction, the southern studied area may represent a position closer to the upwind margin of the erg, with a greater influence of the water table on the interdune area.

The vertical transition from fluvial to aeolian deposits can be regarded as the result of a climate change towards more arid conditions. However, the characteristics of coeval deposits in other parts of the basin suggest that local climatic conditions may have controlled the vertical succession observed in the Quebrada del Sapo Formation. This could be related to the development of a topographic barrier to the west reflecting growth of a magmatic arc. Alternatively it could reflect compartmentalization of the basin and development of a southern depocentre dominated by a low water table favoring widespread aeolian sedimentation.

Soft-sediment deformation at the top of the Quebrada del Sapo Formation and below a major marine flooding surface suggests that the Late Jurassic marine transgression might have occurred quickly and while aeolian sedimentation was still active. This has been observed in other transgressions of aeolian successions in the Cretaceous record of the Neuquén Basin.

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