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Aeolian/fluvial interactions and high-resolution sequence stratigraphy of a non-marine lowstand wedge: the Avilé Member of the Agrio Formation (Lower Cretaceous), central Neuquén Basin, Argentina

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ABSTRACT

Accumulation within the unconformity-based Hauterivian Avilé Sandstone of the Neuquén Basin, Argentina, was characterized by a close interaction between fluvial and aeolian processes developed after a major relative sea-level drop that almost completely desiccated the entire basin and juxtaposed these non-marine deposits on shallow- and deep-marine facies. Aeolian deposits within the Avilé Member include dune (A1) and sand sheet (A2) units that characterize the lower part of the unit. Fluvial deposits comprise distal flood units (F1) interbedded with aeolian dune deposits in the middle part of the succession, and low- (F2) and high-sinuosity (F3) channels associated with floodplain deposits (F4) towards the top. The internal characteristics of the aeolian system indicate that its accumulation was strongly controlled by water-table dynamics, with the development of multiple horizontal deflation super surfaces that truncate dune deposits and form the basal boundary of flood deposits and sand sheet units. A long-term wetting-upward trend is recorded throughout the entire unit, with an increase in fluvial activity towards the top and the development of a more permanent fluvial system overlying a major erosion surface interpreted as a sequence boundary. The upward increase in water-table influence might be related to relative sea-level rise, which controlled the position of the water table and allowed the accumulation of tabular aeolian units bounded by horizontal deflation surfaces. This high-frequency, eustatically driven process acted together with a long-term climatic change towards wetter conditions.

Keywords Aeolian/fluvial interactions, Argentina, Avilé Sandstone, Cretaceous, Neuquén Basin, water table.

INTRODUCTION

Several authors have described intertonguing between aeolian and fluvial deposits in different basins, suggesting that the interaction between these two processes is common in both modern environments (Langford, 1989) and the rock record (Langford & Chan, 1989; Herries, 1993).

The Lower Cretaceous (Hauterivian) Avilé Sandstone Member of the Agrio Formation is exceptionally well exposed in the central part of the Neuquén Basin. It consists of aeolian and fluvial deposits intercalated between ammonite-bearing shales of the Lower and Upper Members of the Agrio Formation (Fig. 1). It has been interpreted as a lowstand wedge produced by a major relative sea-level drop (Legarreta & Gulisano, 1989).

Although the Avilé Sandstone has been discussed in terms of its depositional environments (Veiga & Vergani, 1993) and aeolian processes

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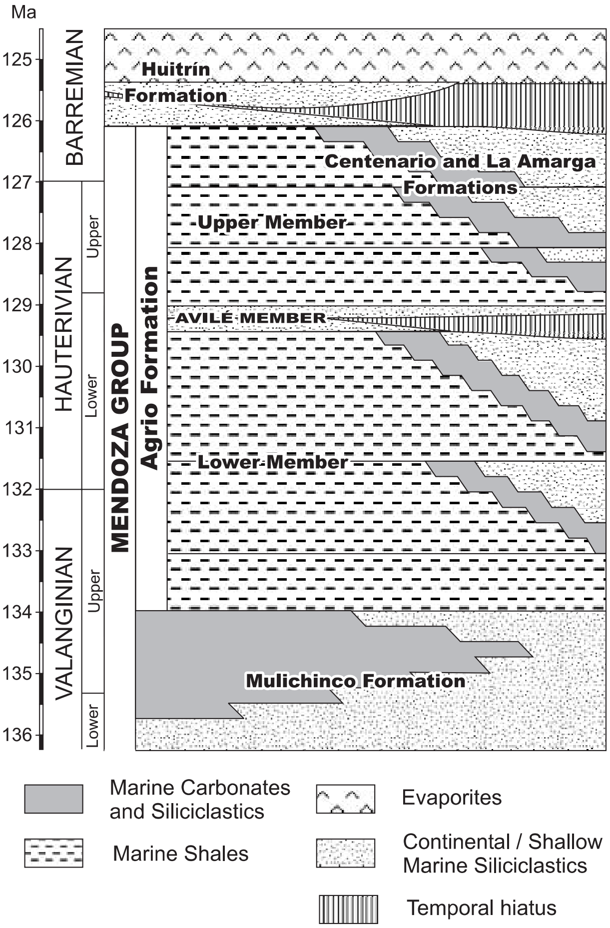

Fig. 1. Chronostratigraphic chart for the Lower Cretaceous in southern Neuquén Basin. Numerical time scale based on Gradstein *et al.* (1996). Age of units from Aguirre-Urreta & Rawson (1997), Aguirre-Urreta *et al.* (1999) and Legarreta & Uliana (1991).

(Gulisano & Gutiérrez-Pleimling, 1988), no attempt has been made previously to produce a detailed description of the interactions between fluvial and aeolian processes and the implications for the sequence stratigraphy of this unit.

It is also important to assess the effects of external controls (climate, tectonics, sea-level change) on the development of the Avilé Member in order to understand and predict the geometry, continuity and interconnection of sandstone bodies, because this unit forms important hydrocarbon reservoirs in the central Neuquén Basin.

GEOLOGICAL SETTING AND PREVIOUS WORK

The Neuquén Basin of west-central Argentina is a back-arc depression that was active between the Upper Triassic and the Lower Tertiary. It is limited by a volcanic arc to the west and by two cratonic areas, the Sierra Pintada System and the North Patagonian Massif, to the north-east and south-east respectively (Fig. 2a).

Despite the complicated tectonic history of this basin (Vergani *et al.*, 1995), during the Early Cretaceous, it was characterized by a sag stage with relatively constant thermal subsidence (Mitchum & Uliana, 1985). The lithostratigraphic units that characterize this interval constitute the Mendoza Group and represent shallow- to deep-marine deposition in a ramp setting, without a major shelf break. Late Valanginian to Early Hauterivian deposits in the central part of the basin include ammonite-bearing marine shales and mudstones of the Lower Member of the Agrio Formation (Fig. 1).

During Early Hauterivian times, a major relative sea-level fall led to the accumulation of a thin but widespread wedge of shallow-marine (Lower Avilé Member) and non-marine (Upper Avilé Member/Avilé Sandstone) deposits (Legarreta & Gulisano, 1989).

The non-marine Avilé Sandstone overlies shallow-marine deposits in basinal localities (northern Neuquén Province) but, in marginal areas, the Lower Avilé Member is absent, and the non-marine deposits directly overlie deep-marine facies of the Lower Member of the Agrio Formation. This contact is interpreted as a major sequence boundary (Fig. 1). The shoreface deposits of the Lower Avilé Member overlying deep-marine shales of the Lower Agrio Member are interpreted as a falling stage systems tract (Plint & Nummedal, 2000).

The upper boundary of the Avilé Member is characterized by the accumulation, once again, of deep-marine shales, mudstones and bioclastic carbonates of the Upper Member of the Agrio Formation (Early Hauterivian–Barremian) across a sharp and regionally developed transgressive surface (Fig. 1).

Legarreta & Gulisano (1989) first assigned the Avilé Member to a lowstand systems tract in the initial stage of the Upper Mendoza 'mesosequence'. Legarreta & Uliana (1991) defined at least two episodes of relative sea-level fall during Early Hauterivian times. They also related the Avilé Member to a lowstand systems tract and the transition from a marine euxinic environment to a shallow evaporitic pan, fringed by extensive mud flats. The excellent ammonite record of the Lower and Upper Members of the Agrio Formation allowed Aguirre-Urreta & Rawson (1997) to show that the Avilé Sandstone lies stratigraphically between the *Wavericeras vacaensis* and

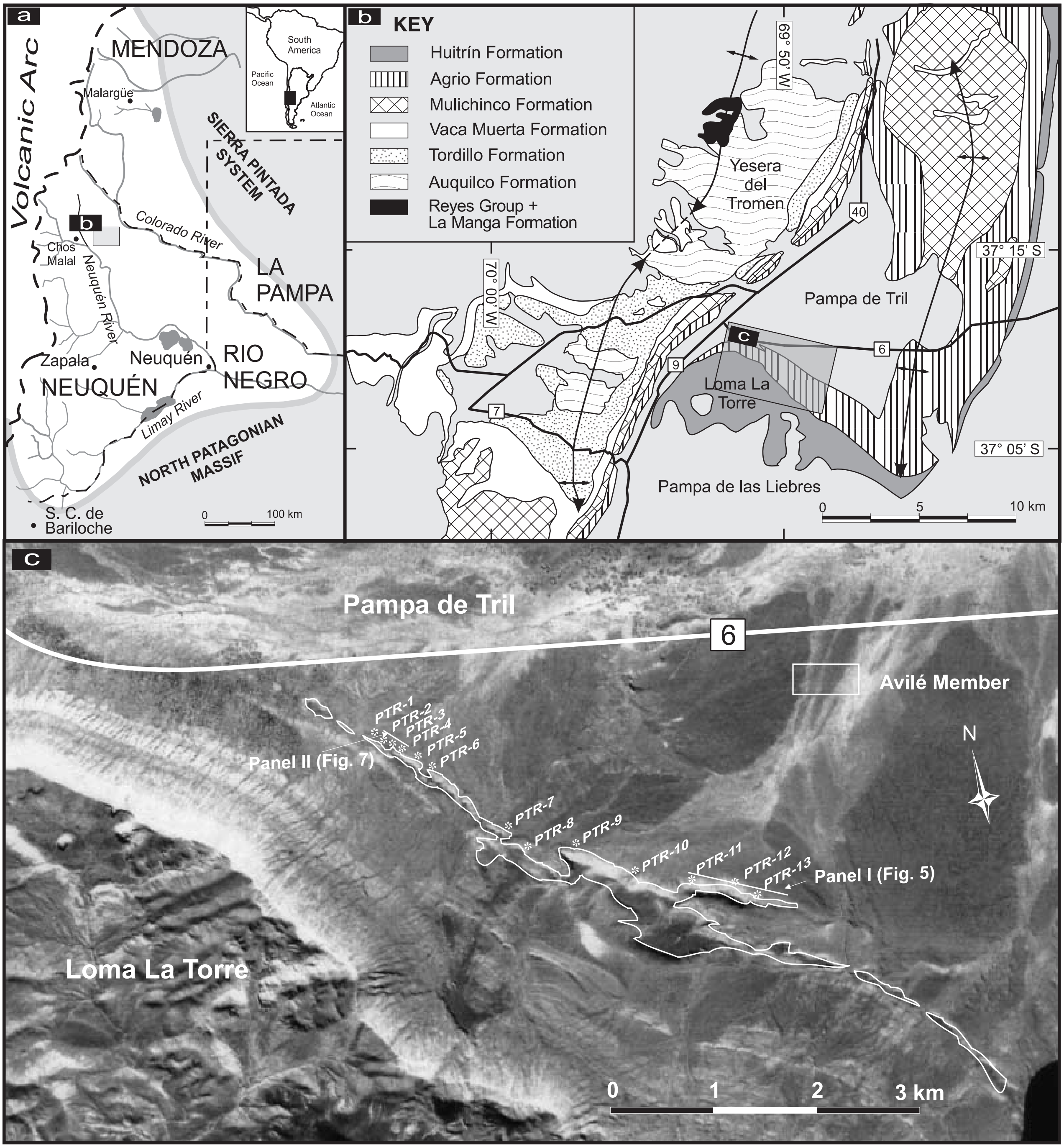

Fig. 2. (a) Location and limits of the Neuquén Basin and location of the study area. (b) Schematic map showing the geology of the study area. (c) Avilé Sandstone outcrops and location of the sedimentary logs and architectural panels of Figs 5 and 7.

Spitidiscus ricardii ammonite zones and is therefore Lower Hauterivian in age. This means that, if a more complex scenario is present, it is beyond biostratigraphic resolution.

Mutti *et al.* (1994) suggested that complete desiccation of the Neuquén Basin was required to explain the accumulation of non-marine deposits in the central part of the basin. However, Veiga & Vergani (1993) correlated the lowest non-marine facies of the Avilé Sandstone with shallow-marine deposits and, towards the northern sector of the Neuquén Basin, equivalent facies to this unit are entirely shallow marine (Legarreta *et al.*, 1981; Sagasti, 1998).

Veiga & Vergani (1993) also defined two cycles in the Avilé lowstand systems tract, relating the lower one to shallow-marine conditions (their lower prograding complex) and the upper one to non-marine conditions (upper prograding complex).

STUDY AREA AND METHODS

The study area is a small but continuous outcrop belt in the southern portion of the Pampa de Tril area, 50 km east of Chos Malal (Fig. 2b). The Avilé Sandstone is well exposed and sharply overlies shallow-marine deposits of the Lower Avilé Member. The basal relationship between the Avilé Member and the Lower Member of the Agrio Formation is not exposed in the studied area but, 20 km north (Portón de Tril), it is a sharp contact between the ammonite-bearing shales and overlying shallow-marine facies. The upper boundary of the studied unit is a sharp contact with overlying organic-rich black shales of the Upper Member of the Agrio Formation (Fig. 1).

To investigate the vertical variation and spatial relationship between fluvial and aeolian deposits within the Avilé Sandstone, 13 detailed vertical sections were logged and complemented with several architectural panels, constructed from photomontages and surface tracing along the outcrop (Fig. 2c). In these panels, the detailed distribution of facies and bounding surfaces has been recorded in order to facilitate correlation of logged sections and to document the geometry of the sedimentary units.

SEDIMENTARY UNITS

Six sedimentary units were defined, based on distinctive geometry and internal facies distribution. These can be grouped into two main facies associations (end-members) in terms of the main sedimentary processes identified (Table 1). The aeolian facies association comprises dune deposits (A1) that can be related to sand sheet units (A2). The fluvial facies association comprises distal flood deposits (F1), low-sinuosity channel units (F2), minor high-sinuosity channels (F3) and fine-grained floodplain units (F4).

Aeolian facies association

Aeolian dunes (A1)

Description. Aeolian dune units are characterized by fine- to medium-grained, subrounded to rounded and well-sorted sandstones arranged in cross-stratified sets with planar to tangential foresets, rarely trough shaped (Fig. 3a). These foresets comprise coarse- to medium-grained, wedge-shaped laminae that intercalate with structureless fine-grained laminae. Rarer is the presence of bimodal lamination with scarce isolated cross-laminated sets and preserved ripples. Sets are usually up to 6 m thick and smaller sets (0·5–2 m) group into 3 to 5 m thick cosets. Large-scale sets can be replaced laterally by small-scale sets and vice versa.

Foreset dip is <30° and usually between 20° and 25°. Palaeocurrent orientation of large sets shows a unimodal trend towards 340° (Fig. 4). In contrast, small sets are more variably oriented and can be perpendicular to the larger ones. Internally, both types of cross-bedded sets show abundant reactivation (third order) surfaces, defined by slight changes in the strike and dip of foreset packages.

Even when the geometry of the individual sets is wedge shaped, they are arranged in distinctively tabular bodies, with sharp horizontal upper and lower boundaries. The lower contact is sharp and truncates older aeolian dune and sand sheet units or lies sharply on top of distal flood deposits. The upper boundary of these units is characterized by a truncation of dune foresets and the internal bounding surfaces within the unit. The upper 10–20 cm can be leached or reddened.

Interpretation. The alternation of cross-bedded, wedge-shaped, coarse- to medium-grained laminae with structureless, fine-grained laminae is interpreted as the accumulation of grainflow and grainfall deposits at the bottom of high-angle lee-slopes of aeolian bedforms (Hunter, 1977).

Large-scale planar to tangential cross-bedded sandstones with grainfall/grainflow laminae and bimodal horizontal and cross-lamination interpreted as wind-ripple lamination (Hunter, 1977) suggest the development of straight-crested, slip-faced aeolian dunes that migrated towards the NNW. The presence of small-scale cosets of aeolian deposits also suggests the presence of compound slipfaceless draas (Rubin & Hunter, 1983; Mountney & Howell, 2000; Scherer, 2000) with small superimposed dunes on the lee face of larger bedforms, in this case oblique to the main transport direction. Slipfaced draas can be transitional from slipfaceless ones, and their development can be related to an increase in the gradient of the lee-slope of the draas (Herries, 1993).

Table 1. Facies associations and sedimentary units identified in the Avilé Sandstone.

	Code	Sedimentary unit	Lithology	Sedimentary structures	Geometry	Dimensions	Bounding surfaces
Aeolian facies association	A1	Aeolian dune	Fine- to medium-grained sandstones	Grainfall and grainflow laminae; wind-ripple lamination; large- and small-scale planar cross-bedding	Tabular/wedge shaped	1 to +10 m thick 100s m wide	Base and top: horizontal and sharp
	A2	Aeolian sand sheet	Fine- to coarse-grained sandstones	Horizontal and wind-ripple lamination; massive	Tabular	1–2 m thick 100s m wide	Base and top: horizontal and sharp; trans-itional to wet interdune units
Fluvial facies association	F1	Distal floods	Fine-grained sandstones, siltstones and mudstones	Horizontal lamination; asymmetric subaqueous ripples (climbing); massive layers; desiccation cracks	Tabular/wedge shaped	Up to 8 m thick; 100s m wide	Base and top: horizontal and sharp
	F2	Low-sinuosity fluvial channel	Medium- to coarse-grained sandstones; rip-up clast conglomerates	Horizontal and trough cross-bedding; massive rip-up clast conglomerates	Lenticular	Up to 6 m thick; 10s m wide	Base: concave-up and erosional Top: sharp and horizontal
	F3	High-sinuosity fluvial channel	Medium- to coarse-grained sandstones and rip-up clast conglomerates	Horizontal and trough cross-bedding; well-developed lateral accretion structures	Lenticular	1–3 m thick and 10 m wide	Base: concave-up and erosional; Top: sharp and horizontal
	F4	Fine-grained floodplain	Fine-grained sandstones and mudstones	Asymmetric subaqueous ripples, massive and horizontal lamination; rootlets and desiccation cracks	Tabular: mainly remnants resulting from fluvial erosion	Up to 2·5 m thick and 40 m wide	Base: sharp, planar Top: sharp

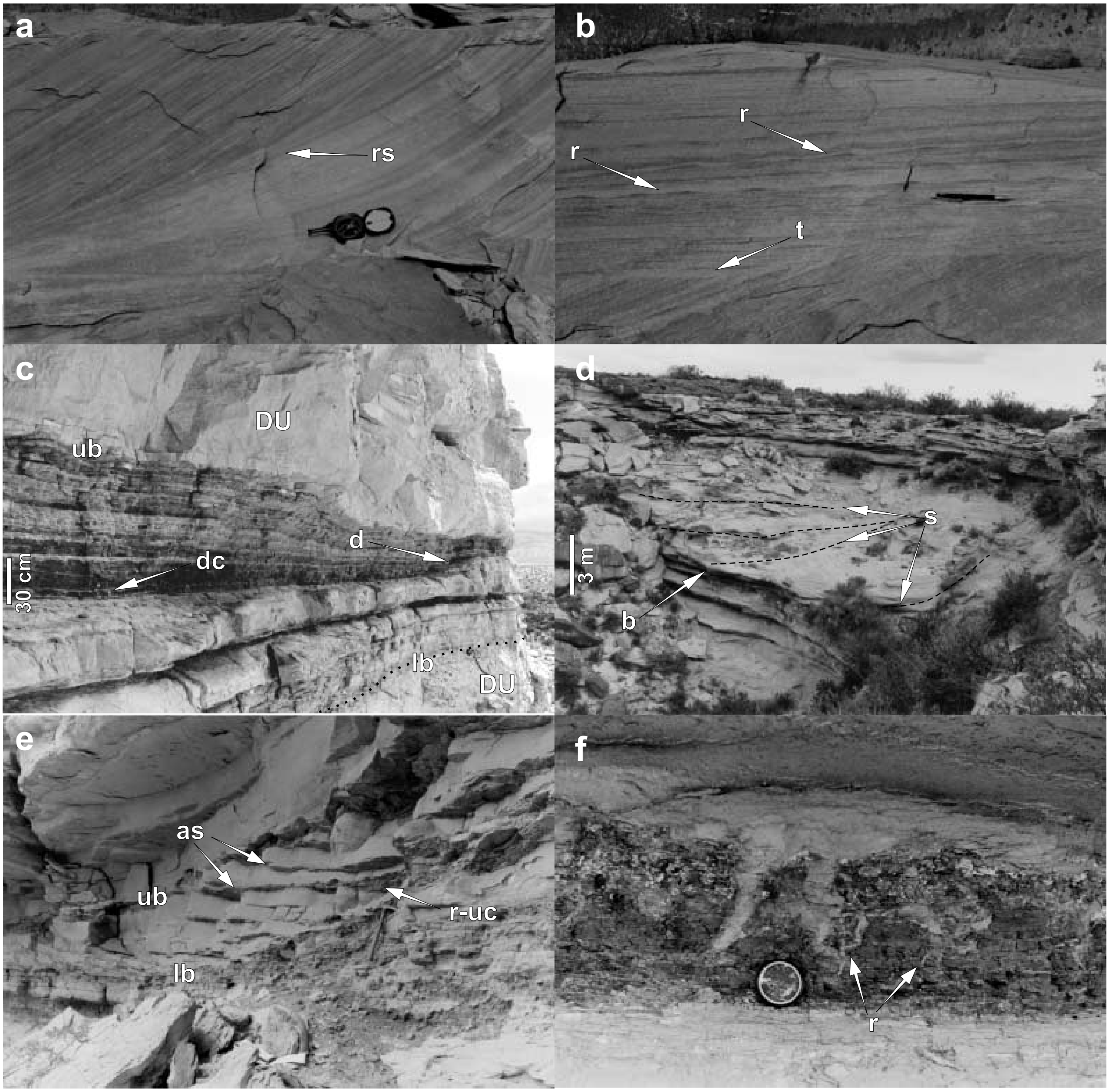

Fig. 3. Main characteristics of the sedimentary units identified. **(a)** Alternation of grainfall/grainflow laminae in foresets of aeolian dune units (A1). Note the sharp lower boundary and the presence of internal reactivation (third order) surfaces (rs). (Compass length = 24 cm). **(b)** Horizontal- and wind-ripple-laminated deposits of aeolian sand sheet units (A2). Also note the sharp and horizontal lower boundary truncating dune foresets (t) and the presence of small, preserved wind ripples (r). (Pen length = 14 cm). **(c)** Tabular, distal flood deposits (F1) intercalated between dune units (DU) composed of alternating mudstones with desiccation cracks (dc) and fine-grained sandstone layers. Small 'delta' (d) prograding into the flood deposits. Note the sharp nature of both lower (lb) and upper (ub) boundaries. **(d)** Low-sinuosity fluvial channels (F2). Note the erosive and concave-up lower boundary (b) and internal amalgamation surfaces (s). **(e)** Lenticular, high-sinuosity fluvial channel unit (F3) with concave-up erosional lower boundary (lb) and horizontal and sharp upper boundary (ub). Note internal lateral accretion structures (as) and abundant rip-up clast levels (r-uc) (hammer length = 33 cm). **(f)** Fine-grained floodplain unit (F4) with rootlets (r) (lens cap diameter = 5 cm).

The horizontal and sharp nature of both the upper and lower boundaries of these units, the absence of any intertonguing between these deposits and sand sheet or flood deposits and the leaching of the upper boundary suggest that these surfaces could be related to deflation processes down to the water table (Stoke's surfaces) rather than to the natural climbing of migrating

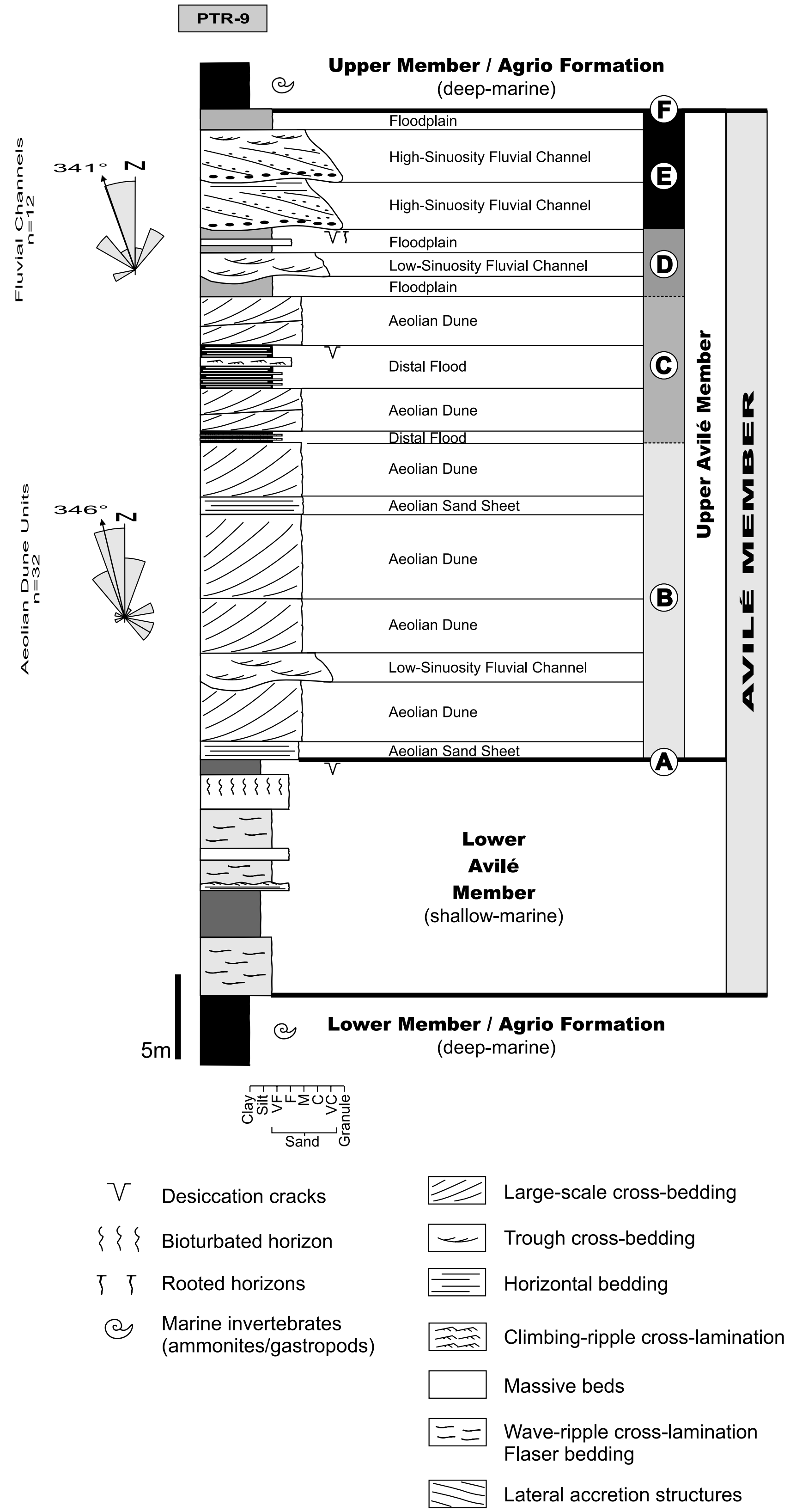

Fig. 4. Schematic log for the Avilé Member in the study area showing the distribution of the sedimentary units and the different evolutionary stages. Rose diagrams show the orientation of aeolian dune units (lower) and fluvial channel units (upper) for the whole interval (each reading represents the mean orientation of one individual body).

bedforms. These surfaces can also represent bypass surfaces promoted by a reduction in the angle of climb of the aeolian bedforms (to zero) due to water-table control (Kocurek & Havholm, 1993).

The presence of reddened horizons at the top of these units indicates the preferential precipitation of haematite or ferric hydrates, a process that requires time and low interstitial water content, which can be achieved after long periods of water-table lowering (Pye, 1983). This feature characterizes high-order bounding surfaces in aeolian strata produced by deflation to the water table (Kocurek, 1988), despite the fact that it can also be the result of diagenetic processes.

Aeolian sand sheet (A2)

Description. These units are not common in the Avilé Sandstone and are composed of fine- to coarse-grained, moderately sorted sandstones in tabular bodies up to 1 m thick, intercalated between dune deposits. The lower boundary of these units is horizontal, sharp and truncates dune deposits. The upper boundary is also sharp, horizontal and is usually overlain by dune units. However, on some occasions, it can be transitional to wet-surface deposits.

Internally, A2 units are characterized by thin horizontally laminated sandstones with bimodal grain-size sorting. In some cases, discontinuous centimetre-scale, cross-laminated sets and preserved ripples are present (Fig. 3b). These deposits locally show gentle convolute bedding.

Interpretation. Finely horizontally laminated sandstones with bimodal sorting and preserved ripples, interpreted as wind-ripple lamination (Hunter, 1977), internal horizontal bedding and lack of inclined foresets suggest the accumulation of wind-laid deposits but without the development of aeolian dunes.

The horizontally laminated sandstones and the presence of isolated preserved wind ripples can be related to the type ‘a’ and ‘b’ laminations of low-angle aeolian deposits described by Fryberger *et al.* (1979) and developed in the lee of small topographic features by gentle deceleration of wind and migration of wind ripples. Kocurek (1981) related type ‘b’ lamination to less uniform and less sand-saturated conditions and to the stabilization of wind ripples by armouring rather than the deposition–erosion process proposed by Fryberger *et al.* (1979).

These deposits characterize dry interdune environments, located lateral to dunes, under sand-saturated conditions. These attributes can also be found in aeolian sand sheets, where wind regime conditions or sand supply are limited and prevent the development of dunes (Kocurek & Nielson, 1986). The fact that, in the Avilé Sandstone, these deposits are usually located above a sharp horizontal surface and no intertonguing with dune deposits is observed suggests accumulation after a period of intense deflation and under different conditions from those governing the development of dunes. This also indicates that the accumulation of these units is not contemporary with the accumulation of dunes; hence, it is unlikely that they represent real interdune deposits.

Even when most of the structures indicate a dry environment, the presence of discrete wind-laid layers with convolute bedding suggests that the water table may have been close to the surface, at least after deposition, saturating the sand and facilitating its deformation once loaded with younger dune deposits (McKee *et al.*, 1971).

Fluvial facies association

Distal floods (F1)

Description. Fine-grained deposits, mainly claystones, siltstones and fine-grained sandstones, form tabular to wedge-shaped bodies up to 4 m thick and are laterally extensive and intercalated between dune units (Fig. 3c).

Internally, these units are characterized by 2 to 15 cm thick massive to laminated claystones and siltstones with abundant rootlets and desiccation cracks. In addition, 5 to 20 cm thick couplets are present, composed of laminated mudstones interbedded with fine-grained sandstones, mainly massive or with asymmetrical subcritical climbing ripples.

The most conspicuous feature of these deposits is that both upper and lower contacts are sharp, horizontal and parallel to the underlying shallow-marine deposits of the Lower Avilé Member (Fig. 5). Tabular dune units (A1) always overlie these deposits across a sharp horizontal contact and, in some cases, these deposits can be upward transitional from sand sheet units.

Metre-thick sandstone bodies showing a fining-upward trend from horizontally bedded medium-grained sandstones to subcritical climbing-rippled, fine-grained sandstones are interbedded with the laminated mudstones (Fig. 3c). Also,

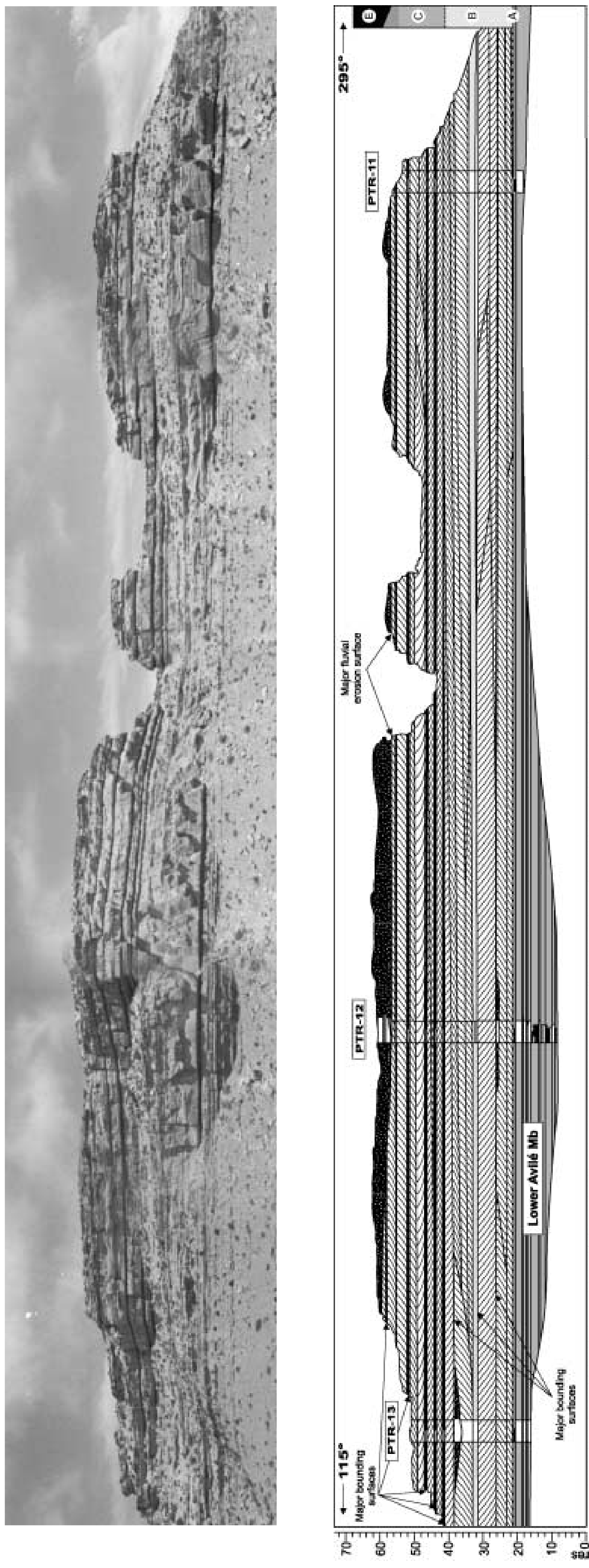

Fig. 5. Architectural panel (I) showing the horizontal nature of dune, sand sheet and flood units and the erosive lower boundary of the upper fluvial section (stage E). Note that the boundaries of dune and interdune units are also parallel to the shallow-marine deposits of the Lower Avilé Member. See Fig. 2 for location.

fine- to medium-grained sandstones with convex-up top and internal accretion surfaces interdigitate with laminated mudstones (Fig. 3c).

Interpretation. The presence of laterally extensive laminated mudstones alternating with sandstone–mudstone couplets suggests the combination of pond accumulation and repeated flooding of flat and extensive areas. Fining-upward tabular sandstones with frequent subcritical climbing ripples and horizontal bedding are interpreted as a record of major unconfined floods (sheet floods).

Mudcracks within fine-grained deposits indicate the periodic desiccation of these areas. Usually, these cracks are filled with fine- to medium-grained sand that may have been blown across the desiccated surface and become trapped within the cracks.

Sandstone bodies, showing a clear progradation into these water bodies, suggest the development of minor deltas formed through flood-related processes.

Fine-grained sediments intercalated with aeolian dunes can be regarded as the product of accumulation in wet interdune areas (Kocurek, 1981). This implies a relatively high water table and the development of temporary water bodies in interdune depressions. Although these fine-grained facies indicate accumulation in standing water bodies combined with periodic flooding in the Avilé Member, the fact that no lateral relationship between these deposits and dune units is observed (as for sand sheet units) suggests that there was no dune deposition at these times. Therefore, the extensive horizontal bounding surfaces cannot be related to the simple migration (and climbing) of dunes and interdune areas (Kocurek, 1981; see Fig. 2). They are rather interpreted as recording periods of non-aeolian deposition, during which deflationary processes took place. After such periods, a combination of flooding processes and a high water table led to the accumulation of these fine-grained overlying units under subaqueous conditions.

Low-sinuosity fluvial channels (F2)

Description. Fluvial channels comprise medium- to coarse-grained sandstones and thin layers of rip-up clast conglomerates, with lenticular cross-sectional geometry in bodies up to 5 m thick and tens of metres wide (Fig. 3d). They have highly erosional lower boundaries, and the upper boundaries are flat and sharp or transitional to fine-grained sandstones and mudstones. Most of these units show a simple internal fill, with well-developed trough cross-bedding and without any major internal erosion surface (simple ribbons; Friend *et al.*, 1979; Blakey & Gubitosa, 1984). Trough cross-bedded sets show the same orientation as the base of the channels, and their palaeocurrent trend is towards the north with a very low spread (Fig. 4). Mudstone clast conglomerates with clasts up to 10 cm in diameter are common at the base of these units or in the foresets of the trough cross-bedded sandstones. No evidence of regular lateral migration of these channels has been identified.

Several of these sandstone bodies show a more complex internal geometry with multiple major scouring surfaces that separate storeys (complex ribbons; Friend *et al.*, 1979). Each of these storeys is characterized by a lenticular geometry, a basal erosional surface (which truncates the previous accumulated storeys) and a sandstone fill composed almost exclusively of trough cross-bedded sands with abundant rip-up clasts.

These units dominate the upper section of the Avilé Sandstone in the studied area, where they are intercalated between high-sinuosity channels and fine-grained floodplain units. They can also be associated with aeolian dune deposits in the lower part of the unit, where they are present in the contact between dune units, strongly related to the deflation surfaces that separate them.

Interpretation. Lenticular sandstone units vertically and laterally related to fine-grained floodplain units with erosive lower boundaries and filled with trough cross-bedded sandstones suggest well-developed fluvial channels with sand transported as three-dimensional dunes.

The presence of simple channels, with stable margins and encased into floodplain deposits, suggests the development of single low-sinuosity channels with a relatively stable position. The multistorey stacking of some of these channels indicates the successive alternation of scouring and sand deposition processes (Friend *et al.*, 1979). The vertical stacking of these channels and the absence of lateral accretion structures reflecting lateral migration suggest a relatively fixed fluvial system, in which the position of the channels is strongly influenced by their predecessors and can be related to topographic conditions.

High-sinuosity fluvial channels (F3)

Description. These units are less abundant than F2 channels and are also composed of medium- to coarse-grained sandstones with minor mud clast conglomerates in lenticular bodies up to 3 m thick and 5–20 m wide. They are bounded by a concave-up and erosional lower contact and, internally, they show multiple, subparallel concave accretion surfaces that dip perpendicular to the channel axis (Fig. 3e). Laterally to these accretion surfaces, trough cross-bedded, medium- to coarse-grained sandstones with rip-up clasts are present. Rip-up clasts are more abundant than in low-sinuosity channels, and they are usually concentrated on the accretion surfaces and at the bottoms of bodies, where they constitute layers with a clast-supported texture and very low amounts of coarse-grained sandstone matrix.

As for the low-sinuosity channels, these units are located within fine-grained sandstones and rooted mudstones. Although these deposits show a greater variance in palaeocurrent direction, directions broadly coincide with those of the low-sinuosity fluvial system, with transport mainly towards the north (Fig. 4).

Interpretation. The development of lateral accretion structures within erosive-based lenticular sandstone bodies laterally related to fine-grained deposits with rootlets and desiccation cracks suggests the presence of high-sinuosity fluvial channels with the development of point bars on their concave margins. The abundance of mudstone clasts in the channel fills indicates both aggradation of fine-grained sediments at the sides of the channels and a greater degree of lateral migration and reworking.

Fine-grained floodplains (F4)

Description. The most conspicuous character of these deposits is the massive nature of both mudstones and sandstones that comprise them. Only occasional remnants of horizontal lamination are preserved in the mudstones and asymmetrical ripple cross-lamination (showing subcritical climbing) in the fine-grained sandstones. Root-penetrated upper surfaces and desiccation cracks filled with fine- to coarse-grained sand are also common in the mudstones (Fig. 3f).

These deposits are up to 2·5 m thick and sharply overlie low- and high-sinuosity channel units. Individual beds range between 5 and 30 cm thick and show a conspicuous tabular geometry. These units are common in the upper part of the section, despite the fact that overlying fluvial channels always erode their upper portion, and they are usually preserved as erosional remnants between channel units.

Interpretation. The fine-grained nature of these deposits, their tabular geometry and the presence of fine-grained sandstones (with climbing-ripple lamination) suggest accumulation in a floodplain environment by recurrent unconfined floods and subaqueous settling in temporary shallow-water bodies. The massive character and the abundance of root-penetrated horizons reflect intense biological activity that masked primary sedimentary structure. Desiccation cracks suggest the alternation of wet and dry periods and the periodic desiccation of the floodplains.

EVOLUTIONARY DEPOSITIONAL MODEL

Six stages of evolution have been interpreted for the Avilé Member, each representing different accumulation conditions and different degrees of interaction between fluvial and aeolian processes. There is a clear trend from aeolian-dominated processes at the base to a more permanent fluvial system at the top (Fig. 4).

Phase A – establishment of an aeolian system

In the study area, the basal surface of the non-marine deposits of the Avilé Member is extremely sharp and horizontal (Fig. 5). Aeolian sandstones directly overlie bioturbated and ripple-laminated, fine- to medium-grained sandstones and heterolithic deposits of shallow-marine origin (Veiga & Vergani, 1993). Desiccation cracks can also be found in the uppermost shallow-marine deposits, indicating subaerial exposure as a result of a relative sea-level fall. This relationship can also be observed in other areas, where the transition between the Lower and Upper Avilé is also sharp and indicative of considerable shallowing.

The abrupt juxtaposition of aeolian deposits above shallow-marine deposits represents a dramatic change in accumulation conditions that can be related to a relative sea-level fall and the development of subaerial conditions in this part of the Neuquén Basin. This surface is interpreted as a sequence boundary in agreement with previous workers (Legarreta & Gulisano, 1989). The shallow-marine deposits, especially lower and upper shoreface facies deposited in the previous stage, could have been reworked and represent a local source of sand for the building of the aeolian system.

Phase B – 'dry' aeolian system

Above the Upper Avilé sequence boundary, an aeolian system developed. The deposits are up to 25 m thick and are characterized by tabular aeolian dune units intercalated between thin tabular sand sheet units (Fig. 5).

As pointed out earlier, there is no evident lateral relationship or intertonguing between these two facies, and the contacts between them (both lower and upper) are sharp horizontal surfaces. This may suggest that, rather than interdune facies accumulating laterally to the active aeolian dunes, these deposits may overlie deflation surfaces under a limited sand supply. The development of sand sheet units, where the conditions are not suitable for the growth of dunes, can be related to different factors. A relatively high position of the water table, for instance, can dramatically increase the threshold velocity required for the entrainment of sand grains under the same wind conditions (Kocurek & Nielson, 1986), reducing the amount of sand available for wind transport (sediment availability; Kocurek & Lancaster, 1999). If the rise in water table can equilibrate the rate at which sediment is accumulated (and therefore the rate at which the sediment surface rises), the restriction in sand availability can continue and facilitate the vertical accretion of sand sheet units. Also, wind-rippled sandstones showing convolute lamination indicate a shallow water table that may have saturated the sand sheet deposits before they were overloaded by subsequent dune deposits.

The presence of horizontal surfaces at the contact between dune units (Fig. 5) suggests the development of deflation surfaces to the water table (Stokes surfaces) or bypass surfaces as the angle of climb of the dunes was reduced to zero (Loope, 1985), a condition that can be achieved when dune climbing is controlled by water-table position (Kocurek & Havholm, 1993). This can also imply that, although a shallow water table might have been responsible for the development of the horizontal surfaces (Stokes, 1968), in some cases, the conditions after deflation were suitable for the growth of aeolian dunes. In these cases, the water table is not at the depositional surface or close enough to it that the capillary fringe can reduce the amount of sand available. Therefore, the actual transport rate is not limited and equilibrates the potential transport rate ($q_a = q_p$), winds become saturated and promote the accumulation of aeolian dunes (Kocurek & Lancaster, 1999). This does not necessarily imply an absolute water-table drop, but a relative one, which can be obtained when the depositional surface rise overtakes the rate of water-table rise (Havholm & Kocurek, 1994).

The development of these deflation surfaces (in the dune–dune contact or in the dune–sand sheet contact) indicates that the accumulation of this basal section was not continuous and may have been characterized by long periods of non-deposition, bypass or deflation. These surfaces can be related to super surfaces (Kocurek, 1988) and, as suggested by Loope (1985), the time represented by these surfaces may be much longer than the time involved in the accumulation of the dunes and sand sheets themselves.

Although this system is characterized by the development of dunes and sand sheet units accumulated under dry conditions, it cannot be classified as a dry aeolian system in the terms proposed by Kocurek & Havholm (1993). The aeolian system described here is devoid of subaqueous deposits, and there is no direct evidence of a surface water table; nonetheless, the water table has influenced the amount of available sand and controlled the accumulation of sand sheet units.

Furthermore, small channel deposits have been recognized intercalated between dunes (Fig. 5). These channels show well-developed lenticular geometry and trough cross-bedding with concentrations of rip-up clasts, even when they are intercalated exclusively between dune and sand sheet deposits. These channel deposits indicate active running water in topographically lower areas and are interpreted as the record of flood events. They are not common and may represent extraordinary floods in proximal areas that cut the erg on their way to the coast located to the north of the study area.

Phase C – 'wet' aeolian system

The dune/sand sheet association that characterizes the lower section of the Avilé Member was replaced gradationally by aeolian dune (A1) deposits interbedded with distal flood units (F1). This change in accumulation conditions was gradual, without major breaks, and is reflected in some of these intercalations in which both sand sheet and flood deposits are present between dune units.

During this phase, the depositional conditions were still suitable for the development of aeolian dunes, but the main difference is that the deposits interbedded with them are now fine grained, with evidence of stagnant water accumulation and flooding processes that alternated with aeolian dune accumulation (Fig. 6).

The development of a wet aeolian system (in the sense of Kocurek & Havholm, 1993) requires a high water table, at or near the depositional surface, which influences accumulation within the aeolian system. Although it is clear that the influence of the water table increased upward, there is no evidence that these subaqueous deposits were accumulated laterally to active dunes in interdune depressions. They also lie parallel to the depositional surfaces (defined by the shallow-marine deposits of the Lower Avilé Member) and therefore do not show an evident climb angle and, furthermore, truncate climbing surfaces within the dune units (Fig. 5).

As described above, the flat and sharp surfaces that separate dune and interdune deposits suggest the operation of deflationary processes before the flooding of these areas. The final position of these bounding surfaces could have been controlled by the water-table position. The lack of interdigitation of flood and dune deposits (Fig. 3c) suggests that they were separated in time and not generated by flooding of interdune areas while dunes were still active. Therefore, these deposits accumulated as wetting-upward cycles consisting of a lower interval in which dunes migrated under dry conditions with a sufficient sand supply and an upper interval in which the depositional surface was flooded.

The subsequent flooding of these flat areas or a relative water-table rise (resulting from a combination of local flooding, the transition to more humid conditions or a relative sea-level rise in coastal environments) would have severely reduced the sand supply, preventing the development of aeolian deposits. If the water table continued rising, the flooding of these extensive areas would have occurred, leading to the accumulation of wet-surface deposits in stagnant water bodies. Evidence for a relatively shallow water table exists even for the previous phase, which means that only a small water-table rise would have led to flooding of the previously deflated and flattened areas.

Phase D – increase in fluvial activity

The 'wet' aeolian system is vertically and laterally related to fluvial deposits. Low-sinuosity fluvial channels are intercalated between dune deposits, and massive floodplain units are observed at the top of this interval (Fig. 7). These deposits represent the establishment of a more permanent fluvial system characterized by single low-sinuosity channels and extensive floodplains indicating a transition to wetter conditions. Even where fluvial channels lie between dune deposits at the base of the unit, the presence of massive floodplain facies and the increased density of

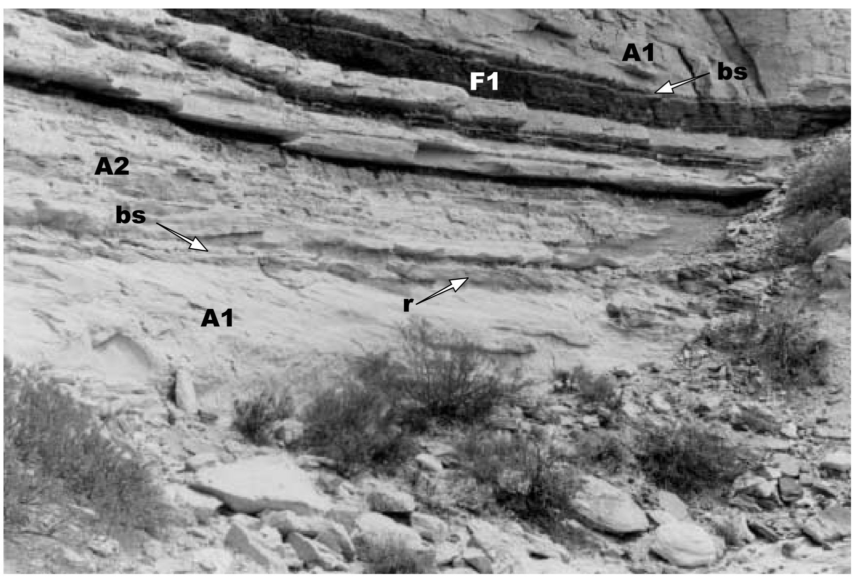

Fig. 6. Close-up of the relationships between aeolian dunes (A1), sand sheet deposits (A2) and distal flood units (F1). Note the horizontal nature of bounding surfaces (bs) and the truncation at the top of the dune unit that is accompanied by a more cemented horizon (r).

root-penetrated horizons indicate more humid depositional conditions. However, mud-cracked horizons indicate that desiccation of the floodplains still occurred.

Phase E – fluvial system

The top of the Avilé Sandstone in the studied area is characterized by a well-developed fluvial system comprising both low- and high-sinuosity fluvial channels and intercalations of floodplain units no more than tens of centimetres thick. Channel units show a very high degree of amalgamation. The contact between these deposits and the underlying fluvial/aeolian system is an erosion surface with up to 4 m of relief (Fig. 7).

The abrupt facies juxtaposition indicates a substantial change in environmental conditions. Phase E deposits are interpreted as recording deposition under wetter conditions, with enough rainfall to allow the establishment of a well-developed fluvial system without evidence of aeolian activity in this location. Although the top of the underlying section contains the record of a fluvial system, channel units tend to be isolated within floodplain deposits, whereas in this upper section, they show a high degree of amalgamation. The multistorey stacking of these deposits indicates low accommodation, with lateral and vertical reworking of channel and floodplain material. Relicts of fine-grained floodplain deposits suggest that overbank accumulation took place laterally to these channels (Fig. 7). The local preservation of these fine-grained deposits together with the abundance of rip-up clasts at the base of channels reflects the importance of reworking of floodplains by low- and high-sinuosity fluvial channels under low accommodation conditions.

The combination of a reduction in accommodation and the development of a major erosion surface at the base of this section suggests that this change might be associated with a relative fall in the base-level of the fluvial systems rather than a decrease in the aggradation rate of the floodplain or an increase in the fluvial discharge.

Phase F – flooding of the fluvial/aeolian system

The Avilé Member is overlain across the whole Neuquén Basin by deep-marine deposits of the Upper Member of the Agrio Formation. The abrupt contact is interpreted as a major flooding surface (Fig. 1). The overlying shales across the whole basin contain ammonites of the *Spitidiscus ricardii* zone, assigned by Aguirre-Urreta & Rawson (1997) to the uppermost Lower Hauterivian, establishing the regional synchroneity of the flooding surface.

This major shift in facies reflects a drastic increase in the rate of relative sea-level rise, allowing the flooding of extensive areas within the basin and the complete cessation of non-marine sediment accumulation in the central Neuquén Basin.

DISCUSSION

Interaction between fluvial and aeolian processes in the Upper Avilé Member is demonstrated by the gradual transition to wetter conditions and to the development of a more permanent fluvial system, and also by intercalations between fluvial and aeolian deposits throughout the entire unit.

Fluctuation between fluvial and aeolian processes can control sediment accumulation in

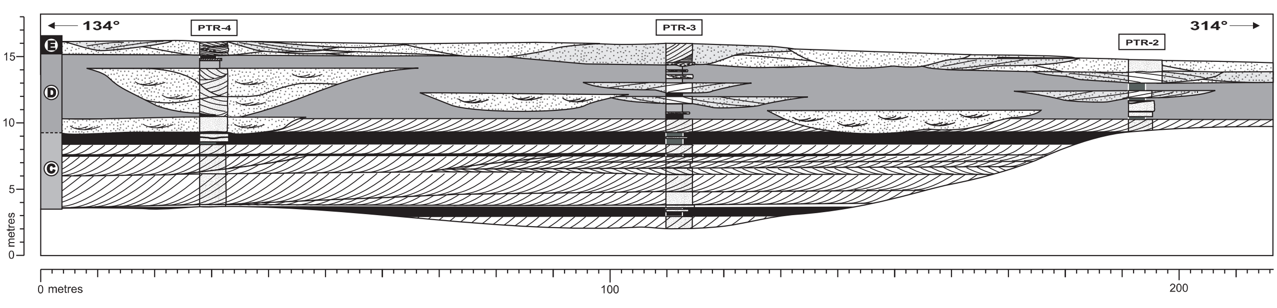

Fig. 7. Architectural panel (II) for the upper section of the Avilé Sandstone showing the increase in fluvial deposits towards the top of the unit and the development of more amalgamated low- and high-sinuosity fluvial units (stage E) above a sharp and erosional surface, interpreted as a high-frequency sequence boundary. See Fig. 2 for location.

marginal areas of ergs, related to the contraction or expansion of the aeolian system (George & Berry, 1993; Herries, 1993). However, such interaction is not restricted to marginal areas and, in some systems, major rivers enter (or completely cross) the erg, interacting with aeolian accumulation even in more central areas.

To understand the factors that governed the overall wetting-upward transition, it is important first to discuss the different depositional cycles or sequences observed within the Avilé Sandstone and then to explain the main factors controlling the development of this fluvial/aeolian system.

Fluvial/aeolian interactions – super bounding surfaces

One of the more conspicuous aspects of the Avilé Sandstone is the presence of multiple horizontal (parallel to the depositional surface) boundaries between dunes, sand sheets and flood deposits. The development of these surfaces can be related to deflationary processes down to the water table (Stokes, 1968; Fryberger *et al.*, 1988), and represents a hiatus in aeolian sediment accumulation and a change in accommodation conditions. In this sense, these surfaces can be correlated with super bounding surfaces described by Kocurek (1988), Kocurek & Havholm (1993) and Havholm & Kocurek (1994). The development of these super surfaces requires sediment influx to the system to be reduced or terminated, resulting in undersaturated winds entering the system.

In the case of the Avilé Sandstone, it is not possible to define precisely which external factors may have controlled the development of these deflation surfaces, but the fact that planar surfaces devoid of any bedforms are common suggests that regional deflation was a recurrent process. However, the final position of these super surfaces can be controlled by water-table position, and water-table behaviour after the formation of the super surface also controls sediment availability (Kocurek & Lancaster, 1999) and, therefore, the nature of the overlying deposit (Fig. 8).

If the water table drops well below the surface (so that not even the capillary fringe interacts with the depositional surface), there are no restrictions on sand availability, and all the sand at this surface is available for transport and building of aeolian dunes. If, after deflation processes, the water table (or at least the capillary fringe) is still at the depositional surface, this reduces sand availability, preventing the development of aeolian dunes and favouring the accumulation of aeolian sand sheets. If the water table continues rising after the formation of the super surface, then the whole area is inundated, leading to the accumulation of wet-surface deposits.

Tectonic activity, climate change or eustatic oscillations (in coastal aeolian environments) may control the position and dynamics of the water table (Kocurek *et al.*, 2001). During the Lower Cretaceous, the Neuquén Basin was characterized by steady thermal subsidence (Uliana & Biddle, 1988; Legarreta & Uliana, 1991). Therefore, local tectonic movements are not likely to have had a major influence on high-frequency water-table oscillations. As this aeolian system is related to marine facies in the northern part of the basin, then eustatic sea-level oscillations together with climatic fluctuations may have controlled the position and behaviour of the water table.

In the Avilé Member, an increase in water-table influence upsection is recorded. In the context of the whole Avilé Member representing a lowstand systems tract deposited after a major relative sea-level fall, then the increase in water-table influence may be related to long-term water-table rise during a relative sea-level rise. As deflationary processes were active during the accumulation of this unit, aeolian deposits would be preserved only if the water table was rising. Any subsequent fall in water table would have led to the deflation of previously accumulated units (Kocurek *et al.*, 2001).

However, the frequent deflation surfaces provide good evidence that the rise in sea level (and therefore water table) was not a uniform process. Episodes of water-table fall were associated with high-frequency oscillations superimposed on the general rising trend (Fig. 9). Although the precise duration of these cycles cannot be calculated because of a lack of more sensitive biostratigraphic indicators, these high-frequency water-table (hence sea-level) cycles could be a response to orbital processes such as those described by Sagasti (2000) for the deep-marine Upper Member of the Agrio Formation.

Overall aeolian to fluvial transition

In addition to the high-frequency oscillations in water table that produced the intercalations of dry- and wet-surface deposits within the Avilé Member, there is also a general trend towards a more prominent fluvial influence that culminates

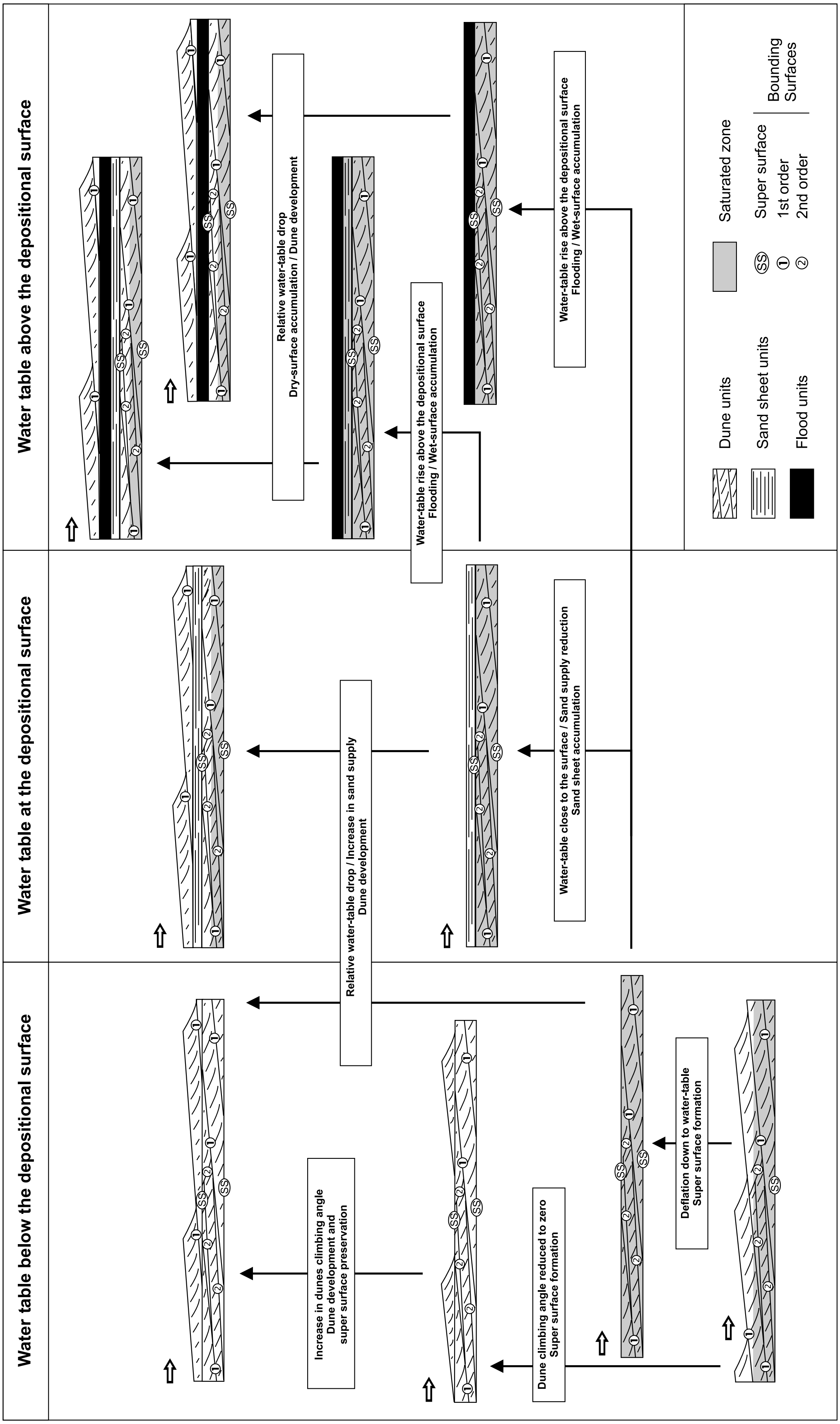

Fig. 8. Different vertical successions observed in the Avilé Sandstone and development of super surfaces in relation to water-table position and oscillations.

with the development of a well-established fluvial system at the top of the unit.

The amalgamated upper fluvial section has been interpreted as a response to base-level fall associated with a relative sea-level fall. During base-level fall, the fluvial system must erode earlier deposits to re-establish its equilibrium profile, leading to the development of the conspicuous erosion surfaces at the base of the upper section. Under these circumstances, reduction in accommodation is also expected, with a consequent increase in amalgamation of channel units and lateral reworking of floodplain deposits. The magnitude of this fall must be of a lower order than the fall producing the overall Avilé lowstand systems tract. This high-frequency fall can have a similar magnitude to the base-level oscillations responsible for the development of deflation surfaces within the aeolian succession. The establishment of a permanent fluvial system after a relative sea-level fall near the top of the Avilé Member contrasts with the nature of its lower contact, where, after a relative sea-level fall, a dry aeolian system was established above the sequence boundary. This may be an indicator of a climate shift towards the upper part of the sequence associated with a general increase in rainfall, leading to wetter conditions.

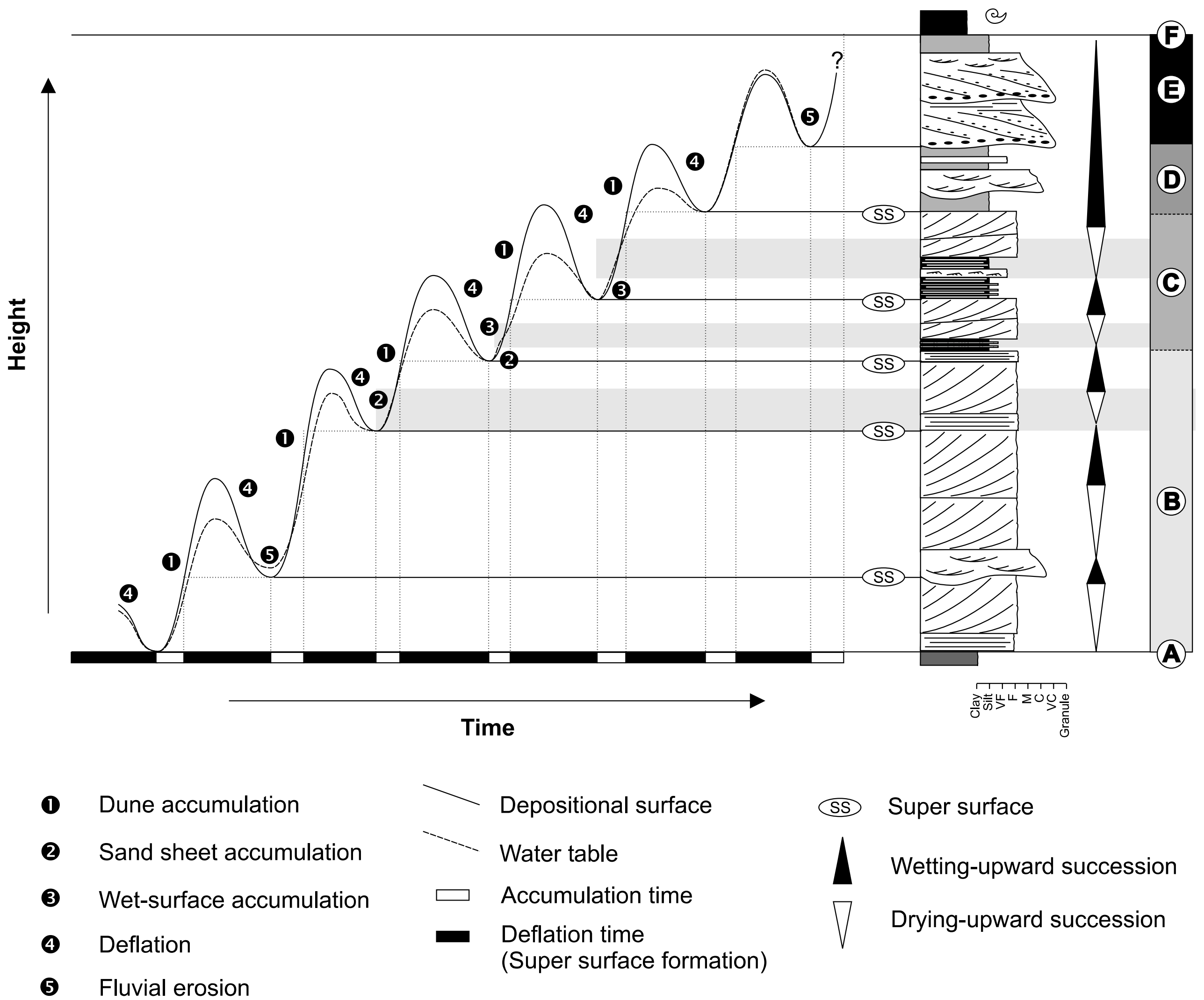

Fig. 9. Relationship between water-table oscillations and the different units and vertical successions observed in the Avilé Member. Water-table oscillations might be related to sea-level oscillation in coastal systems, and the accumulation of this interval is related to a long-term water-table rise. Grey areas depict drying-upward successions that contrast with the general water-table rise proposed, suggesting an increase in the rate at which the depositional surface rose.

The top of the Avilé Sandstone is again characterized by a sharp surface that juxtaposes deep-marine facies on non-marine deposits not only in this central part of the basin, but also in more marginal areas. This surface is extremely planar and represents flooding of the whole area, produced by a dramatic increase in the rate of sea-level rise that led to the beginning of a transgressive systems tract. The sudden appearance of immigrant ammonite species (such as *Spitidiscus ricardii* derived from north-west Europe species) suggests that this flooding might be related to the main 'mid-Hauterivian' sea-level rise recorded in boreal sequences (Aguirre-Urreta & Rawson, 1997) and therefore might be related to a low-frequency eustatic rise.

CONCLUSIONS

1 Detailed description of sedimentary units within the Avilé Sandstone led to the identification of a close interaction between aeolian and fluvial processes. The evolution of this unit is characterized by the establishment of a 'dry' aeolian system overlying shallow-marine deposits; the transition to a 'wet' aeolian system; the gradual increase in fluvial activity; the development of a well-developed fluvial system and, finally, the flooding of the whole area with the accumulation of deep-marine deposits above.

2 Throughout the entire unit, multiple deflation surfaces have been identified. The development of these super surfaces (together with the development of sand sheet units and wet-surface deposits) has been related to water-table dynamics produced by high-frequency (sea level–climatic) oscillations superimposed on a long-term relative sea-level rise.

3 A wetting-upward succession has also been recorded for the Upper Avilé Member, which resulted in the abandonment of aeolian deposition and the development at the top of fluvial deposits that record a well-established fluvial system. This trend was associated with a progressive climatic change towards wetter conditions. This is also evidenced by the accumulation of amalgamated fluvial facies overlying a high-frequency sequence boundary of the same magnitude as the one responsible for the development of deflation surfaces within the aeolian succession. This also implies that a combination of a relative sea-level rise together with climatic change to wetter conditions may have controlled the accumulation of this unit.

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