Sedimentary architecture of an ancient linear megadune (Barremian, Neuquén Basin): Insights into the long-term development and evolution of aeolian linear bedforms

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ABSTRACT
Linear aeolian bedforms are the most abundant bedform type in Earth’s dune fields, and are very common in the Solar System. Despite their abundance, the long-term development of these bedforms and its impact upon the resulting sedimentary architecture in the geological record is still poorly understood. The aim of this paper is to study the exposed record of an ancient linear megadune in order to discuss its development and the factors that impact the sedimentary architecture of aeolian linear bedforms. The outcrops of the ancient Troncoso Sand Sea (Barremian, Neuquén Basin, Argentina) provide a unique opportunity to study a preserved megadune record with an external body geometry that confirms its linear morphology. Architectural analysis reveals significant differences in cross-stratified set bodies and bounding surfaces’ features and allows for the identification of three architectural complexes within the bedform’s record. Analysis of deterministic models, sedimentary body relative chronology and distribution suggest that these architectural complexes result from distinctive phases in bedform development. It also clearly shows that construction of the megadune was achieved by expansion from a core, and that its development was characterized by sustained growth and strong longitudinal dynamics, without net accumulation. This study indicates how sustained bedform growth, rather than accretion, can be a critical factor conditioning linear bedform architecture towards a more ‘classic’ (bimodal bounding surface and cross-bedding dip directions) concentric sedimentary architecture style. Furthermore, this research reveals how this style of architecture could only be relatively common in the geological record when related to bedform topography preservation.

Keywords Aeolian linear bedforms, bedform development, Cretaceous, Neuquén Basin, sedimentary architecture, Troncoso Inferior.

INTRODUCTION
Linear dunes – relatively symmetrical, continuous, simple forms – (Lancaster, 1995; Livingstone & Warren, 1996) and linear megadunes – dunes with superimposed dunes – (also known as draa; Wilson, 1972; Mountney, 2006) are the most abundant bedform type in Earth’s sandy deserts (Lancaster, 1982) and are very common in the Solar System (Bourke et al., 2010). In spite of this, establishing the dominant characteristics of the sedimentary architecture associated with these bedforms has been problematic over several decades (Rodríguez-López et al., 2014; Besly et al., 2018). The difficulty in accessing the interior of modern dunes (McKee

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& Tibbitts, 1964; Tsoar, 1982), the apparent scarcity of this dune type in the geological record (Rubin & Hunter, 1985) and open questions about the long-term behaviour of these particularly slow-moving bedforms (Rubin et al., 2008), have made it difficult to record, identify and predict the sedimentary architecture associated with linear bedform development.

In this study, the term ‘linear’ is used strictly to refer to bedform morphology, following Rubin & Hunter (1985). Dunes of linear morphology include a variety of scales and shapes, such as seifs (Bagnold, 1941; Tsoar, 1982; Lancaster, 1995), linear ridges (vegetated linear dunes of Tsoar, 1989; Warren, 2013) and complex or compound (McKee, 1979) linear megadunes. Linear bedforms can be further classified according to their dynamics in longitudinal or oblique (sensu Rubin & Hunter, 1985) which result from the balance between elongation (sensu Tsoar et al., 2004) and lateral migration (Bristow et al., 2005; Rubin et al., 2008) processes.

In the past decades, ground-penetrating radar (GPR) and optically stimulated luminescence (OSL) techniques on modern dunes have allowed the characterization of the sedimentary architecture of linear dunes and have improved current understanding of their dynamics (Bristow et al., 2000, 2007; Roskin et al., 2011). However, long-term variability in linear bedform dynamics, scale and shape, and their effect on the sedimentary architecture preserved in the geological record, are still poorly understood. Considering that GPR studies of recent dunes have spatial limitations (for example, imaging penetration depth), the study of well exposed ancient successions offers a great opportunity to test models of sedimentary architecture attributed to linear bedforms, especially regarding larger megadune-scale forms, and to obtain further insights regarding their long-term development.

In the geological record, two types of sedimentary architecture are commonly attributed to deposition by linear bedforms. These are commonly referred to as ‘lateral migration’ and ‘vertical accretion’ types, given their interpreted association with bedform dynamics (Rubin & Hunter, 1985; Clemmensen, 1989; Scherer, 2000). Examples from the former category are broadly characterized by unimodal spread of cross-stratification dip-azimuths, oblique to the dip-azimuths of the internal bounding surfaces (Clemmensen, 1989; Ahmed Benan & Kocurek, 2000; Scherer, 2000; Rodríguez-López et al., 2008; Besly et al., 2018), and are consistent with lateral migration-dominated models proposed by Rubin & Hunter (1985). Other ancient examples fall within the latter category and are characterized by a bimodal (not bipolar) distribution of cross-stratification dip-azimuths (Glennie, 1972; Steele, 1983; Clemmensen, 1989; Bose et al., 1999) and are consistent with longitudinal behaviour dominated models (well explained in Rubin & Hunter, 1985). These types of architecture are based on empirical evidence of modern dunes, most notably from the studies of Tsoar (1982) and Bristow et al. (2000, 2005), and their likelihood has been evaluated from experiments (Rubin & Ikeda, 1990), theory on flow conditions and computational studies (see review in Rubin et al., 2008). In contrast, well-exposed examples from the geological record, combined with an external geometry that clearly confirms linear morphology, are very scarce (Clemmensen, 1989; Scherer, 2000).

The aeolian deposits within the Troncoso Inferior Member of the Huitrín Formation (Neuquén Basin, Argentina) are characterized by the exceptional preservation of megadune-scale and dune-scale bedform topography (Veiga et al., 2005). Large-scale bedforms of linear morphology have been identified in this ancient aeolian system both in remarkable quality exposures (Strömbäck et al., 2005; Argüello Scotti & Veiga, 2015) and in the subsurface (Dajczgewand et al., 2006). The aim of this work is to study the sedimentary architecture of an exceptionally preserved and exposed linear megadune from the geological record of the Troncoso Inferior Member, in order to discuss its development and the factors that impact the sedimentary architecture of linear aeolian bedforms.

**GEOLOGICAL SETTING AND STUDY AREA**

The Troncoso Inferior Member of the Huitrín Formation (Groeber, 1946) is part of the sedimentary infill of the Neuquén Basin (Howell et al., 2005; Fig. 1). It is considered to be Barremian in age, constrained by fossil assemblages in underlying and overlying marine units (Lazo & Damborenea, 2011; Aguirre-Urreta et al., 2017). In the north-eastern sector of the basin, the study unit is characterized by sandstones related to the development of a large dune field, or erg, overlying sandstones of fluvial/aeolian origin or, in some cases, a variety of sedimentary
deposits of marine origin. This erg, known as the Troncoso Sand Sea (Argüello Scotti, 2017), has a preserved extension of over 6000 km² and was developed during a period when the basin was completely disconnected from the proto-Pacific Ocean, being therefore considered as an inland erg. The final morphology of the dune field is partially preserved due to the abrupt marine flooding of the basin and the subsequent deposition of evaporites, due to a partial reconnection with the open ocean (Veiga et al., 2005).

The area selected for this study is the Loma La Torre outcrop at the southern Pampa de Tríl plain, in the north-western Neuquén Province (Figs 1 and 2). Previous studies in this location show that large-scale sandstone ridges that characterize the uppermost interval of the study unit constitute exceptionally preserved linear-shaped bedforms (Strømbäck et al., 2005; Veiga et al., 2005). These ridges are oriented WSW–ENE and have a width close to 1 km, a symmetrical cross-section, a spacing close to 1.5 km, and a preserved remnant height of 24 to 30 m (Argüello Scotti & Veiga, 2015). The erg system’s record, which constitutes the study interval, is bounded at the base by a planar and subhorizontal sand-drift surface (sensu Clemmensen & Tirsgaard, 1990; Rodríguez-López et al., 2013), characterized by signs of deflation, and capped at the top by a marine transgressive super surface (sensu Havholm & Kocurek, 1994). This interval regularly thins out in the so-called ‘interdune sectors’, as the two previously mentioned surfaces merge, indicating that the Troncoso Sand Sea record in this locality comprises solely the record of the preserved large-scale bedforms. When the system record thickness drops below 1 m, interdune facies can be observed which lack indications of water-lain, or even water-influenced, deposition. According to the facies observed in the interdune sectors, the aeolian system in the study area can be classified as dry (sensu Kocurek & Havholm, 1993). Furthermore, the very low or null thickness of the system’s record in the interdune indicates the absence of a rise in the accumulation surface, confirming that the system did not undergo accumulation (sensu Kocurek, 1999). Finally, considering regional studies (Fig. 1), the system at the study area was most likely to be located in a marginal erg setting.

The most accessible large-scale preserved bedform at the Loma La Torre outcrop was selected for this study (Fig. 2). Additional information on the preserved morphology and thickness of the bedform’s record are available from a previous study (Argüello Scotti & Veiga, 2015). The outcrops of the preserved bedform’s record comprise a continuous two-dimensional cliff section of its southern flank, oriented N110°–290° and oblique to bedform orientation (N81°–261°), and a discontinuous but more ‘pseudo’ three-dimensional exposure of its northern flank.

Previous facies analysis of the study interval at this locality (Veiga et al., 2005; Argüello Scotti & Veiga, 2015) recognized a low variability of sedimentary facies, belonging to aeolian and subordinated soft-sediment deformed facies associations. The most abundant facies are well to moderately sorted, fine to medium-grained, cross-stratified sandstones. Cross-stratification can be of both trough and planar type, and from high to low dip angle. More rarely, subhorizontally bedded sandstones occur (Fig. 3A and B). Basic aeolian stratification types characteristic of deposition in a dry sandy substrate are abundant (grainfall laminae, grainflow strata and subcritical climbing translatent strata; Fig. 3B to D), while stratification types indicating deposition

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**Fig. 1.** (A) Location of the Neuquén Basin, extension of the Troncoso Inferior Member and the Troncoso Sand Sea, and location of the study area. (B) Chronostratigraphic context of the study unit.
under a damp surface (adhesion ripple forms) have only been found in one sector of the preserved large-scale bedform core (and not in the interdune). Soft-sediment deformation of aeolian facies is evidenced by structures distorting primary aeolian strata by folding, such as convolute laminae, wavy subparallel bedding, cone-shaped diapirs and broad synclines, and by dish structures. These facies are only abundant in the upper sectors of the study interval, and have been associated with rapid upward escape of water and/or air associated with pressure changes within the dunes resulting from flooding (Strömberg et al., 2005).

**METHODS**

The workflow designed for this study is centred on a sedimentary architecture analysis (Kocurek et al., 1991). Field data acquisition (qualitative and quantitative) focused on two key elements...
of the sedimentary record of the preserved bedform: the cross-stratified set bodies and their bounding surfaces. Characterization of these elements allowed for the definition of contrasting architectural styles, identified as ‘architectural complexes’, whose internal complexity, distribution and chronology of set bodies was analysed.

**Data acquisition and processing**

A combination of surveying methods was used to characterize the sedimentary architecture exposed in the outcrops, including: (i) ground-based and aerial-based photography; (ii) sedimentary logs; and (iii) direct measurements and observations over the accessible parts of the

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outcrop. Aerial photography was used to build a digital 'photomosaic' over which the inferred sedimentary architecture was mapped, and later confirmed or corrected with field observations, resulting in three architectural panels. From these panels, the shape and position of the individual cross-stratified bodies and bounding surfaces were analysed. The position of each element was established in relation to the morphological features observed in the study section, such as megadune flank and crest sectors (Fig. 2D). Six detailed sedimentary logs were measured across the study section (Fig. 4), allowing for grain-size and sorting inspection (using a magnifying lens and comparative charts), aeolian stratification type recognition and estimation of their abundance within set bodies, set body thickness measurements, and dip angle and azimuth readings of cross-stratification and bounding surfaces using a Brunton compass (Brunton Inc., Riverton, WY, USA). Direct measurements and observations were carried out for all set bodies and intervening bounding surfaces that were accessible by foot, delivering the same information as logs. Specific categories were defined to estimate the relative abundance of aeolian stratification types within set bodies. Criteria used for recognition of aeolian stratification types are the same as in Argüello Scotti & Veiga (2015). The following categories were identified from the relative abundance between wind-ripple laminae (climbing translatent strata of Hunter, 1977) and grain-flow strata (Kocurek & Dott, 1981): (i) wind-ripple dominated (no grainflow); (ii) wind-ripple abundant; (iii) wind-ripple/grainflow couplets; (iv) grainflow abundant; and (v) grainflow-dominated (no wind-ripple). Grainfall laminae were...
identified and usually present at all of these categories, but they were of little volumetric importance in the section and across the study interval in general. Finally, a virtual outcrop model was generated from ground-based and aerial-based photography, following a ‘structure from motion’ workflow. The model was built from approximately 200 photographs, using Visual SFM (Wu, 2011) and MeshLab (Cignoni et al., 2008) software, and was scaled and referenced with data from a total station survey. The model was then imported into Virtual Reality Geological Studio (Hodgetts, 2009; Rarity et al., 2014), where cross-stratified set body dimensions (maximum thickness and apparent width) were obtained with vertical and horizontal measuring tools, and additional measurements of dip angle and azimuth of cross-stratification and bounding surfaces were extracted with the dip-azimuth tool (that calculates dip-azimuth from three points manually picked in the model). The final architectural panels (Fig. 5) combine the information obtained from all of these sources.

As a result, a total of 70 cross-stratified set bodies were analysed for the preserved bedform studied. The final dataset includes a total of 137 dip-azimuth readings of cross-stratification from 46 set bodies, and a total of 37 dip-azimuth readings from bounding surfaces. Dip-azimuth cross-stratification measurements were averaged for each set body, resulting in what is here referred to as ‘palaeocurrent direction’. In addition, the intra-body variability of cross-stratification dip-azimuth was measured as a strength vector (Collinson et al., 2006) when at least three values per body were available.

**Data analysis**

The architectural complexes identified within the study section are defined by significant differences in several aspects of the set bodies and bounding surfaces, such as maximum thickness, apparent width, palaeocurrent, and bounding surface orientations and external geometry (Figs 5 and 6; Tables 1 and 2). Minor differences are also seen in the abundance of aeolian stratification types and textural and compositional aspects of the sandstones. Statistically significant differences were found between the maximum thickness of set bodies belonging to different complexes by Fisher’s variance test (ANOVA) at a level of $P < 0.05$ ($F (3, 64) = 23.36; P < 0.0001$), and by Kruskal–Wallis test also at $P < 0.05$ ($H = 40.85; P < 0.0001$). Very similarly, significant differences of apparent width measurements of set bodies were established by Fisher’s variance test (ANOVA) ($F (3, 48) = 20.25; P < 0.0001$) and Kruskal–Wallis test ($H = 34.79; P < 0.0001$), always at a level of $P < 0.05$. Tukey’s and Dunn’s tests for multiple comparisons (Table 2) indicated the specific differences between each population.

Reconstruction and interpretation of the bedform morphodynamics and development that relate to each complex was assisted by deterministic modelling using BEDFORMS software (Rubin, 1987). In addition, the distribution of the complexes (i.e. location within the study section, abundance and relative superposition) and the internal relative chronology of their set bodies was inspected. These analyses provided a wealth of information that allowed reconstruction of the development of this ancient linear megadune.

**SEDIMENTARY ARCHITECTURE**

**Architectural complexes**

The sedimentary architecture observed in the study section is separated into three complexes with particular architectural styles (Figs 5 and 6; Tables 1 and 2). The architectural style is considered in terms of the dimensions, shape and distribution of set bodies and orientation of both foresets and bounding surfaces. The differences between complexes (quantitative and qualitative) are demonstrated to be the result of a particular phase in the development of the preserved bedform, indicating that each complex is composed of genetically-related set bodies and bounding surfaces.

**Complex 1**

*Description.* Complex 1 is characterized by small cross-stratified set bodies (maximum thickness usually between 1 m and 2 m; apparent width around 20 m, Table 1) with a wedge-shaped geometry (Figs 5 and 7A). The complex occupies a very small area (only 1%) in the bedform section, in which only seven set bodies were identified. The set bodies show a higher proportion of clasts of opaque heavy minerals in comparison to the other complexes in the study section (Fig. 7C). Regarding aeolian stratification types, the set bodies that comprise the first complex are usually composed of wind-ripple/grainflow couplets...
particular accumulation conditions, different of the preserved set bodies show evidence of the subsequent complex, the characteristics eroded to a great extent before the deposition. The cross-stratification in the first set is around 10° towards 340°. Even if this complex was eroded to a great extent before the deposition of the subsequent complex, the characteristics of the preserved set bodies show evidence of particular accumulation conditions, different from the following complexes.

**Interpretation.** A bimodal distribution of palaeocurrent directions and bounding surface’s dip-azimuths, coupled with individual cross-stratification in set bodies dipping oblique to the strike of its associated lower bounding surface and to the largest axis of the set body, is consistent with the architecture expected for a sinuous linear dune with a sustained longitudinal dynamic (dominant elongation and minor lateral migration; Tsoar, 1982; figs 55 and 77 of Rubin, 1987; Rubin et al., 2008). In this case, each opposing side of the same dune crest is responsible for the formation of set bodies with one of the two palaeocurrent modes. The strike of the bounding surfaces and the orientation of the set body’s largest axis is sub-parallel to the dunes elongation direction. On the other hand, the texture and stratification types of the oldest preserved set body indicate that its associated original bedform lacked an active slipface and could represent the remains of an incipient bedform like a dome dune (sensu Pye & Tsoar, 2009; Warren, 2013).

The spatial relationship between the first set body and the rest of the sets in this complex is similar to what could be expected from a growing, elongating sinuous linear dune, as shown in the models of Bristow et al. (2000, stage 1, fig. 3), Rubin et al. (2008) and in the models built for this study (Perspectives gained from deterministic models section) which emulate the behaviour and growth of seif dunes. Taking those models into consideration, the first set of the complex is probably the remains of a linear dune tip or nose, later covered by the deposits of the same elongating dune. In this way, the sedimentary architecture of Complex 1 can be explained by the growth (i.e. size increment) and longitudinal behaviour (i.e. sustained longitudinal dynamics) of a single, simple linear dune or seif.

**Complex 2**

**Description.** Complex 2 is characterized by the occurrence of very large-scale set bodies (maximum thickness average at 4 to 5 m, and up to 8.5 m; apparent width average at 65 to 66 m, Table 1; Figs 5 and 7) occupying a large area (around 47%) of the study section. Set bodies in this complex show a clear bimodal palaeocurrent and bounding surface dip-azimuth distribution, dependent on the position in the section. A 315° to 15° palaeocurrent mode is dominant in the northern flank of the preserved bedform section, while a 45° to 165° mode is dominant in the southern flank (Fig. 8, considering both wedge and trough-shaped set bodies). Bounding surfaces in the flank sectors are planar/tangential in shape and have dip-azimuths from 315 to 0° in the northern flank and from 100 to 150° in the southern flank. In contrast, bounding surfaces in the crest sector are concave-upward and have a bimodal dip-azimuth distribution. Furthermore, large-scale set bodies can also be separated into trough-shaped and wedge-shaped bodies (Table 3; Figs 5, 7 and 8). Trough-shaped bodies (Figs 7D and 8) are located within the centre of the section, they have a high intra-set body variability.

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**Fig. 5.** Sedimentary architecture of the studied section. (A) Close-up of the photomosaic shown in Fig. 2A, with the study section marked in yellow. (B) Architectural panel a–a’ (location on Figs 2B and 5A). (C) Architectural panel b–b’ (location on Figs 2B and 5A). (D) Architectural panel c–c’ (location on Figs 2B and 5A). Colours indicate the extent of the different architectural complexes. Each cross-stratified set body is identified by a letter, ‘c’ for centre, ‘n’ for northern flank and ‘s’ for southern flank, and a number.

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of cross-stratification dip-azimuth (low \(S\) value, Table 3) and an acute bimodal palaeocurrent distribution. Wedge-shaped bodies (Figs 7F and 8) are found in the flank areas; they have fairly constant intra-set cross-stratification dip-azimuth (high \(S\) value, Table 3) and show an obtuse bimodal palaeocurrent distribution. Trough-shaped bodies are dominated by wind-ripple/grainflow couplets (Fig. 7E), whereas wedge-shaped bodies are more abundant in wind-ripple lamination, increasing gradually in importance towards the base of the set and away from the section crest until becoming wind-ripple dominated (Fig. 7G). Towards the top of this complex, very small-scale set bodies (maximum thickness average less than 1 m; apparent width average around 12 m) are found in groups between the large-scale sets, bounded within a trough-shaped lower bounding surface (Figs 5 and 7D). They comprise a particular population (Tables 1 and 2; Fig. 6), despite having little volumetric importance (2% of Complex 2 section).

**Interpretation.** Very much like Complex 1, large trough-shaped bodies found at the bedform centre of Complex 2, characterized by a bimodal palaeocurrent distribution and separated by bounding surfaces stacked in a zigzagging pattern, are consistent with the architecture expected for a sinuous, simple linear dune with a strong longitudinal behaviour (Tsoar, 1982, 1983; Rubin & Hunter, 1985; Rubin, 1987; profiles 4 and 5 of Bristow et al., 2000; Rubin et al., 2008). However, the dimensions of the set bodies indicate the presence of a larger bedform in comparison to the first complex. Regarding the wedge-shaped bodies, their palaeocurrent directions, their intra-set body cross-stratification dip-azimuth variability, and the evidence of dominant wind-ripple activity, indicate that they represent relatively stable dune sectors where bedform sinuosity is reduced. Sectors with these characteristics are very common in large linear dunes (larger than seifs, with a width over 100 m), where they represent the majority of the bedform section down to the dune toes (Lancaster, 1995) and are herein referred to as dune flanks. The trough-shaped sets on the other hand, are interpreted as the deposits of the more active and sinuous crest area, given their position in the section core, the aeolian stratification types present, the palaeocurrent directions and the intra-set body cross-stratification dip-azimuth variability. Considering that the dip-azimuths of bounding surfaces within this complex are oblique to the palaeocurrent directions of the set bodies they bound, and that such orientation

**Table 1.** Differences in scale and geometry between cross-stratified set body populations of different architectural complexes

|                | Maximum thickness | Apparent width |
|----------------|-------------------|----------------|
|                | Mean (m)          | SD             | N   | Mean (m) | SD     | N   | Geometry    |
| Complex 1      | 1.4               | 0.7            | 5   | 20.0     | 7.1    | 5   | Wedge       |
| Complex 2 (large-scale sets) | 4.4               | 1.6            | 31  | 65.6     | 29.7   | 22  | Wedge + trough |
| Complex 2 (small-scale sets) | 0.9               | 0.4            | 13  | 12.4     | 9.9    | 10  | Wedge + trough |
| Complex 3      | 3.1               | 1.4            | 19  | 23.2     | 13.7   | 15  | Trough      |

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depends on which flank the surfaces are located, they are interpreted as a product of long-crest migration of bedform sinuosity, either in the dune crest or flank sectors (Rubin, 1987; Rubin et al., 2008). The small-scale sets at the top of the complex are most likely to represent the record of minor, superimposed dunes, developed over the large linear dune mentioned earlier. These sets are only preserved within concave-upward surfaces, which suggest that superimposed bedforms were related to overall erosive sectors of their host bedform and had little potential to be incorporated into the bedform record.

Following this conceptual model, the architecture of Complex 2 is probably the result of a single, large linear dune evolving into a slipfaced linear megadune as superimposed dunes developed (similar to the model presented by Bristow et al., 2000 from modern dunes), while sustaining a dominant longitudinal behaviour.

**Complex 3**

*Description.* Complex 3 is characterized by stacked, intermediate-scale, trough-shaped sets (maximum thickness between 1 m and 5 m, mode of 2 to 3 m; apparent thickness between 5 m and 40 m, mode of 23 m, Table 2), better preserved in the southern flank (due to modern erosion of the outcrop, Fig. 5), that occupies a large area in the study section (52%). Soft-sediment deformation related to the subsequent transgression (Strömbäck et al., 2005) has locally modified the upper portions of this complex, but not enough to prevent interpretations (Fig. 5). The palaeocurrents from trough-shaped bodies of this complex show an acute bimodal distribution similar to the trough-shaped bodies of Complex 2 (Fig. 8). They are also characterized by wind-ripple lamination/grainflow couplets that pass abruptly into thin (1 or 2 dm thick) wind-ripple abundant or dominated set body bases (Fig. 3B). Bounding surfaces within this complex are of concave-upward shape, given the trough shape of the sets they bound and show a wide dip-azimuth distribution. These dip-azimuths span from 315° to 60° in the northern flank and 50° to 120° in the southern flank (Fig. 8), which can also be inferred from the apparent dip in the architectural panels (Fig. 5). The general dip-azimuth trend is therefore dependent upon position within the section and therefore broadly similar to the bounding surface dip-azimuth trend of Complex 2. The upper surface that separates this complex from overlying marine sandstone and evaporite facies, has been mapped in previous studies (Argüello Scotti & Veiga, 2015). Small-scale, elongated features were apparent in the southern flank of the large-scale preserved bedform both from the surface reconstructions and from direct observation of the outcrops. These are oriented subparallel to the large-scale bedform and have a relief reaching up to 6 m.

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**Table 2.** Results of applying Tukey’s and Dunn’s multiple comparison tests for maximum thickness and apparent width for cross-stratified set body populations of different architectural complexes.

|                         | Mean difference | 95% CI of difference | Significant | Mean rank difference | Significant |
|-------------------------|-----------------|----------------------|-------------|---------------------|-------------|
| **Maximum thickness**   |                 |                      |             |                     |             |
| C2l versus C1           | 3.036           | 1.296 to 4.78        | Yes         | C2l versus C1       | 31.77       | Yes        |
| C2l versus C2s          | 3.542           | 2.34 to 4.74         | Yes         | C2l versus C2s      | 39.26       | Yes        |
| C2l versus C3           | 1.288           | 0.23 to 2.34         | Yes         | C2l versus C3       | 12.63       | No         |
| C1 versus C2s           | 0.5065          | −1.40 to 2.42        | No          | C1 versus C2s       | 7.48        | No         |
| C1 versus C3            | −1.748          | −3.57 to 0.08        | No          | C1 versus C3        | −19.14      | No         |
| C2s versus C3           | −2.254          | −3.56 to −0.95       | Yes         | C2s versus C3       | −26.62      | Yes        |
| **Apparent width**      |                 |                      |             |                     |             |
| C1 versus C2l           | −45.55          | −73.91 to −17.18     | Yes         | C1 versus C2l       | −21.61      | Yes        |
| C2l versus C2s          | 53.15           | 31.31 to 74.98       | Yes         | C2l versus C2s      | 30.46       | Yes        |
| C2l versus C3           | 42.35           | 23.17 to 61.52       | Yes         | C2l versus C3       | 20.71       | Yes        |
| C1 versus C2s           | 7.60            | −23.76 to 38.96      | No          | C1 versus C2s       | 8.85        | No         |
| C1 versus C3            | −3.20           | −32.77 to 26.37      | No          | C1 versus C3        | −0.90       | No         |
| C2s versus C3           | −10.80          | −34.18 to 12.58      | No          | C2l versus C3       | −9.75       | No         |
Fig. 7. Details of set bodies and bounding surfaces belonging to different complexes. (A) Small-scale set bodies from Complex 1, showing a stacking that forms a zigzagging arrangement of the intervening bounding surfaces (pen for scale). (B) Detail of a climbing adhesion ripple stratum (lower limit marked by white arrow) found at the top of the C1 set body. Climbing translatent strata dip to the left and therefore climb in the opposite direction. (C) Thin section of a sample taken from Complex 1 (location on Fig. 5B) showing the abundance of clasts of opaque minerals. (D) Large-scale trough-shaped set body from Complex 2. Towards the top of the image, very small-scale set bodies also from Complex 2 are grouped within a concave-upward bounding surface. (E) Interval dominated by wind-ripple lamination, highlighted by reddish colour, between massive-looking amalgamated grainflow intervals. This is referred to as wind-ripple/grainflow couplets, which are the most common form of aeolian stratification type distribution in the study section – repeated in (D) and (F). (F) Large-scale wedge-shaped set bodies (n18 to n19) from Complex 2. (G) Wind-ripple lamination dominated lower sector of a wedge-shaped set body from Complex 2.
Interpretation. The trough-shaped bodies of intermediate scale represent, by their size and position within the section, the migration of superimposed dunes over the large-scale bedform. Therefore, the bounding surfaces within this complex are interpreted as superimposition surfaces. The large-scale bedform associated with this complex lacked an active slipface and its behaviour was controlled by the development of its superimposed dunes (compare to stage 5 of Bristow et al., 2000; GPR profiles of Bristow et al., 2007). By similarity in palaeocurrent directions to the trough-shaped sets of the previous complex, it is inferred that the superimposed dune types at megadune crest and upper flanks positions were of linear type and longitudinal behaviour. This is also indicated by the small-scale elongated features observed at the top of the complex, which represent the exceptional preservation of superimposed bedforms oriented subparallel to the large-scale preserved bedform. Other bedforms types, however, could have been present closer to the megadune plinth. Some small-scale features with different orientation and morphometry (asymmetrical section, 2 m relief and 100 m wavelength) are present in the interdune sector and clearly represent other bedform types (Argüello Scotti & Veiga, 2015).

Considering the characteristics of Complex 3, its deposition can be associated with the development of a slipfaceless linear megadune, probably of compound type (McKee, 1979). The overall dip-azimuth distribution of the bounding surfaces, dependent upon position, indicates that superimposition of bedforms was preserved in both flanks of the host bedform. This indicates once again that the major bedform had an overall dominant longitudinal behaviour.

Fig. 8. Palaeocurrent (averaged cross-stratification values for each set body) and bounding surface dip-azimuth distribution, arranged by complex. Panel a–a’ (location on Figs 2A and 5B) is shown as well, indicating not only the different architectural complexes but also the different set body types within Complex 2. Palaeocurrents of Complex 2 are further arranged by these set body types in very small-scale, large-scale trough-shaped and large-scale wedge-shaped set bodies. Bounding surfaces of Complex 2 are arranged by shape and position within the section.

Perspectives gained from deterministic models
To gain further understanding of the bedform development conditions that could have led to
the deposition of each complex, the program BEDFORMS (Rubin, 1987) was used. This software simulates bedforms by 3D surfaces from sine curves, and determines the sedimentary architecture resulting from the successive positions of such surfaces in time. Given that existing BEDFORMS models for linear dunes (both simple and complex/compound) assume a rise of the accumulation surface (sensu Kocurek, 1999) over time (Rubin, 1987; Clemmensen & Tirschgaard, 1990; Bose et al., 1999; Scherer, 2000), modelling was aimed at reproducing the sedimentary architecture expected for a simple linear dune under non-accumulation conditions (sensu Kocurek, 1999) and compared with the outcrops. Original models available were modified to test two different scenarios for simple, sinuous linear dunes (Fig. 9). Firstly, on Model 1, the effect of bedform growth on sedimentary architecture was tested. The represented bedform has an along-crest sinuosity migration and a lateral component in bedform motion, the later being an order of magnitude smaller than the former [considering rates observed in modern examples by Tsoar et al. (2004), Bristow et al. (2005) and Rubin et al. (2008)]. Model 2 intends to represent the morphodynamics and resulting sedimentary architecture of a seif dune in detail. For that purpose, some of the most remarkable studies on the morphology (Tsoar, 1982; Bullard et al., 1995; Lancaster, 1995; Pye & Tsoar, 2009) and dynamics (Tsoar, 1983, 1986; Livingstone & Thomas, 1993; Livingstone, 2003; Tsoar et al., 2004; Rubin et al., 2008) of small sinuous linear dunes or seifs were consulted. The bedform represented has peaks and saddles with a spacing half to that of the wavelength of bedform sinuosity, and a high frequency cyclic variation in the symmetry of the dune section. As in the first model, a lateral migration component in dune migration was added. Lastly, both models have a climbing angle of 0°, to emulate non-accumulation conditions observed in the Troncoso Inferior Member at the study area.

The results from the first bedform model show that with an important rate of bedform growth, sinuosity migration of a single dune can result in the deposition of a considerable number of cross-stratified set bodies. This is also apparent from the models developed by Bristow et al. (2000) and Rubin et al. (2008). Once the width of the bedform exceeds the sinuosity’s amplitude, both flanks of the bedform are incorporated into its record. Moreover, Model 1 shows that as long as the width increment (growth) exceeds the rate of lateral migration, more set bodies will be incorporated into the record of both flanks of the dune with time (Fig. 9). These results are key to explain the sedimentary architecture observed in the study section, especially for Complexes 1 and 2, highlighting that a single dune can give origin to a high number of set bodies separated by sinuosity migration surfaces that generate a zigzagging arrangement of bounding surfaces at the section centre (see crest sector, indicated in Fig. 5A, occupying the centre of the panel in Fig. 5B; close-up in Fig. 7A).

The results from the second model show the expected effect of peaks and saddles on the angle formed between the bedform orientation and the two modes in cross-stratification dip directions observed in the set bodies (Fig. 9). While the peaks are in the southern bends, or meanders, of the dune, the saddles are in the northern counterparts. As a result, the depositional areas corresponding to southern flanks (downdrift of a peak) are dipping in a direction...
closer to parallel to the main bedform orientation, when compared with depositional areas on the northern flanks. This is evident by the strike of the cross-stratification in Model 2, and in classical field models (fig. 13 of Tsoar, 1982; fig. 9 of Tsoar, 1983). More information on the actual cross-stratification dip directions of modern dunes would be necessary to confirm such palaeocurrent distribution. So far, the results of Model 2, based on field evidence (Tsoar, 1982, 1983; Bullard et al., 1995; Lancaster, 1995; Pye & Tsoar, 2009), can explain the relationship between overall bimodal palaeocurrent pattern and bedform orientation registered in the Troncoso Aeolian System record.

Relative chronology of cross-stratified set bodies
To analyse the internal relative chronology of set bodies within architectural complexes, a relative superposition order was built from the architectural panels (in a similar approach as Bristow et al., 2005, fig. 4). Because of the complexity of the stacking, at an early stage the chronology is divided, and each flank of the study section (north flank and south flank) has an independent chronology. As a result, each set body is identified by a letter (‘c’ for centre, indicating the initial chronology, ‘n’ for northern flank and ‘s’ for southern flank) and a number (Fig. 5).

The resulting chronostratigraphic scheme (Fig. 10) confirms that the oldest sedimentary bodies lie at the section core and indicates the general trend, already suggested by the architecture of the complexes and further confirmed by their distribution, that the record of the studied bedform was deposited from a core outward, forming what could be described as a concentric record. From Complex 1 into Complex 2, there is a noticeable asymmetry in this concentric distribution, the northern flank being the one with the most perceivable expansion in relation to the position of the dune core. On Complex 3 however, this asymmetry is reverted, the southern flank being the one that experienced the biggest expansion from the previous complex. The asymmetry in both complexes cannot be quantified precisely because of the discontinuous record in the northern flank.

Distribution of architectural complexes
The distribution of each architectural complex was analysed across a width-corrected study section, in order to better represent the actual dimensions in a transverse cut of the megadune. Over this corrected section, the general distribution of the complexes was mapped from the sedimentary logs and from virtual logs in the architectural panel (Fig. 11), which allowed for determining areal percentage occupied by each complex, measuring their width and height, contrasting the abundance in each sector, and establishing superposition relationships between the complexes.

Complexes 2 and 3 comprise almost the whole megadune record, combining for 99% of the section area. These complexes share the record in similar parts (Fig. 11). While Complex 2 is more abundant in the section centre, Complex 3 is far more abundant towards the megadune flanks. Each complex extends successively higher in the body of the preserved bedform and occupies a wider lateral section than the previous complex. Complex 1 has a corrected width of 50 m and a height of around 2 m; Complex 2 has a corrected width of around 350 m and a height of approximately 20 m; and Complex 3 has a corrected width of 860 m with a preserved height of 24 m. As such, the distribution of the complexes could be described as concentric, and this is yet further evidence of the bedform record being constructed from a core outward. At this point it is important to consider the distribution of marine reworking facies that overlie the study section, studied by Strömback et al. (2005) and mapped by Argüello Scotti & Veiga (2015). These facies are believed to have been formed by saturation and wave action during marine flooding, leading to collapse and remobilization of dune sand. They are nearly absent in the dune crest but are thickest in dune flanks and interdune sectors. Therefore, it is interpreted that aeolian sand remobilization from the crest to the flank sectors has reduced preserved bedform height and the relative volumetric importance of Complex 3, which accounts for its low proportion in the crest sector.

DISCUSSION

Conceptual development model of the studied megadune
This study demonstrates that each architectural complex has been formed by a phase in bedform development, in which a combination of a
specific bedform behaviour, growth and evolution resulted in a particular sedimentary architecture style. In this regard, the terms ‘evolution’, ‘behaviour’ and ‘growth’ are considered herein to refer to the long-term changes in shape, dynamics and scale of a bedform, respectively, while bedform ‘development’ is considered as the sum of the long-term changes over those variables. Each phase of bedform development can therefore be associated with specific bedform configurations. Overall, the deposits of the studied bedform record a story of gradual development through the configurations of a small seif dune, a large linear dune, a slipfaced linear megadune and finally a slipfaceless linear megadune (Fig. 12).

Analysis of Complex 1, indicates that the oldest registered phase of bedform development was characterized by the development of a small seif dune (probably also from an incipient bedform), a large linear dune, a slipfaced linear megadune and finally a slipfaceless linear megadune (Fig. 12).

Complex 2 represents the second phase in bedform development (Fig. 12B). The initiation of this phase is related to the evolution of a large linear dune from the previous small seif. This large linear dune had well-developed flanks and plinths and a more sinuous and mobile crest. Gradual growth of this bedform eventually allowed for superimposed dunes to develop on its flanks, evolving as a result into a slipfaced linear megadune. The change in the overall sedimentary architecture produced by this evolution was minimal because superimposed set bodies make up only 2% of the complex section area.

Complex 3 represents the third and final phase in bedform development, related to a slipfaceless linear megadune configuration within a deflationary context associated with the development of a sand drift surface (Fig. 12A).

Fig. 9. Deterministic models generated in BEDFORMS. Model 1 shows the resulting overall architecture from bedform development characterized by growth. Model 2 is a more detailed representation that shows the range of surface types expected in simple linear dunes. Both models show asymmetry in palaeocurrent bimodal distribution in relation to bedform trend. The higher-hierarchy surfaces that bound cross-stratified set bodies are formed by along-crest sinuosity migration. The lower-hierarchy surfaces that are found within cross-stratified set bodies are the result of cyclic variation in dune profile.
Factors that conditioned the sedimentary architecture of the studied bedform

The characteristics of the architectural complexes and their distribution (Figs 5, 8, 10 and 11) indicate that the preserved bedform had an overall consistent and dominant longitudinal behaviour throughout its recorded development. The action of lateral migration is evidenced by a certain degree of asymmetry in each complex (Figs 5 and 11). However, in all three complexes, evidence indicates that both flanks of the bedform were preserved, even under the effect of lateral migration. Considering that this bedform never produced accumulation (senso Kocurek, 1999), then the process that allowed both flanks to be preserved must be bedform growth (i.e. increment in bedform scale) and not accretion (i.e. rise in the accumulation surface). Therefore, during the development of the studied bedform, lateral migration rates were surpassed by the growth component. Even if growth in one flank wasfavoured in relation to the other, both flanks showed an overall long-term growth. From all of the above, bedform growth together with a dominant longitudinal behaviour were the crucial factors in shaping the sedimentary architecture of the preserved bedform, which notably matches some predictions made by Bagnold (1941, fig. 80) in his pioneering work.

It is likely that, after the bedform had stopped its growth as a megadune, a little component of lateral migration could have completely changed its sedimentary architecture given sufficient time. However, such a lateralmigration rate should have been consistent and sustained through the extended periods of time that these bedforms need to reach equilibrium with environmental conditions (which are rarely achieved). In this case, marine flooding of the Troncoso Sand Sea hindered further development of this bedform.

Since the genetic link between different types of linear aeolian bedforms has been mostly inferred, and rarely documented (Warren, 2013), the studied record provides an exceptional example of the evolution between different types of aeolian linear bedforms during the development of a large linear megadune. It documents the link between small seif dunes, large linear dunes and linear megadunes and, in particular, the scale at which the transition between a simple dune and a megadune occurs, that is as the bedform width reaches 300 to 400 m.

Sinuosity migration surfaces: a bounding surface type for simple linear dunes

Detailed analysis of the architecture of Complexes 1 and 2, together with the lessons learned from deterministic models, highlight that the internal architecture of simple sinuous linear dunes can be characterized by the predominance of bounding surfaces generated by the longitudinal (along-crest) migration of the bedform sinuosity. These surfaces had already been predicted
Fig. 10. (A) Chronostratigraphic scheme based on architectural panel a–a’. The cross-stratified set bodies are ordered in time according to a likely order of relative superposition. The set bodies have upper erosive unconformable surfaces, indicated by cross-stratification truncation, and lower depositional conformable surfaces, indicated by cross-stratification downlap and therefore time transgressive. Interpreted phases of bedform development and their associated bedform configurations are shown in time. Note the fragmentary nature of the bedform record and the gradual expansion of the preserved set bodies from a core outward. (B) Chronostratigraphic scheme of the Station Dune, Namibia Sand Sea, from Bristow et al., 2005. Note the shifting nature of the deposition preserved in the bedform record, strikingly different from the studied Troncoso bedform.
and registered by several studies of linear dune architecture and behaviour (Tsoar, 1983; Rubin, 1987; Bristow et al., 2000; Rubin et al., 2008). The term ‘sinuosity migration surfaces’ is suggested in this study to refer to such bounding surface types.

The particular characteristics of this bounding surface type are dip-azimuths which are oblique to the palaeocurrent directions of the set bodies they bound and strikes subparallel to the bedform orientation (Fig. 9). If both flanks of the bedform are preserved in the rock record, then two modes of surface dip-azimuths will be recorded. The angle between these two modes will probably be a high obtuse angle and each dip-azimuth mode will be dominant in the respective flank of the bedform record. If, on the other hand, only one flank of the dune is preserved due to a predominance of lateral migration, the dip-azimuth distribution of the preserved surfaces will have only one clear mode. In the context of autocyclic surfaces generated by aeolian bedforms, the hierarchy of sinuosity migration surfaces is lower than that of interdune migration and superimposition surfaces, and higher than that of reactivation surfaces. This surface type introduces a remarkable complexity into the deposits of a simple linear dune, and its impact upon identification and sedimentary heterogeneity characterization in this type of deposit must be highlighted.

Estimating bedform orientation from the strike of this bounding surface, although a much more accurate indicator than palaeocurrent orientation, must be exercised with caution. Because the two modes of dip-azimuths are not bipolar, one must choose the strike of one of the modes, or perform the bisector between the two. In this regard, more theoretical and field work is needed to determine the causes that lead to a non-bipolar bounding surface dip-azimuth distribution.

Factors conditioning the sedimentary architecture of linear bedforms

As with any other bedform type, behaviour, growth and evolution are major factors that condition the sedimentary architecture of aeolian of linear bedforms (alongside, for example, the relative motion of the accumulation surface). However, some of the discussed factors gain or lose relative importance for this particular bedform type.

What this case study in particular suggests is that bedform growth can be an important conditioning factor in the long-term development of linear bedforms, and particularly critical in shaping its internal sedimentary architecture. Growth exponentially reduces the lateral migration rate of a linear bedform by reducing its surface/volume relationship. Furthermore, as growth does not potentially impact along-crest sand transport, it should favour a longitudinal bedform behaviour. In other words, growth has a considerable impact in behaviour (i.e. long-term dynamics). This probably indicates that, as linear bedforms reach large dune and especially megadune-scale sizes, lateral migration rates can become so low that its influence over the preserved internal architecture could be greatly overshadowed by other factors. In the far more mobile transverse ridges (sensu Rubin & Hunter, 1985), any effect of a growth
component will not produce a lasting impact in the sedimentary architecture, due to their higher migration rates.

Finally, it must also be considered that the parameters associated with bedform development are ultimately controlled by the larger dune field self-organization, which dictates the bedform pattern of the system (Kocurek & Ewing, 2005). This can explain why the record of adjacent linear bedforms (or even the record of the same bedform along its extension) can be quite different, as seen in the many dunes studied in the northern extreme of the Namib Sand Sea (Bristow et al., 2000, 2005, 2007).

Fig. 12. Conceptual model for the development of the studied megadune. The diagrams show the phases of bedform development, characterized by certain bedform configurations, inferred to be responsible for the deposition of the architectural complexes. This model matches the model presented by Bristow et al. (2000), developed from a modern bedform, which bears a strong similarity in overall sedimentary architecture.
Models of linear bedform sedimentary architecture

Considering previous case studies and the example provided in this study, assigning a simple model of the expected sedimentary architecture for sandy, aeolian linear bedforms is far from a simple task. The overall internal architecture of aeolian linear bedforms, however, can be considered to vary between two opposite extremes (Fig. 13): (i) a concentric or quasi-symmetrical style, where the oldest deposits are found in the bedform core (likely modern example in Bristow et al., 2000; ancient example in this case study); and (ii) an asymmetrical style, where the oldest deposits are found in one of the flank’s extremes (modern example in Bristow et al., 2005; ancient example in Scherer, 2000). This differentiation can be made for the deposits of both simple and compound/complex bedforms. Bounding surface’s dip-azimuths would be bimodal and dependent upon their position in the concentric style, while they would be unimodal and evenly distributed in the asymmetrical counterpart. In the latter case, palaeocurrent distribution can be very similar to that of transverse bedforms (Rubin & Hunter, 1985), and therefore further evidence must be used for recognition of the bedform type (Besly et al., 2018). In the concentric style, the architecture is likely to have been strongly conditioned by a sustained and consistent lateral migration. This scheme departs from earlier classifications by using a descriptive terminology, independent from the possible mechanisms that may have shaped the sedimentary architecture and from the simple/compound/complex nature of the originating bedform.

Rubin & Hunter (1985) made it clear that the natural conditions necessary for accretion of a bedform pattern of linear dunes that would allow preservation of both flanks (a concentric style of architecture) in the geological record, are very specific (for example, a climbing angle of at least $30^\circ$), and would be extremely uncommon and restricted spatially. Therefore, an asymmetrical style of sedimentary architecture would be expected for linear bedforms under normal preservation conditions. However, following an aeolian sequence stratigraphic conceptual framework (Kocurek, 1999), preservation can occur without accumulation (i.e. rise in the accumulation surface), usually referred to as exceptional preservation (a frequent scenario for ancient deposits of linear bedforms; for example, Entrada Sandstone, Lower Permian Yellow Sands, Botucatu Formation and Troncoso Inferior Member). In these cases, since bedform climb is not accounted for, both asymmetrical and concentric styles of sedimentary architecture could be common. Therefore, the Troncoso example confirms that in cases of bedform topography preservation, the conditions...
CONCLUSIONS

The methodology followed in this paper was successful in identifying significant differences within the sedimentary architecture of a preserved linear bedform exposed in a natural section of the ancient Troncoso Sand Sea. These differences allowed for the identification of three sedimentary architecture styles or architectural complexes. These were demonstrated to be formed by genetically related cross-stratified set bodies and bounding surfaces, associated with a specific phase in bedform development in which bedform evolution, behaviour and growth resulted in a relatively homogeneous style of sedimentary architecture.

A conceptual model for the development of the studied preserved bedform was presented, composed by three phases. Phase one comprises a possible incipient bedform (dune dome or seif dune tip) evolving into a small linear seif. Phase two represents the development of a large linear dune that evolves into a slipfaced linear megadune. Finally, phase three is characterized by a slipfaceless linear megadune coincident with the final preserved morphology of the bedform. The assumptions made in this model are based on evidence from previous modern dune studies, most notably by Tsoar (1982) and Bristow et al. (2000).

Development of the studied bedform was characterized by sustained growth and a dominant longitudinal behaviour, which were the key parameters shaping its final internal architecture, while the lateral migration component in bedform behaviour was never a critical factor. Preservation of bedform evolution provided a unique example to document the link between different types of linear bedforms.

Characterization of the bedform’s record allowed a discussion of which parameters are most critical in shaping the sedimentary architecture of linear bedforms. It suggests that growth can be an important factor for this bedform type given the low migration rates, which become exponentially lower as bedforms increase their size.

Finally, linear bedform deposits can be characterized by two contrasting styles of sedimentary architecture: a concentric style and an asymmetrical style. In the former, the oldest deposits are found in the bedform core while, in the latter, the oldest deposits are found in one of the flank’s extremes. While a concentric style is more likely to be the result of bedform growth coupled with a strong longitudinal dynamic, the asymmetrical type is most likely to be conditioned by consistent lateral migration as a result of a weak longitudinal dynamic or oblique dynamic.

Since a concentric style of architecture generated by accretion requires conditions regarded as very unlikely in nature (Rubin & Hunter, 1985), an asymmetrical style of architecture is expected in cases of linear dunes that underwent net accumulation. In exceptionally preserved records, however, the occurrence of a concentric style of architecture may be much more common than previously thought.

ACKNOWLEDGMENTS

This research was funded by the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET-PIP 112-201101-00322) and through a co-operation agreement between YPF S.A. and the Centro de Investigaciones Geológicas (UNLP-CONICET). The authors are grateful to the insightful comments and suggestions made by Associate Editor Nick Lancaster, reviewers Juan Pedro Rodriguez-Lopez and Charlie Bristow, and to two anonymous reviewers. Nicolás Scivetti and Joaquín Bucher’s very valuable assistance in the field is greatly appreciated.

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Manuscript received 15 April 2018; revision accepted 6 March 2019

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