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ON THE UNDERSTANDING OF AEOLIAN SEQUENCE STRATIGRAPHY: AN EXAMPLE FROM MIOCENE - PLIOCENE DEPOSITS IN PATAGONIA, ARGENTINA.

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Riassunto. Successioni di origine eolica (Formazione Rio Negro, Cenozoico superiore) affiorano estesamente lungo le falesie marine della Patagonia settentrionale. Questi affioramenti mostrano una successione completa di sub-ambienti eolici o ad essi connessi. Forniscono anche eccellenti affioramenti per analizzarne sedimentologia e architettura interna dal punto di vista della stratigrafia sequenziale. Analisi di terreno, unite a tracciamento su fotografie oblique, hanno consentito l'individuazione di sette sequenze deposizionali eoliche, ciascuna delimitata da super-superfici regionali (superfici di deflazione). Al loro interno queste sequenze eoliche mostrano una ripetizione ciclica di facies, che consentono di costruire un modello genetico tentativo. Ogni sequenza deposizionale eolica fu accumulata durante un singolo episodio aggradazionale, ed è delimitata da non conformità connesse con periodi di degradazione. Ogni periodo di degradazione corrisponde a eventi di deflazione regionale, che produssero superfici da piane a profondamente incise. Queste sono caratterizzate da erosione o non deposizione in cui i soli eventi di accumulo sono larghi e isolati blocchi di aggregati a grana fine, qui interpretati come depositi residuali della sequenza precedente. I periodi aggradazionali sono caratterizzati da un accumulo pressoché continuo, responsabile della costruzione della sequenza. Le differenze nel bilancio sedimentario eolico e l'innalzamento della superficie freatica controllano i diversi tipi di facies e consentono di discriminare sub-periodi di aggradazione precoci o tardivi. I sub-periodi di aggradazione precoce si formarono durante un innalzamento relativamente veloce della falda freatica, associato con un modesto apporto di sedimenti eolici, formando estesi campi interdune umidi, associati a dune eoliche e ad interdune asciutte. Invece durante i sub-periodi aggradazionali tardivi, la superficie di deposizione si trovò ampiamente al di sopra della superficie della falda. Tendono quindi a predominare dune eoliche ed interdune asciutte. Questo sub-periodo è anche caratterizzato dalla crescente tendenza alla stabilizzazione, evidenziata dalla diffusa presenza di paleosuoli nei livelli sommitali. Sebbene lo spessore conservato per ciascuna sequenza deposizionale eolica sia connesso strettamente al tasso di subsidenza, l'evoluzione interna delle facies suggerisce che nell'insieme vi sia un controllo climatico sulla loro genesi.

Abstract. Upper Tertiary aeolian strata (Río Negro Formation) outcrop in extensive sea cliffs at the Northeast of Patagonia. These outcrops show deposits corresponding to a complete suite of aeolian and aeolian related sub-environments, and also provide excellent exposures to analyse the sedimentology and internal architecture from a sequence stratigraphic point of view. Field studies, supplemented with line-drawings of oblique photographs, allowed the recognition of seven aeolian depositional sequences within the succession, each one bounded by regional super surfaces (or deflation surfaces). Internally these aeolian sequences display a cyclic recurrence in facies, that yields a tentative genetic model for their evolution. As documented from field examples, each basic aeolian depositional sequence was deposited during a single aggradational period, and is bounded by unconformities related to degradational periods. Degradational periods are regional deflationary events, that resulted in deep-scoured to flat surfaces, characterised by erosion/non deposition in which the only recognised accumulation is isolated and large angular blocks of fine-grained aggregates, interpreted as residual remnants of deposits of the previous sequence. Aggradational periods are characterised by a near- continuous accumulations responsible for the sequence building. Differences in the aeolian sediment budget to the area and the rising rate of water table control the related facies types and allow to discriminate early and late aggradational sub-periods. Early aggradational sub-periods form under conditions of relatively fast rising water tables associated with moderate aeolian sediment budget, thus resulting in the development of extended wet interdunes laterally associated with aeolian dunes and dry interdunes. During late aggradational sub-periods, the depositional surface outdistanced the water table, and aeolian dunes and dry interdunes tend to predominate. This sub-period is also characterised by an upward tendency to stabilisation, evidenced by the common occurrence of palaeosols in upper levels. Although the preserved thickness of each aeolian sequence is closely related to the average subsidence rate, the internal facies evolution suggests an overall climatic control for their origin.

Introduction.

Recent studies in aeolian sedimentation have emphasised the role of allocyclical controls in the development of genetic units of deposition (Havholm et al. 1993; Langford & Chan 1993; Havholm & Kocurek 1994; Kocurek 1996). The typical expression of these allocyclical controls is the repetitive alternation of periods of hiatus, and periods of generalised accumulation in a number of different aeolian and aeolian-related sub-environments.

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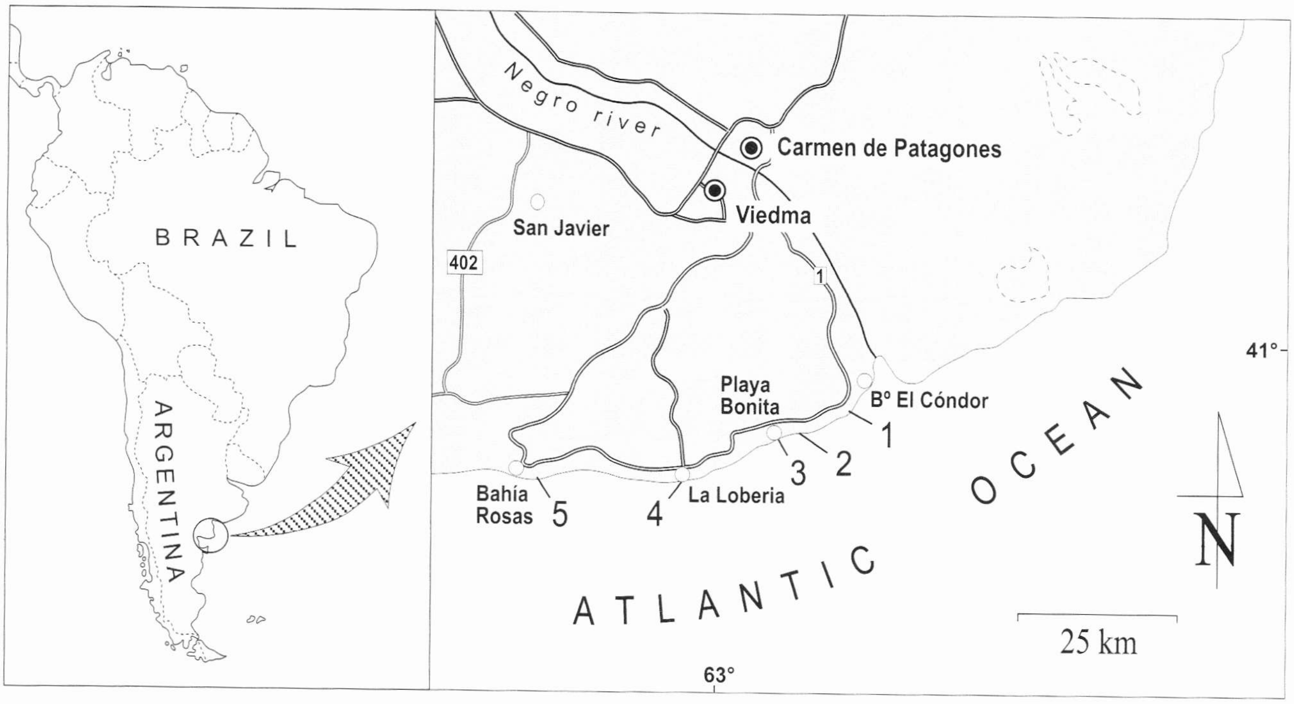

Fig. 1 - Location map of the study area (Northeast Patagonia, Argentina).

The recognition of laterally extensive surfaces of erosion/non-deposition (or "super surfaces", Talbot 1985 ; Kocurek 1988) has consequently been considered a fundamental tool for regional correlation and sedimentological understanding, because they everywhere bound genetically-related deposits (aeolian sequences) located at different basin positions (Kocurek & Havholm 1993). Nevertheless, neither the relationships of these non-marine sequences with those of classic sequence stratigraphy in marine-related systems nor their precise controlling factors (tectonics, climate and sea-level changes) have been properly assed yet (Havholm et al. 1993; Reading 1996).

The Mio-Pliocene Río Negro Formation, in northern Patagonia (Fig. 1), provides an excellent opportunity to analyse the internal architecture of genetically-related sedimentary packages of aeolian deposits. This unit extensively crops out as a near-tabular body with an average thickness of 50 meters, in continuous sea cliffs along a distance in excess of 100 km.

The goal of this contribution is to discuss the sedimentology, internal architecture and lateral changes of aeolian and aeolian-related strata within a sequence stratigraphic framework. The application of unconformity-bounded stratigraphic criteria allows the discrimination of several discrete aeolian depositional sequences, from which a generalised model for their internal evolution can be achieved.

Methods

All the conclusions outlined in this paper came from field studies that consisted of measurement of five detailed stratigraphic sections using a Jacob´s staff, over a distance of about 49 km (Fig. 1). The sections chosen were the only accessible points along the sea cliffs. In order to properly analyse lateral facies changes and architecture, local observations were supplemented using line drawings of oblique photographs and lateral field surveys.

Special attention was taken to carefully describe lithology, primary sedimentary structures, palaeocurrents, bounding surfaces, and all other useful macroscopic features. The recognition, analysis, and lateral tracing of erosional surfaces provide the criteria used to identify genetically-related facies associations for regional correlation.

Stratigraphic framework

The sedimentological and sequence stratigraphic analysis presented here have been carried out in coastal outcrops at the north-east of Patagonia, Argentina (Fig. 1). The landscape is a flat and arid-steppe, where the only exposure of the underlying rocks are located at well-developed sea cliffs (up to 65 meters high), closely related to marine erosion during the Pleistocene (González 1984). Regionally, the region under study belong to a cratonic area located between two coenozoic sedimentary basins, the Colorado Basin (North) and the San Jorge Basin (South). The absence of significative evidences of tectonic disturbance in the section considered suggests a relatively quiescence period at least during late Tertiary.

The first stratigraphic scheme for the area came from D'Orbigny (1842), who described a base-missing mainly sandstone succession (denominated as *Gres Azuré*) assigned to the Miocene. Other essential early contributions were provided by Roth (1898), Ameghino (1906) and Wichmann (1918). These sandstones were more recently assigned to the Río Negro Formation (Andreis 1965), and interpreted as mainly fluvial succession based on their textural and petrological characteristics (Andreis 1965; De Ferrariis 1966; Angulo & Casamiquela 1982). Recent studies propose an aeolian origin for the sandstone deposits of the Río Negro Formation, based on diagnostic sedimentary structures and detailed facies analysis (Zavala *et al.* 2000). They recognised the existence of three unconformity-bounded subunits (hereafter assigned into "members") (Fig. 2). The lower member (Rl) is composed of medium to coarse-grained sandstone and mudstone, deposited in a complex of aeolian dunes, dry and wet interdunes, and minor fluvial (*wadi*) processes (Zavala *et al.* 2000). The base of this unit is not exposed. The middle member (Rm) (or La Lobería Member, Angulo & Casamiquela 1982) uncoformably overlies the Rl member near the base of the cliffs, and consists of up to 6 meters of marine deposits. It consists of dark-grey mudstone and bioclastic sandstone that record a complete marine transgressive-regressive cycle deposited in a shallow and partially confined sea, with some evidence of wave reworking processes (Zavala et al. 2000; Zavala & Freije 2000). Marine macrofossils are locally abundant, and include *Chione sp., Venericardia sp., Chlamys tehuelchus, Pododesmus papyraceus, Ostrea patagonica* and *Balanus laevis* (Farinati *et al.* 1981). The upper member (Ru) sharply overlies the Rm member, and is well exposed across the study area. Facies analysis and diagnostic depositional structures suggest a mainly aeolian depositional environment similar to that of the Rl member (Zavala *et al.* 2000). Near the top of the Ru member, the occurrence of arid palaeosols and tuff deposits becomes common.

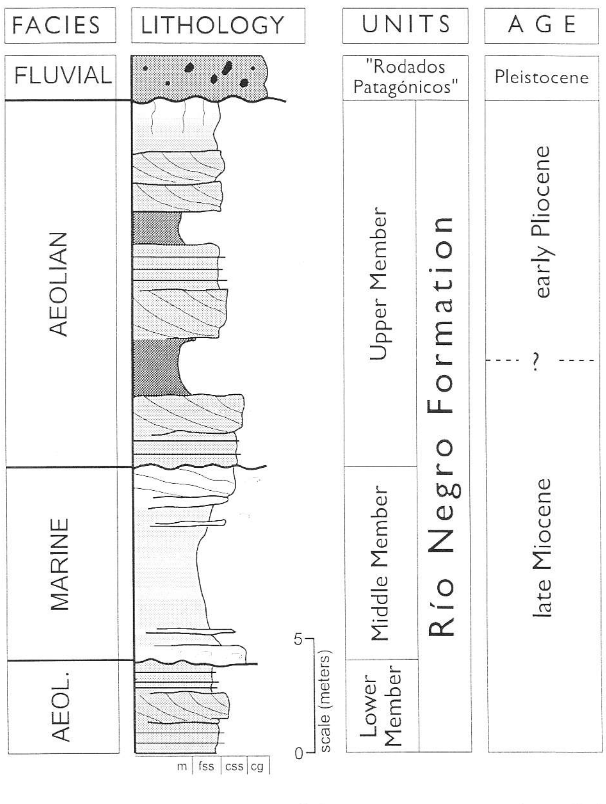

Fig. 2 - Stratigraphic scheme of the Río Negro Formation (slightly modified from Zavala & Freije 2000).

Mammal fossils indicate an early Pliocene age (Montermosean Land Mammal age) for the upper levels of the Río Negro Formation (Aramayo 1987), supported also by fission-tract dating of volcanic ash levels (mean = 4.41 Ma, Alberdi *et al.* 1997). On the other hand, K/Ar dating of tuff levels in marine deposits equivalent to the Rm member indicates a late Miocene (Tortonian) age (mean = 9.41 Ma, Zinsmeister *et al.* 1981).

The Río Negro Formation is everywhere unconformably covered by Pleistocene fluvial conglomerates up to 2 metres thick ("Rodados Patagonicos" Doering 1882) (Fig. 2).

Although field analysis involved all three units, only the Ru member of the Río Negro Formation will be described and discussed in this paper. The lateral continuity and excellent exposures of this formation allowed a detailed analysis of sedimentological relationships in a sequence stratigraphic framework.

Aeolian facies associations and erosional surfaces

The Ru member of the Río Negro Formation displays a complete suite of exceptionally well-exposed aeolian and aeolian-related deposits and erosional surfaces. Aeolian deposits include several facies associations (hereafter abbreviated into facies with a genetic significance) mainly corresponding to dunes, dry interdunes, wet interdunes, ephemeral fluvial deposits, and arid palaeosols. Aeolian erosional surfaces, on the other hand, have regional extent and are related to deflation processes, which in turn can be locally associated with residual aeolian facies. The lateral facies relationships proposed in this paper, and the significance of super surfaces, are illustrated by the line-drawing of oblique photographs (Fig. 3, 4).

Dune facies

This facies is composed of 0,1 to 2 meters thick fine- to medium-grained sandstone beds with medium- to large-scale tabular to trough cross-bedding (Fig. 5a). Main paleocurrents are from the west and southwest. Cross-strata dip between 25 and 30 degrees and frequently are asymptotic at the base. Individual frontal laminae display evidences of both grain fall and sand flow (avalanching) depositional processes (Hunter

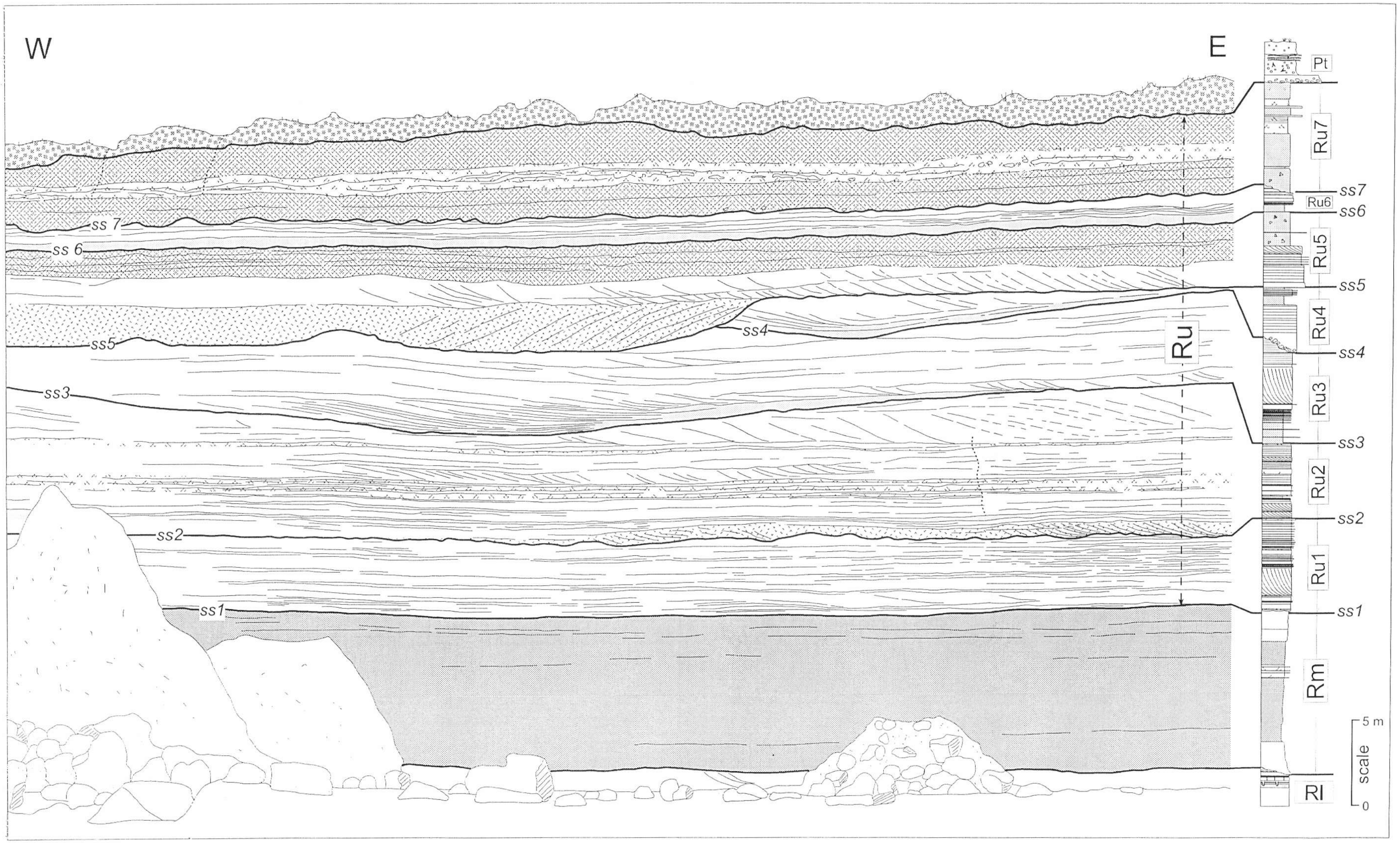

Fig. 3 - Line-drawing of photohorizons over an oblique photograph of the complete sea cliff taken immediately westward of section 2 (Fig. 1). Note the lateral extension of erosional surfaces (super surfaces) recognised in the measured section (right). These surfaces (ss1 to ss7) allowed to identify the existence of seven aeolian depositional sequences within the Ru unit. Each sequence internally displays a distinctive cyclic arrangement of aeolian and aeolian-related facies (indicated). Note also the extension and thickness of wet interdunes at this locality. Persons near the base of the figure for scale.

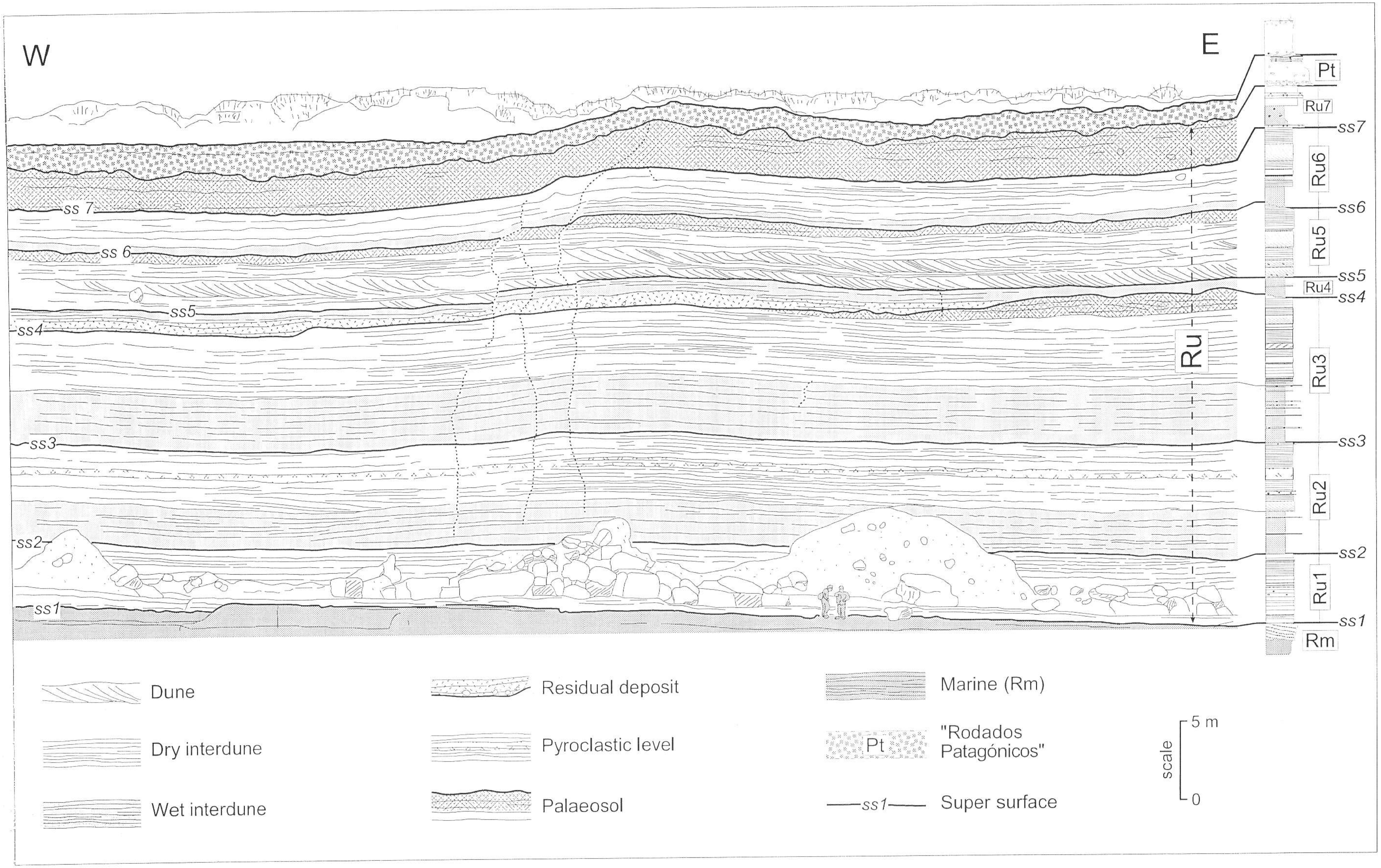

Fig. 4 - Line-drawing over an oblique photograph near section 3 (*Playa Bonita*, Fig. 1). The super surfaces indicated are the same as in Fig. 3, and their equivalence was controlled by field survey. Note the deep-scoured deflationary relief of some super surfaces (e.g. ss3, ss4 and ss5), and the common occurrence of wet interdunes and residual deposits (indicated) over them. It could also be noted in the basal levels of sequences Ru3 and Ru4, that the fine-grained deposits of wet interdunes progressively onlap the super surface relief to the right, and being accompanied at the same time by deposition of prograding aeolian dunes from the left. This supports the relation between aeolian deposition and periods of rising water tables. Legend as in Fig. 3.

1977). Grainfall deposits appear as internally massive near-tabular laminae up to 5 cm thick, and both coarsen and fine-upward. Sand flow deposits are less frequent and occur between the grainfall laminae. They display a well defined wedge-shape geometry (up to 3 cm thick), which is best developed near the base of the large-scale cross-beds (Fig. 5b). Other common features between the frontal laminae are cross-bedding caused by back-flow. Back-flow deposits appear as a discrete (up to 20 cm thick) and repetitive cross-bedded units that climb up the dune lee slope; palaeocurrents are opposed to those of the main aeolian bedform.

Individual sets of dunes appear isolated or stacked in a coset bounded by slight erosional surfaces. In a

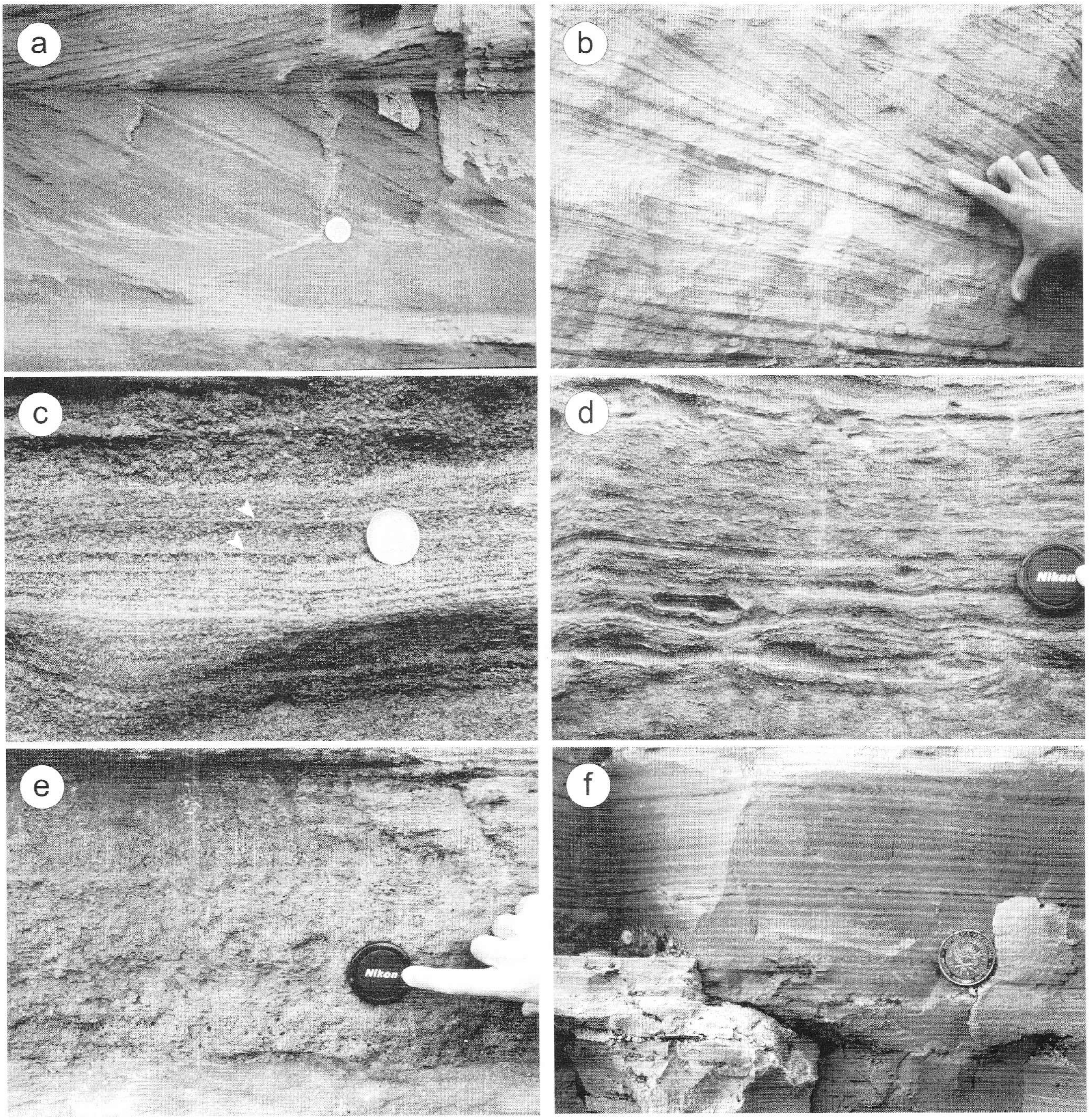

Fig. 5 - Main characteristics of dune and interdune facies. (a) General view of the toe-sets of an aeolian dune (coin for scale). (b) Close-up of some sand flow strata at the toe of aeolian dunes. Note the wedge geometry and the interbedding with massive grain fall deposits. (c) Subcritically climbing translatent stratification, a diagnostic structure for aeolian deposition. This structure is very common in dry interdune facies. Arrows show inverse grading within different laminae. (d) Crinkly to wavy and contorted lamination, interpreted as inland *sabkha* bedding. Lens cap for scale. (e) Millimetre-size open voids within laminated sandstones here interpreted as boxworks, and related to dissolution of evaporite crystals in an inland *sabkha*. (f) Laminated mudstones deposited from quiet, shallow water bodies here thought as wet interdunes. The cyclic nature of these laminae may reflect seasonal changes.

wider lateral scale (Fig. 3 and 4) it is common to observe climbing relationships between different dunes.

Dry interdune facies

Dry interdunes constitute the most common aeolian facies in the Ru member. Deposits are characterised by light gray laminated fine- to medium-grained sandstones, with an overall tabular geometry (Fig. 3). The most conspicuous feature in this facies is the presence of 0.2 to 1.5 cm thick parallel to near-parallel laminae, characterised in some strata by inverse grain-size grading (Fig. 5c). This sedimentary structure is interpreted as subcritically climbing translatent stratification (Hunter

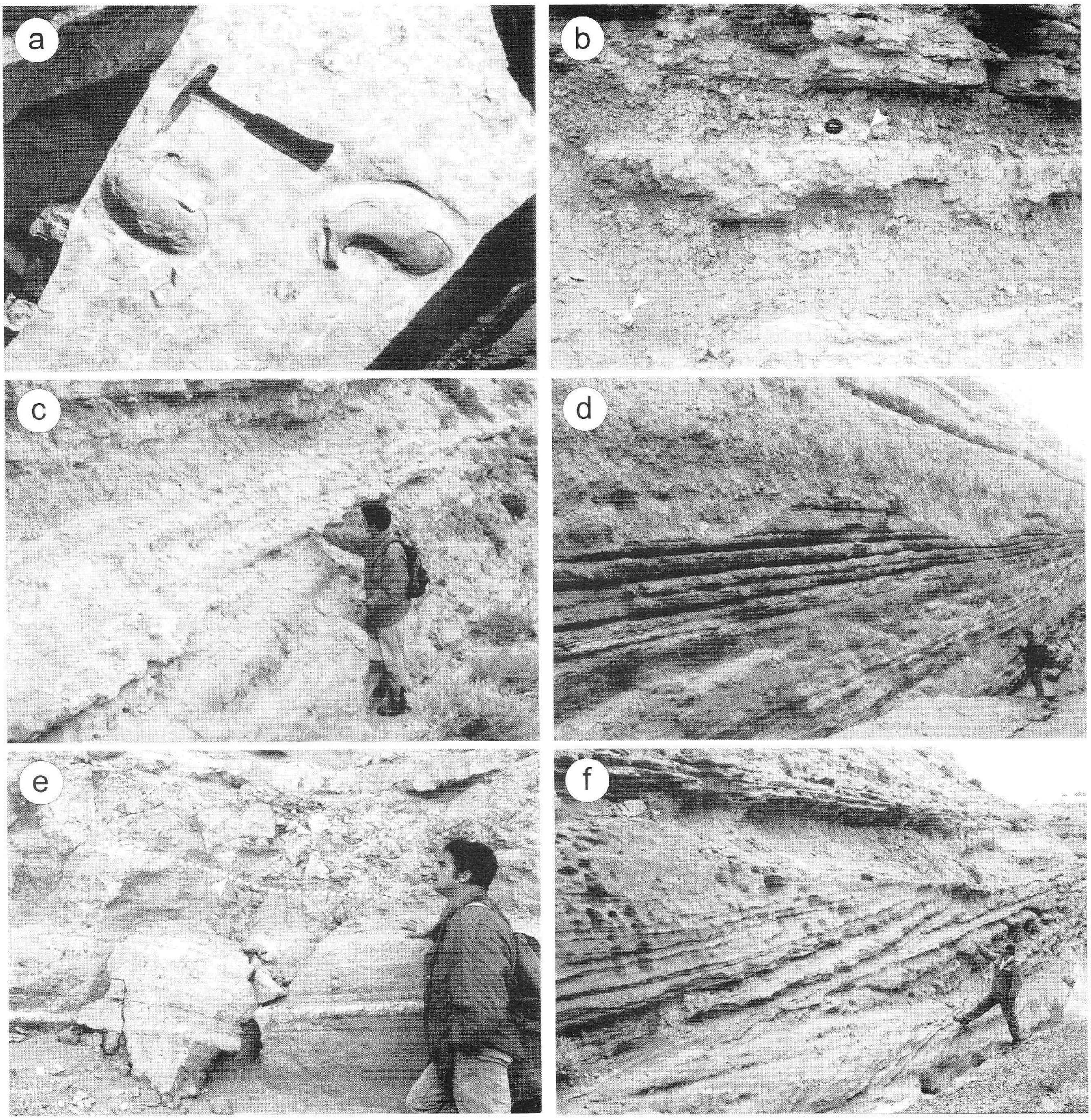

Fig. 6 - Other distinctive features in the Río Negro Formation. (a) Bedding surface at the transition between wet and dry interdunes, showing large mammal ichnites. Their preservation is favoured by a mud-drape settled during the subsequent flooding event. (b, c) Two examples of arid palaeosols usually located near the top of aeolian sequences; their upper horizons are commonly eroded. Note the overall bioturbation and the presence of carbonate nodules (arrows). (d) Irregular and deep-scoured erosional surface of aeolian origin (ss7), related to deflation during degradational periods. (e) Detail of the large scale and fine-grained angular blocks interpreted as residual accumulations during degradational periods. Their occurrence is closely associated with the basal super surface (arrows). (f) The irregular relief of super surface ss6 at section 2. This erosional surface is draped by mudstones related to wet interdunes developed during the following early aggradational sub-period.

1977), produced by the lateral migration of a wind ripples. This structure is considered diagnostic of ancient aeolian deposits (Kocurek 1996). A thin layer of fines commonly drapes the boundary between different laminae and probably corresponds to pin stripe lamination (Fryberger & Schenk 1988).

Other structures include planebed lamination without definitive grading, that probably represents tractional deposition at wind velocities too high for ripple existence. Hunter (1977) relate this structures with winds velocities of about 18 m/s.

In some places, this facies displays a crinkly to wavy and contorted lamination (Fig. 5d), thus suggesting interdune *sabkha* bedding (Glennie 1970; Havholm & Kocurek 1994). Additionally this sandstone level has millimetre open voids here thought as boxworks, and related to the dissolution of growing evaporite crystals (Fig. 5e). The presence of inland *sabkha* levels within dry interdune deposits has been interpreted as reminiscent of salt ridge structures formed in association with a high water table and precipitation of evaporite minerals within and on the surface of the sediments. The syndepositional and early postdepositional evaporite growth and dissolution may cause much of the crinklynature of the strata (Havholm & Kocurek 1994). A near-surface water table in interdunes is also suggested by the occasional occurrence of adhesion ripples, formed by windblown sand over wet surfaces (Hunter 1973). It is important to note that in this paper *sabkha* bedding and adhesion structures are both included into dry interdune facies according to their more common field relationships. On the other hand, wet interdune facies have been restricted to those fine-grained strata having evidences of a subaqueous origin.

Wet interdune facies

This facies is characterised by up to 3-m thick massive or finely laminated reddish mudstone (Fig. 5f), with scarce desiccation cracks. These fine-grained deposits have a tabular (Fig. 3) to irregular geometry (Fig. 4), and were probably deposited from a quiet and fluctuating shallow freshwater (lacustrine) body. Facies relationships suggest that the origin of these deposits were closely related with those of the dune and dry interdune aeolian facies. These freshwater bodies probably developed in the lowermost part of the paleolandscape, where water table level exceeded the depositional surface. Dune and dry interdune facies often prograde directly over wet interdune facies. Some ancient examples can be seen in Fig. 3 and 4.

In some places, centimetre-thick isolated and highly laterally traceable carbonate levels can be observed within the mudstone succession. These carbonates could correspond to inorganic precipitation from carbonate-rich lakes due to restriction or warming of waters (Talbot & Allen 1996).

This facies also contains rare fossil remnants of freshwater bivalves (*Unio diluvii* and *Chilina* sp.) and undetermined fishes (D'Orbigny 1842). Other fossil biological evidences include numerous ichnites of mammals and birds. Angulo & Casamiquela (1982) cited the presence of *Megatherichnum oportoi, Falsatorichnum calceocannabius, Porcellusignum conculcator, Macrauchenichnus rector* and *Caballichnus impersonalis*. Although these ichnites have been also recognised in different palaeosurfaces belonging to dry interdunes, their best preservation potential occurs at transitional areas between wet and dry interdunes (Fig. 6a). At these positions, seasonal changes in the freshwater body extension result in an alternance of periods of subaerial and subaqueous deposition in marginal areas. Consequently, most foot prints registered during periods of emergence could be preserved by the subsequent fine-drape settled during the high water level.

Ephemeral fluvial facies

The ephemeral fluvial facies constitute a minor element (< 5%) in the succession. It is composed of fine- to medium-grained graded sandstone beds with supercritically climbing ripples and water escape structures. These beds locally show clay-chips near the base, and freshwater bivalves in life position. The origin of these fluvial deposits (*wadis*) could be attributed to the runoff of episodic and localised heavy rainfalls, which are common in desert environments. On a more regional scale, these fluvial events could also contribute to wet interdune ponded areas.

Arid palaeosol facies

Light brown and massive fine-grained sandstone and mudstone, with some evidences of burrowing and root marks have been interpreted as palaeosols. This meter-thick facies has been observed overlying different aeolian and aeolian-related facies with a transitional base (Fig. 3, 4). It usually includes irregular to nearly spherical nodules of carbonates (Fig. 6b,c). The top of the facies is often an erosional surface (Fig. 3), thus suggesting that upper soil horizons are partially truncated. The presence of carbonate nodules and concretions in these soils could indicate arid or semiarid climatic conditions (Hanneman et al. 1994) associated with intervals of low to moderate deposition and a low water table.

Deflation surfaces

The presence of laterally extensive and irregular erosional surfaces (Fig. 4) constitutes a distinctive feature within the sedimentary succession. These surfaces commonly display an irregular relief (Fig. 6d) and are

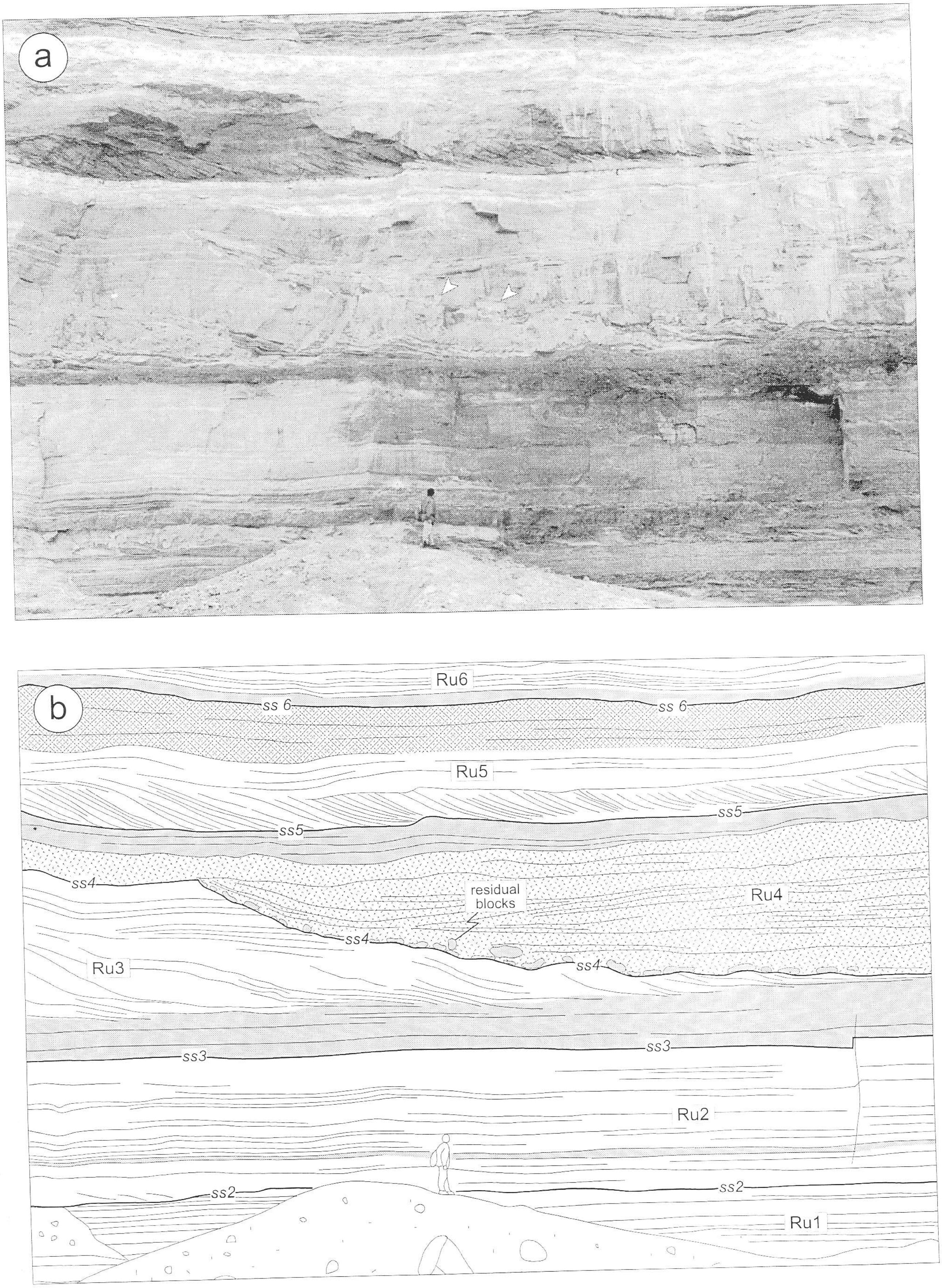

Fig. 7 - Field expression of deflation surfaces (a) Frontal view of the sea cliff near section 3. (b) Line drawing of the above photograph. Large-scale residual blocks (arrows) of stage 1 occur over ss4. The erosional deflationary relief was filled by aeolian dune facies during stage 2, followed by wet interdune facies (stage 3). Geologist for scale. Legend as in Fig. 3.

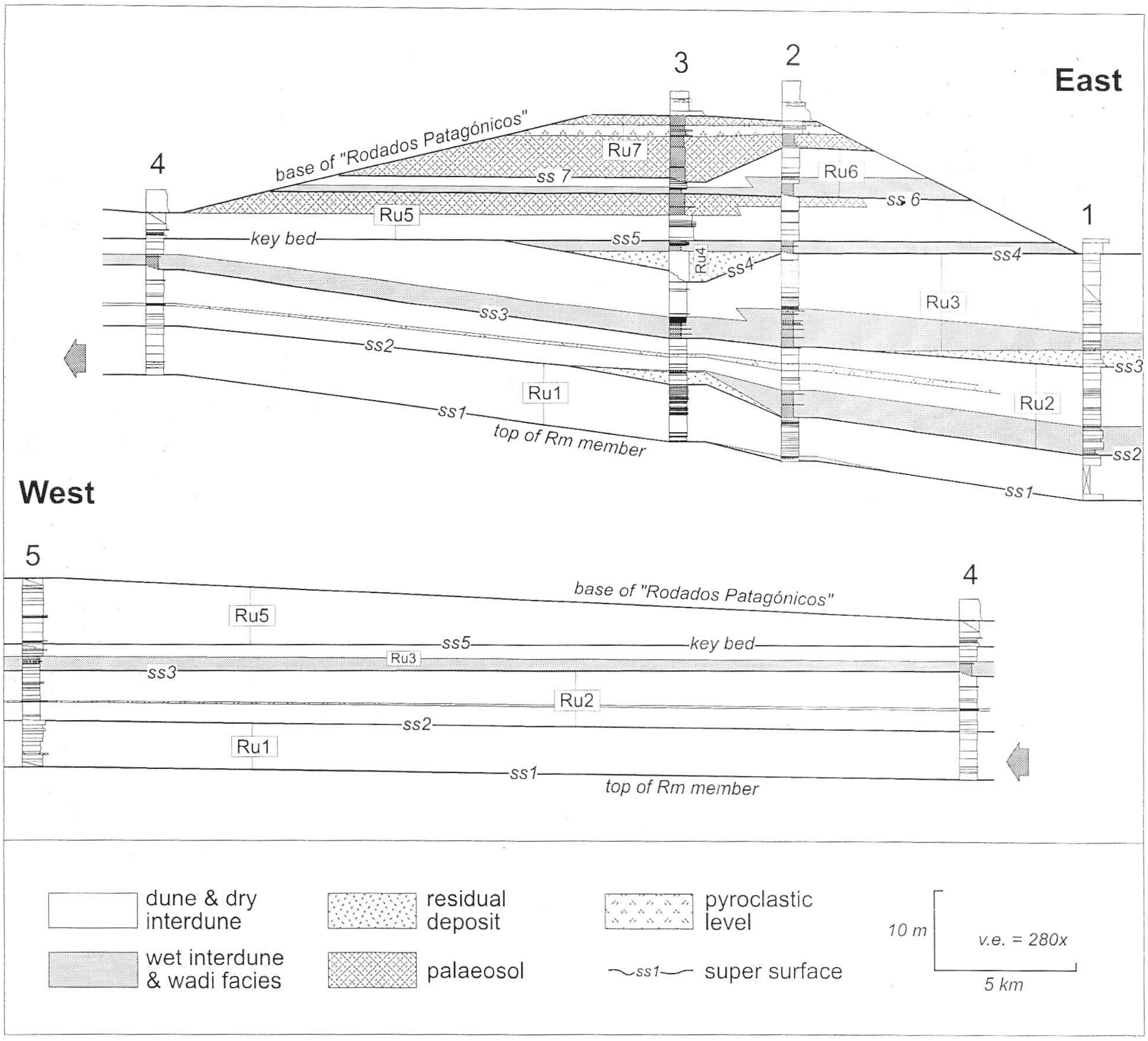

Fig. 8 - Regional cross section of the Upper Member of the Río Negro Formation. Distinctive tuff levels and the particular lithological characteristics of sequence Ru5 facilitate the detailed correlation over long distance (about 50 km). See Fig.1 for the location of the sections.

usually covered by pebble to cobble size fine-grained cohesive aggregates (Fig. 6e, see also Fig. 7). These aggregates are enclosed within a medium to coarse grained sandstone matrix, and in some places appear closely associated with diagnostic aeolian sedimentary structures, such as subcritically climbing translatent stratification. The absence of lithic pebbles and other evidence of fluvial mechanics suggest that these fine-grained blocks and sandstone are residual (relict) deposits generated during, or immediately after, deflation processes. The depth to which deflation occurs can be effectively controlled by the position of water table (Langford 1989). Consequently, the occurrence of irregular surfaces is therefore thought as deflation in areas having relatively low water tables. On the other hand, at low-land areas, where deflation can effectively approach the water table, deflation surfaces can be extremely flat (Fig. 3), and the local relief previously described could not be developed. If a subsequent rise in water table occurs after the deflation period, these low topographic areas are the most suitable to evolve into wet interdunes (Fig. 4). In fact, It has been noted in many examples that deflational surfaces are draped by laminated mudstones corresponding to wet interdune deposits (Fig. 6f). The last denotes a different origin for large scale erosional depressions and their fillings.

Sequence stratigrahy

The use of super surfaces as a tool for distinguishing, analysing and correlating genetic aeolian sequences has resulted in a significant improvement of our understanding of these deposits (Kocurek 1996). Nevertheless, the internal organisation of aeolian depositional sequences is, at present, poorly understood. The lack of detailed studies on this field could be partially related to

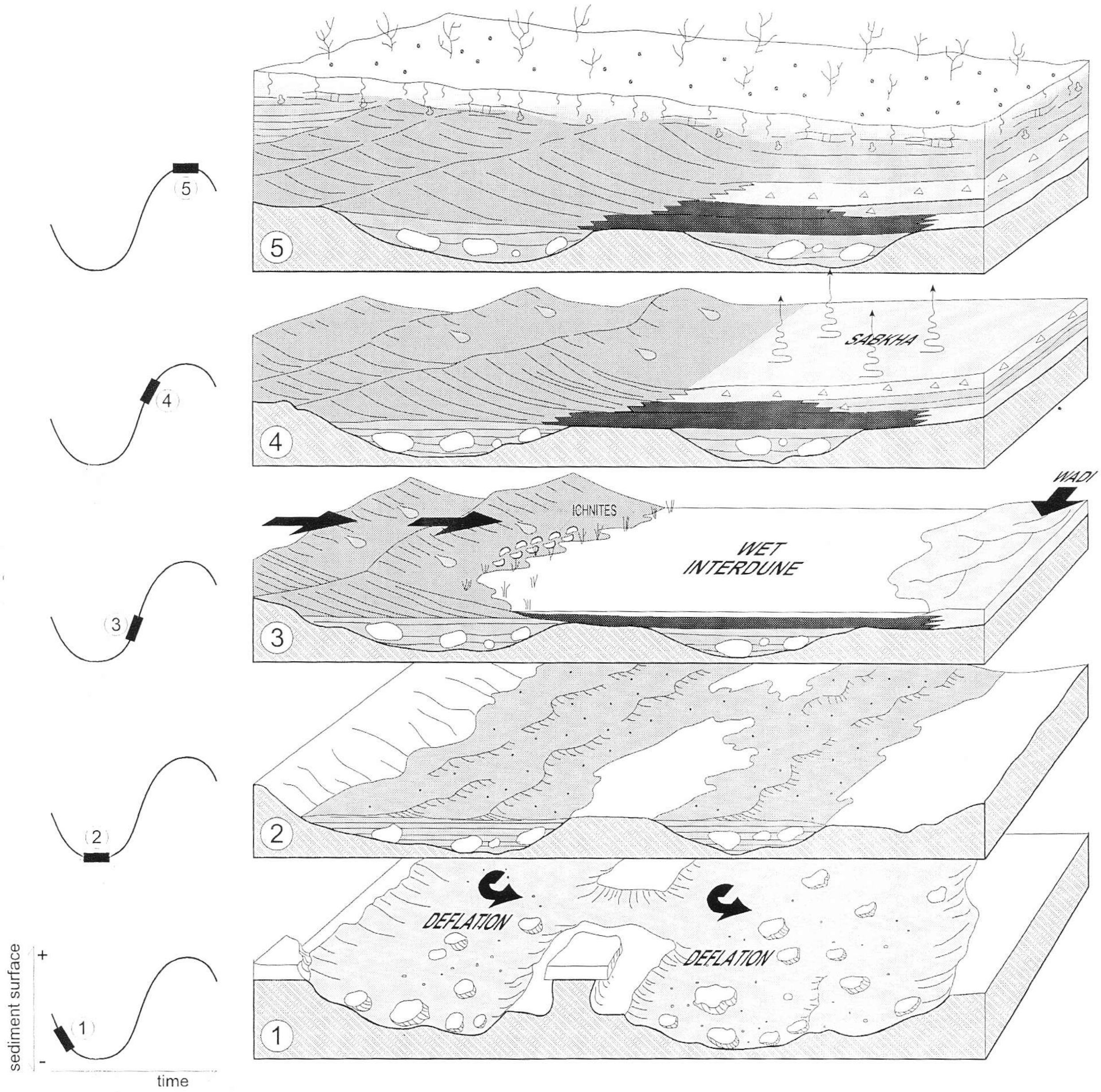

Fig. 9 - Main depositional stages during the development of an aeolian sequence. Curves on the left show the general evolution of the sediment surface (relief) with time. Stage 1: deflation and super surface development; Stage 2: residual aeolian deposition; Stage 3: maximum extension of wet interdunes, with associated aeolian dunes and localised ephemeral fluvial facies (*wadis*); Stage 4: aeolian dunes and related dry interdunes and *sabkhas*; Stage 5: growing tendency to stabilisation, with formation of arid palaeosols.

the relatively scarcity of appropriate exposures. The Ru member of the Río Negro Formation provides excellent and highly laterally traceable outcrops of aeolian deposits to try to achieve an enlightened conceptual model. The analysis of the sedimentary succession from a sequence stratigraphic point of view results in the discrimination of seven aeolian depositional sequences (nominated as Ru1-7, see Fig. 3). All these sequences are bounded by super surfaces, which can be traced for a distance in excess of 50 km. A detailed geological cross-section of the Ru member is shown in Fig. 8. Current classification and discrimination between wet and dry aeolian systems (Kocurek & Havholm 1993; Kocurek 1996) was not useful in our study, because within most of the recognised sequences, aeolian systems evolve vertically from one to another type with time.

Sequences Ru1 to Ru3 display an overall tabular geometry, and were recognised in all the described sections (Fig. 8). These sequences start over relatively flat deflation surfaces, with a limited volume of residual deposits. The Ru1 sequence is almost entirely composed of dry interdune facies with minor equivalent dunes. Wet interdune facies are poorly represented in this former unit, but tend to be extensively developed in Ru2 and Ru3 sequences. In section 2 (Fig. 3) wet interdunes directly overlie flat deflation surfaces without residual facies. These last sequences show also well-developed dune and dry interdune facies, and in some places truncated palaeosols on top. The presence of pyroclastic (tuff) levels in these units facilitates long distance phys-

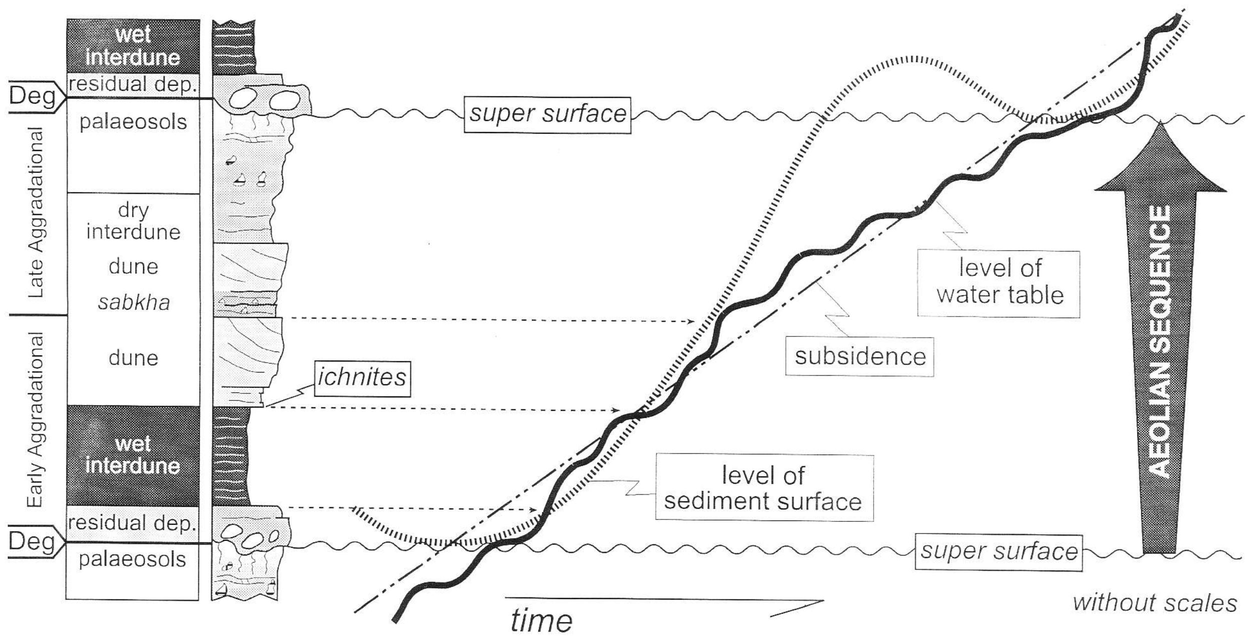

Fig. 10 - Diagram showing the main controlling factors (water table level, subsidence and sediment surface) on aeolian deposition and development of aeolian sequences. Deg: degradational periods.

ical correlation. The Ru4 sequence has been recognised only in eastern positions (Fig. 8), and is composed of localised residual deposits followed by wet interdunes with minor associated dunes (Fig. 7).

Sequence Ru5 has a regional significance and its basal deflationary surface has been used as a key bed for the cross-section shown in Fig. 8. Deposition started over a deep-scoured surface and is integrated by residual deposits, aeolian dunes and palaeosols. Their sandstones are distinctively coarser than those of the previous sequences and display a typical blue-gray coloration. The last characteristics provided an additional criteria for long distance correlation.

The Ru6 and Ru7 sequences were recognised only at sections 2 and 3 (Fig. 8). The Ru6 sequence has an internal organisation similar to the Ru2 and Ru3 sequences, starting with wet interdunes that evolve into dunes and dry interdunes (Fig. 6f). The Ru7 sequence is in turn composed of a monotonous succession of arid palaeosols disposed over an impressive deflationary surface (Fig. 6d). This unit contains well-developed pyroclastic levels in the middle part, which can be traced for relatively long distances.

Some remarks on the sequence stratigraphy of aeolian deposits

The recurrent evolutionary characteristics described above allow the development of new concepts on the sequence stratigraphy of aeolian deposits. The example discussed in this paper shows that the existence of generalised erosional and depositional periods were not coeval all along the study area, thus resulting in the deposition of time and genetically-related deposits bounded by regional unconformities.

The block diagram of Fig. 9 shows the main conceptual evolutionary stages during the development of a single aeolian depositional sequence, as observed on field examples. Curves on the left indicate the evolution of the sediment surface level (relief) with time (in the sense of Havholm & Kocurek 1994).

Stage 1 consists of a widespread deflationary period, mainly characterised by erosion/bypass affecting the underlying sequence. The only related accumulations are minor and localised residual large-scale blocks of fine-grained materials (Fig. 6e) derived from the erosion of pre-existing deposits. Commonly, these residual blocks were recognised where the basal unconformity displayed a marked relief (Fig. 7), and were not recognised over large flat deflational surfaces. Stage 2 is characterised by initially poorly-sorted aeolian sandstone deposition on the lowest part of deep-scoured erosional surfaces. These deposits usually develop over the residual blocks of the preceding stage (Fig. 7). The precise discrimination of deposits belonging to these two initial stages could be difficult, consequently, they were both indicated in the figures as "residual deposits". A generalised aeolian and aeolian-related deposition occurred during stage 3, corresponding to an active aeolian system with dunes, locally dry interdunes and typically, wet interdunes. The common occurrence of extensive wet interdunes is here related to rising water tables and a moderate sediment supply. During stage 4 wet interdune areas undergo an important restriction, resulting in a predomination of dunes and dry interdunes. In certain positions, these interdunes develop inland *sabkha* facies, thus suggesting a water table located close to the depositional surface. Stage 5 is marked by the progressive stabilisation of the aeolian system evidenced by the common presence of palaeosols.

All things been equal, these previously described evolutionary stages could be roughly thought as the "systems tracts" recognised within classical depositional sequences. In order to properly analyse the internal evolution of aeolian sequences, and their controlling mechanisms, the five stages were tentatively grouped into degradational and aggradational periods. The first stage corresponds to degradational periods, which are characterised by a generalised episode of aeolian erosion and/or non deposition, resulting in the development of extensive super surfaces. The lowermost limit to which aeolian erosion could be effective is controlled by the position of water table. Consequently, the deepest deflationary surfaces often display a planar shape (section 2, Fig. 3). As been noted by Havholm & Kocurek (1994) the time span involved in degradational periods could be similar to or even longer than that represented by deposition during the aggradational ones.

The aggradational periods are characterised by a relatively continuous deposition, which are internally organised into basic aeolian sequences. An idealised aeolian sequence and their basic constituents is shown in Fig. 10. Early aggradational (EA) sub-periods comprise stages 2 and 3 (Fig. 9), which are here related with an aeolian deposition associated with a relatively fast-rising water table. The rapid drowning of extensive deflationary surfaces within a moderate aeolian sediment supply results in the common development of shallow water bodies in interdunes. The close interrelationships between dunes and wet interdunes can be clearly seen in the Ru3 and Ru4 sequences at the line-drawing of Fig. 4. The last scheme also documents that aeolian deposition seems to occur associated with rising water tables. Late aggradational (LA) sub-periods are integrated by stages 4 and 5 (Fig. 9), which represent an aeolian system with a depositional surface that tends to outdistance the water table and its ensuing control on deposition. It is also noted in this LA sub-period that aeolian systems display a growing tendency to be stabilised, resulting in the common development of arid palaeosols.

Discussion and conclusion

Deposition of continental systems is often driven by a complex interplay between numerous variables (e.g., climate, sea level, subsidence, sediment budget and water table), where the appropriate evaluation of their relative incidence in the stratigraphic record could be a difficult task, and it is beyond the scope of this paper. Nevertheless, field examples examined in this report allow to outline some considerations about the relevance of certain controlling factors (Fig. 10).

1.- As deflation is limited by the position of the water table, then the preserved thickness for each individual sequence equals the large scale variation in water table with time. Although short-lived water table variations can be effectively controlled by climate or related sea level changes, the preserved thickness in a certain area must equal the average subsidence with time. Nevertheless, the climate and sediment budget probably greatly influence facies types and internal architecture of aeolian depositional sequences.

2.- As noted above, deposition in aeolian systems is closely related with rising water tables. Where the water table intersects the depositional surface (mainly during EA sub-periods) they develop shallow lakes (or *playas*) that could be laterally related with dunes or dry interdunes. The boundary between sub-aerial and sub-aqueous environments is the most sensitive to register high frequency (or seasonal) changes in the water level (Fig. 4). These areas are also the most suitable to preserve ichnites (Fig. 6a).

3.- The progressive tendency to stabilisation during LA sub-periods, and the common occurrence of arid palaeosols at the top of the aeolian sequences strongly suggest an overall climatic control in their origin. The possible relationships of these sequences with glacial/non-glacial events or sea level changes remains untested, and will require future studies.

4.- Although previous studies enhanced the importance of super surfaces in defining genetically related packages of aeolian deposits, this paper introduces for the first time a conceptual scheme to analyse the internal facies evolution within aeolian sequences. Even though the model provided here has been derived from, and it is consistent with all field observations, it was based on a single basin. It is therefore considered necessary to verify in the future their applicability or not in other fossil aeolian systems. We expect to encourage other research groups to work on this problem.

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