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Parabolic megadunes in a subtropical Quaternary inland dune field, southwestern Pampas, Argentina

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ABSTRACT

The Utracán paleo-dune field (La Pampa Province, Argentina, southern South America) was examined by remote sensing, morphometric analyses and field surveys as a case study of complex megadunes of inland deserts. The paleo-dune field is within the Utracán-Argentino valley, one of the transverse valleys of La Pampa Province excavated into a regional structural plain. Similar paleo-dune fields occur within these valleys. Utracán dunes are mostly stabilized by grasses, deeply disturbed by cattle grazing and agriculture. The paleo-dune field is formed by complex parabolic megadunes with superimposed dunes. Parabolic megadunes present lengths of trailing arms of 3.3–12.9 km, widths between them of 2–2.9 km and heights of 7–38 m. The position of the dune noses at the northeastern tip of the bedform and measured SW-NE orientation of arms indicate a mean transport direction to azimuth 68.2°. Above the parabolic arms, and isolated in the paleo-dune field, there are compound blowout dunes (clusters of several blowouts forming a larger bedform). They show the depositional lobes to the NE, with a measured mean transport direction to azimuth 58.1°. The SW-NE longitudinal length varies between 324 and 1302 m and the NW-SE transverse length between 114 and 622 m. Other parabolic arms show low (<3 m) barchanoid dunes, with crest lengths of 48–811 m, a mean crest spacing of 74 m and a transport direction to azimuth 28.2°. The paleo-dune field also shows smaller, simple parabolic and blowout dunes. We hypothesize that the parabolic and blowout dunes are the basic bedforms that emerged under the boundary conditions of the Utracán dune field, related to a high sediment supply coupled with a partial vegetation cover, in a valley that provided accommodation space by means of well-defined depression and wind deceleration due to a change in the longitudinal valley slope direction. The west-to-east spatial progression of dune morphologies along the Utracán-Argentino valley, the general transport direction of dunes to the NE, and the petrographic sand composition allow us the infer that the transverse valleys of La Pampa Province worked as sand transport pathways. These pathways transferred fine to very fine sand from the eastern Andean piedmont to the Pampean plain, likely during the Quaternary.

1. Introduction

Giant dunes or megadunes (Pye and Tsoar, 2009: p.176), reaching 200–300 m in height and >500 m crest spacing (Goudie, 2004), are common geomorphological features in many aeolian systems; they were originally named "whalebacks" by Bagnold (1954). Later on, Wilson (1972) applied the term "draas" (a North African name for a large sand hill) to the largest dunes in a dune field. Systematic remote sensing surveys have revealed the world-wide occurrence of megadunes (Wilson, 1972; Breed and Grow, 1979), both in sand seas (Lancaster, 1988a; Warren and Allison, 1998; El-Sayed, 2000; Yang et al., 2003, 2011; Dong et al., 2004, 2009; Bishop, 2010; Liu et al., 2016) and inland dune fields (Havholm and Kocurek, 1988; Tripaldi, 2002, 2010). More recent analysis has employed digital elevation data (Shuttle Radar Topography Mission, SRTM) to recognize and study megadunes (Blumberg, 2006; Bubenzer and Bolten, 2008). These studies reveal that megadunes and small dunes create regular patterns with different morphologies, like crescentic (barchans, barchanoid ridges and transverse) and linear bedforms.

Megadunes frequently show the superimposition of smaller dunes, which are then called compound or complex dunes if the superimposed dunes present the same or different morphology, respectively (McKee, 1979). Havholm and Kocurek (1988) suggested using draa as a purely morphological term for those aeolian bedforms having superimposed dunes. More recently, Pye and Tsoar (2009) recommend applying the

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term megadunes to very large dunes, independently of whether they are simple, compound or complex.

By means of morphometric analysis of dunes in the Namib and Gran Desierto dune fields, Lancaster (1988b) reprised the hierarchic scheme of draas, dunes and ripples of Wilson (1972), suggesting they denote distinctive sand-transport rates. Draas respond to long-term, regional patterns of sand transport and deposition, whereas simple dunes, including those superimposed over draas, reflect contemporary rates and directions of sand transport (Lancaster, 1988b). More recently, Andreotti et al. (2009) tested field measurements of aeolian dunes from different desert regions with atmosphere conditions and aerodynamic calculations, correlating the size of giant dunes to the depth of the atmospheric boundary layer.

The concept of megadunes is, then, not merely a matter of the size of the aeolian landforms but also of the evolutionary history and dynamics of a dune field. Wilson (1972) interpreted the large and generally complex landforms as a response to a long-lasting development of the aeolian systems, suggesting megadunes would need thousands of years to be formed. Lancaster (1992) proposed that most dune fields experienced a long history of construction, stabilizations and reactivations, eventually producing complex patterns of different size dunes, each one representing a dune generation. In the Wahiba Sands of Oman, Warren and Allison (1998) also described hierarchically-grouped aeolian dunes and, although they considered dune size to be a function of many factors, megadunes mainly respond to wind regimes that persist for long periods. The luminescence dating of aeolian sediments in some dune fields allows validation of this hypothesis of composite bedforms representing multiple periods of construction (e.g. Kocurek et al., 1991; Stokes and Bray, 2005; Beveridge et al., 2006; Bristow et al., 2007; Mason et al., 2011).

Southern South America, particularly the central region of Argentina, shows an extensive Quaternary aeolian cover, at present mainly stabilized, that blankets the Andean piedmont, the Pampean plain (Pampean Sand Sea; Iriondo, 1990; Iriondo and Kröhling, 1995) and northernmost Patagonia (Fig. 1). With the aim of systematizing the study of these deposits, the aeolian system of central Argentina was subdivided into eight morphological units, a classification based on the nature of the deposits, the dominant landforms and the geological-structural setting (Zárate and Tripaldi, 2012). The goal of this contribution is to analyze the Utracán paleo-dune field, located within the Western Pampas Sand Mantles and Dunefields (WPMD) unit (Fig. 1).

Fig. 1. General location of the study area in central Argentina (southern South America) and the units of the aeolian system of central Argentina (after Zárate and Tripaldi, 2012): APD: Andean piedmont dunefields, WPD: Western Pampean dunefields, WPMD: Western Pampas sand mantles and dunefields, CPD: Central Pampean dunefields, SLM: Sandy loess and loessial sand mantles, LMB: Loess and loess-like mantles and blowouts, LLM: Loess and loess-like mantles, PPMD: Northern Patagonia and Southern Pampean sand mantles and dunefields; 'r' denotes River, e.g. San Juan r. is San Juan River.

A particular feature of the Utracán paleo-dune field is the presence of a complex dune pattern with parabolic megadunes and superimposed dunes. Although parabolic dunes are common landforms in many coastal and inland dune fields (Goudie, 2011) the occurrence of parabolic megadunes has been barely mentioned, and only in coastal settings (Pye, 1993; Bailey and Bristow, 2004). The identification and interpretation of the different dune patterns that comprise a dune field was recognized as a crucial tool to design chronological studies for reconstructing the Quaternary history of dune fields (Stone and Thomas, 2008; Thomas, 2013; May, 2013). Therefore, the analysis of dune morphology in the Utracán paleo-dune field is a first and necessary step to studying the paleoenvironmental evolution of this aeolian system. Future challenges are, among others, to calibrate the chronology of the aeolian events that built this dune field. The purpose of this study is the characterization of megadunes developed in an inland setting (i.e. the aeolian system of central Argentina) to infer their genesis and dynamics. To accomplish the proposed objectives, a morphometric and spatial characterization of dunes and megadunes of the Utracán paleo-dune field is reported. The dominant aeolian bedforms, parabolic and blowout dunes, are considered the main attractors (sensu Werner, 1995) that emerge under the boundary conditions of this dune field, organizing the transport of sand at different scales (dunes and megadunes). The sand composition and dune transport direction suggest the transverse valleys are aeolian sand transport pathways, transferring fine-very fine sand eastward, from the source area in the Andes piedmont to the Pampean plain.

2. Study area

2.1. Geologic setting

The study area is mainly situated in the La Pampa Central tectonic block (Folguera and Zárate, 2011, 2018), a morphostructural unit made up of Precambrian and Paleozoic rocks covered by a late Miocene, 150–200 m thick, continental succession capped by a calcrete crust (Cerro Azul Formation; Linares et al., 1980; Verzi et al., 2008). The resulting landscape consists of a structural plain, gently sloping eastward, characterized by the occurrence of several SW-NE depressions, known as transverse valleys, excavated into the late Miocene unit (Calmels, 1996; Fig. 2a). To the southwest another morphostructural unit, the Chadileuvú block (Ramos and Cortés, 1984), is present, composed of a Precambrian–Paleozoic bedrock with a significant record of Permian–Triassic magmatic activity (Choiyoi Group), outcropping mainly at the Lihuel Calel Ranges.

The landscape is covered by Quaternary aeolian deposits; their general characteristics were reported by Visconti (1986), Calmels (1996), and Szelagowski et al. (2004). The chronology of the dune fields of La Pampa province is barely known, with few dates reported of Holocene aeolian deposits (Kruck et al., 2011; Mehl et al., 2012). Two stratigraphic aeolian units were identified by Szelagowski et al. (2004), the lower one is the most extensive and likely deposited during the Late Pleistocene-Holocene. It is covered by sand deposited by the aeolian reactivation that occurred during the early 20th century.

The aeolian unit studied herein is characterized by well-sorted, fine sand forming two main aeolian landscapes: sand sheets covering the structural plain and dune fields within the transverse valleys (Zárate and Tripaldi, 2012). One of these dune fields is the Utracán paleo-dune field, located within the Utracán-Argentino valley (Fig. 2b). This valley is 10 km wide, up to 100 m deep, and >100 km long. Surface runoff is mainly endorheic to lakes of variable size, located within the dune landscape, and in the valley margins (e.g. Utracán saline lake, Fig. 2b), with no rivers but few, up to 1-kmlong, ephemeral streams (Terraza et al., 1981)

2.2. Climatic and environmental setting

The study area is situated in a region characterized by a temperate semi-arid climate, with a mean annual temperature of 15 °C, a similar value of average thermal amplitude between the coolest and the warmest month (Cano, 2004). The central region of Argentina presents a NE-SW precipitation gradient, as a result the annual rainfall along the Utracán-Argentino valley varies from 750 mm in the eastern sector to 600 mm to the west (data for 1961–2000 CE; Díaz Sorita et al., 1998).

Rainfall is seasonal and concentrated during the austral spring-summer months (70–80% of precipitation from October to March, Fig. 3a) regulated by the South American Monsoon (Vera et al., 2006). The region exhibits a water deficit throughout the year, between 200 and 300 mm annually along the Utracán-Argentino valley, mainly concentrated during the austral summer months when maximum temperatures can reach up to 45 °C (Cano, 2004).

The wind rose for General Acha weather station (Fig. 2) (for the period 1985–1989 CE) indicates a strong mode of NE wind and several secondary wind components from the SE to the NW (Fig. 3b).

The natural western Pampas vegetation, at present deeply disturbed by cattle grazing and agriculture (Viglizzo et al., 1995), is a xerophytic woodland (Espinal phytogeographic province; Cabrera, 1976). It originally showed a savanna-like aspect including trees (mainly *Prosopis caldenia* - caldén) and a psammophitic grassland of *Elyonurus muticus* (pasto amargo), *Hyalis argentea* (olivillo), *Aristida mendocina* (flechilla crespa) and *Panicum urvilleanum* (tupe). A xerophytic shrubland of, mainly, *Larrea divaricata* (jarilla), *Condalia microphylla* (piquillín) and *Prosopis alpataco* (alpataco) covers the western area of the study region (Cano, 2004).

3. Materials and methods

The study included remote sensing analysis, stereoscopic examination of aerial photographs, field (in situ) survey, and morphometric analysis of dune patterns. We used orthorectified Landsat scenes (Path228-Row086, acquired at 03/28/2000 and 04/03/2005; spatial resolution 30 m), with different band combinations (mainly RGB 742 and 357), and digital elevation data from the SRTM-C (spatial resolution 1″arc = 90 m, vertical resolution 16 m), and the MDE-Ar (spatial resolution 1″ arc = 30 m, vertical resolution 16 m). The MDE-Ar is a product obtained by correction (ground control points), void filled and filtering of the SRTM-X data performed by the National Geographic Institute of Argentina (Instituto Geográfico Nacional) (IGN, 2016). Aerial photographs (1:35,000 scale) are from year 1962. SRTM data permitted the examination of the topographic variation along regional transects of the Utracán-Argentino valley, the location of the different dune morphologies in relation to the local relief, and the construction of topographical outlines of the measured bedforms.

The morphometric analysis of the different dune morphologies was done following Breed and Grow (1979) and Ewing et al. (2006). The Landsat images and the aerial photographs were overlaid upon the digital elevation data using GIS software, to assist in the characterization, measurement and interpretation of the aeolian bedforms. Google Earth® images, with higher resolution than Landsat ones, allowed measurement of the small dunes.

Morphometric quantification of megadunes included the measurement of length (maximum distance along the trailing arms), width (distance of the transverse line joining the two more distant points), and height (maximum height in MDE-Ar data) (Fig. 4a). The transport direction, indicated by the orientation of the trailing arms, was measured according to its azimuth (Fig. 4a).

Morphometry of blowout dunes consisted of measurement of the longitudinal and transverse lengths, parallel and perpendicular to the interpreted transport direction, respectively (Fig. 4b). The position of the deepest part on one side, and the peripheral depositional lobe on the opposite one allowed us to interpret the transport direction (measured by azimuth) (Fig. 4b). In the barchanoid dunes the length, spacing and transport direction (perpendicular to the crest line) were measured (Fig. 4c).

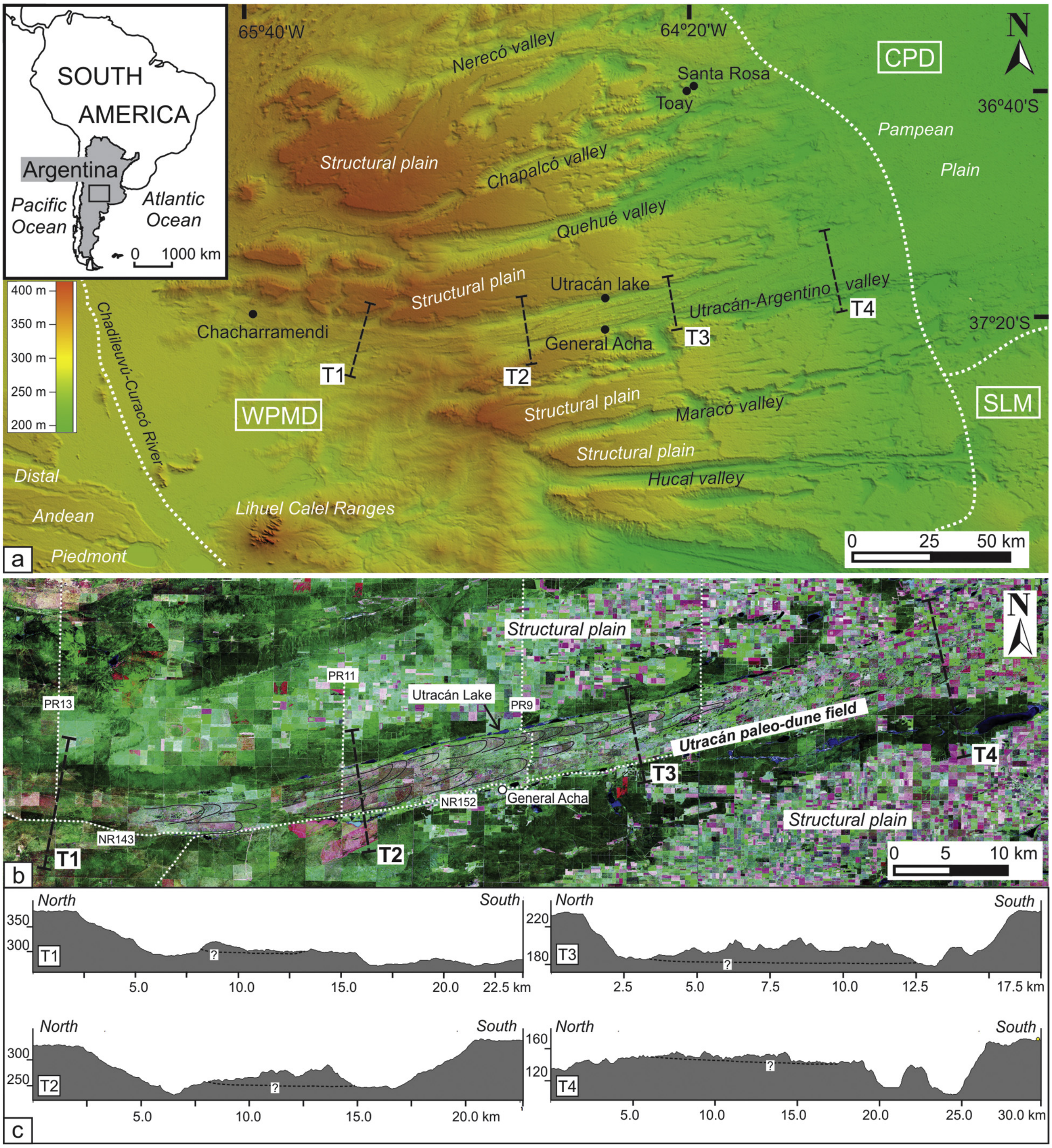

Fig. 2. Location map of the Utracán paleo-dune field in the Utracán-Argentino valley: a) SRTM-C digital elevation data showing the transverse valleys of La Pampa Province, excavated into the structural plain of the La Pampa Central Block and main localities mentioned in the text; white dotted lines mark the aeolian units (after Zárate and Tripaldi, 2012) (see Fig. 1); b) Landsat ETM+ image (RGB 742, image acquired on 2002–18-11) of the Utracán-Argentino paleo-dune field with parabolic megadunes outlined in black, white dotted lines are National (NR) and Provincial (PR) routes; c) topographic profiles (in meters based on SRTM-C digital elevation model) along four north-south transects (T1 a T4 of Fig. 1b), the dotted lines outline the lateral extent of aeolian sand as seen on Landsat images.

Field examination of dune morphology and geomorphic-geologic setting characteristics was undertaken on 40 sites along an *E*-W transect (along national routes 152 and 143, between 64° 17′W and 65° 40′W; Fig. 2b), and in three ways cutting N–S through the valley (along the provincial routes 9, 11 and 13; Fig. 2b). Each site was located by GPS to allow the evaluation of features recognized in the field by remote sensing imagery.

Wind data obtained from General Acha weather station (the nearest station located in the Utracán-Argentino valley, Fig. 2a,b) was analyzed following the method of Fryberger (1979). Wind velocity was measured three times a day, from January 1, 1985 to December 31, 1989, in 36 directions (source: Servicio Meteorológico Nacional).

4. Results

4.1. Wind analysis

The analysis of wind velocity by the method proposed by Fryberger (1979), commonly used in aeolian research, is a useful tool for evaluating the potential and resultant direction of sediment transport by wind,

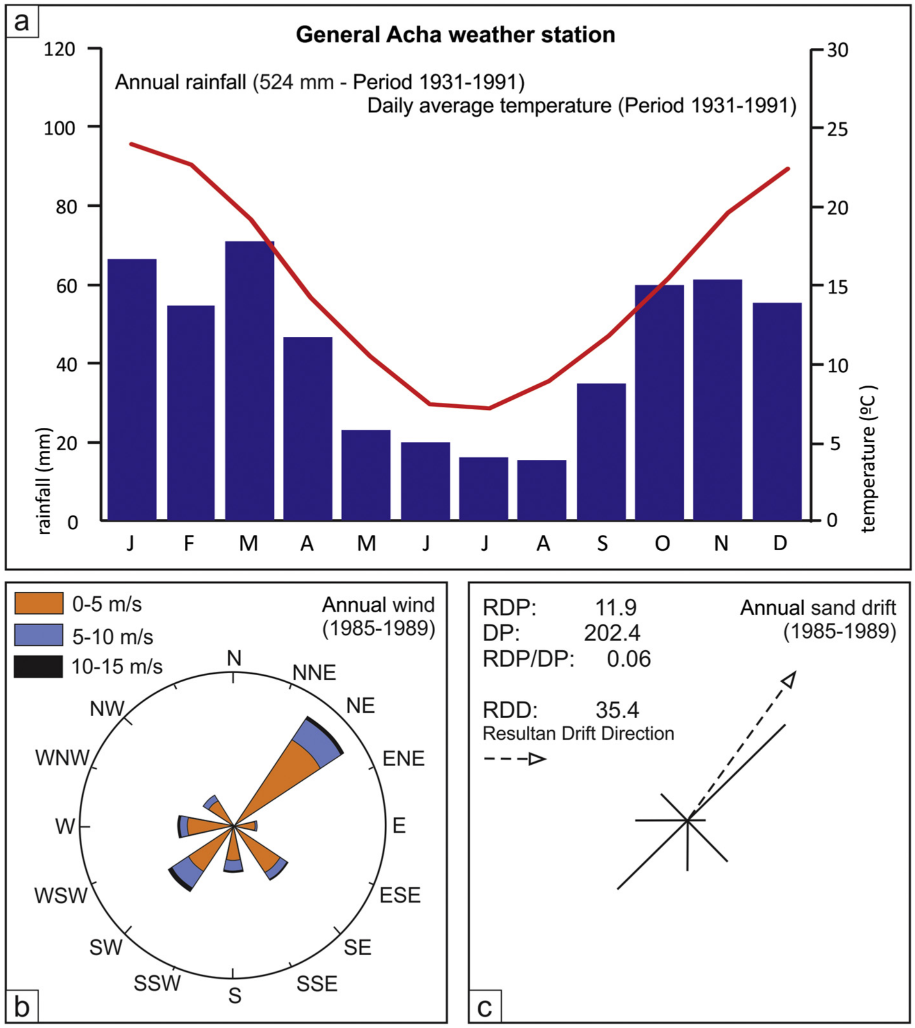

Fig. 3. Climatic condition of the study area: a) daily mean temperatures along the year and annual rainfall pattern (for the period 1931–1991 CE); b) wind rose based on three times a day measurements of wind velocity (for the period 1985–1989 CE); c) annual sand drift potential from vectorial analysis of wind velocity (following Fryberger, 1979); RDP: resultant drift potential, DP: drift potential, RDD: resultant drift direction. All data from General Acha weather station (location in Fig. 2).
(Source: Servicio Meteorológico Nacional, Argentina).

and for comparing wind regimes of different regions. This method estimates the relative rates of sand transport (amount and direction), based on a statistical-vectorial analysis. The employed formulas make assumptions about the surface conditions (mean grain size, surface roughness, amount of vegetation, sand moisture content) and uses a threshold wind velocity of 6.8 m/s at 10 m above the ground (standard height of wind velocity measurement).

Even when the wind rose of General Acha locality indicates dispersed wind directions (Fig. 3b), the vectorial analysis reveals a resultant drift direction (RDD) of 35.4° (Fig. 3c), that expresses a net trend of sand drift to the NNE-NE. The drift potential (DP = 202.4) suggests a setting close to the boundary conditions between low and intermediate energy environments, according to the classification made by Fryberger (1979: 150).

4.2. Dune morphology

The Utracán paleo-dune field is characterized by a variety of aeolian landforms of diverse sizes and morphologies, mainly parabolic, blowout and barchanoid dunes, grouped into a complex aeolian pattern. The dunes are mostly stabilized by a vegetation cover of grasses and woodlands in patches, with shrubs to the western area. This dune pattern is concentrated along the Utracán-Argentino valley, while aeolian sand overlaps the northern side of the valley margin, in some places forming small, isolated parabolic dunes.

4.2.1. Parabolic megadunes

Remote sensing analysis allows the identification of a regular aeolian pattern composed of several kilometer-long landforms (Figs. 2b, 5). A parabolic morphology is inferred by the presence of an apical sand mound or "nose", from where two long trailing arms stretch out (Fig. 5b, d). Longitudinal topographic profiles along these elements, built with SRTM-C digital elevation data, show the characteristic configuration of the parabolic dunes with a downwind sand accumulation or nose (Fig. 5c, e).

The parabolic megadunes are characteristic not only of the Utracán-Argentino valley but also of other transverse valleys of La Pampa Province (Fig. 2). In the Utracán-Argentino valley, at least 23 megadunes are recognized, some of them overlap one after the other, forming chains of consecutive noses and long arms (Fig. 5a).

The described parabolic pattern of all the recognized large bedforms ($N = 23$) is made up of dunes with a mean length of 6.7 km and minimum and maximum values of 3.3 km and 12.9 km, respectively (Fig. 6). These bedforms are 1.2 km to 2.9 km wide (mean value of 2 km), the highest top varies between 7 and 38 m (mean value of 18.8 m, Fig. 6). The dunes show a uniform orientation, with trailing

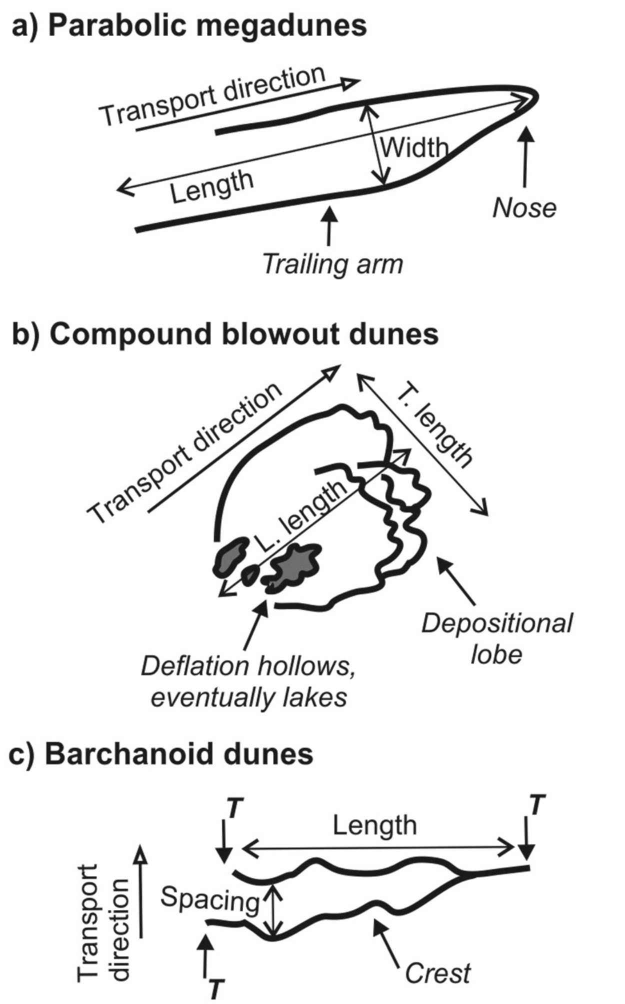

Fig. 4. Diagram of the morphometric parameters measured in the dunes of the Utracán paleo-dune field. Transport direction of each dune indicated by azimuth, in b) L. length and T. length are longitudinal and transverse lengths, respectively; in c) T is crest termination.
(after Ewing et al., 2006).

arms extending SW-NE and the dune noses to the NE. The measurement of these orientations indicates a mean transport direction to azimuth 68.2° (correlation value $R = 0.99$; Fig. 6).

The occurrence of superimposed smaller dunes on the megadunes is identified when Landsat images and aerial photographs are overlapped on SRTM data (Fig. 7). Compound blowout dunes mostly appear above the longitudinal arms, barchanoid dunes above arms or noses, whereas simple blowout dunes and simple parabolic dunes are present between the arms (Fig. 7b–d).

Several of the parabolic megadunes show a N–S topographic asymmetry, with a higher and wider southern arm, and a lower and thinner northern arm (Fig. 7c). The southern arms reach between 25 and 38 m above the marginal lakes level, and are characterized by superimposed barchanoid dunes (Fig. 7c,e). Compound blowout dunes are present over the northern arms, with a 5–15 m-relief above the regional valley floor (Fig. 7c,d).

The parabolic megadunes of the Utracán paleo-dune field are comparable to the vegetated and complex parabolic dunes described in North Queensland coastal dune fields (Australia; Pye, 1993). The Australian parabolic dunes, reaching >6 km in width and 10 km in length, consist of broadly parabolic-shaped sand ramps upon which there are superimposed transverse ridges and small barchans (Pye, 1993).

4.2.2. Blowout dunes

Blowout dunes are characterized by a depression formed by deflation of a pre-existing sand deposit, and sand is then deposited in a bordering depositional lobe; they are very common in coastal and inland aeolian environments (Hesp, 2002).

In the Utracán paleo-dune field blowout dunes appear as isolated and small (few tens of meters in diameter) deflation hollows, and as clusters of several blowouts forming a larger bedform. This second pattern is classified as compound blowout dunes (sensu McKee, 1979: 13) (Fig. 7d). They occur mainly on the northern arms of the parabolic megadunes, but also over the nose area (Figs. 7b, 8). The blowout sides have steep slopes, especially the inner walls which are generally devoid of vegetation. The large blowouts create an irregular, meter-scale relief, and, at present, several of these depressions are occupied by temporary or perennial lakes due to the water table intersecting the surface.

The dimensions of the compound blowout dunes measured in 50 bedforms (Fig. 8) show large sizes, with longitudinal length (oriented SW–NE) between 324 and 1302 m (mean length of 595 m) and transverse length (NW–SE) between 114 and 622 m (mean length of 299 m, $N = 50$; Fig. 9). The measurement of blowout orientations exhibits low dispersion values and suggests a resultant sand-transport direction to azimuth 58.1° (correlation value $R = 0.99$; Fig. 9).

4.2.3. Barchanoid dunes

A group of irregular dunes with discontinuous crests is superimposed on the parabolic megadunes (Fig. 7e). They are low dunes (<3 m), with crest lengths between 48 and 811 m, a mean dune spacing of 74 m (N = 50; Figs. 3, 8, 9), and without a clear asymmetric profile. However, the field survey and the inspection of several dunes on satellite images and aerial photographs permit us to infer the presence of lee slopes facing to the NE, with a mean transport direction to azimuth 28.2° (Fig. 9). Based on these features they are classified as barchanoid dunes (sensu McKee, 1979: p.10–11).

4.2.4. Simple parabolic dunes

The western sector of the Utracán paleo-dune field, from the area of the Chacharramendi locality to around the location of transect T1 (Fig. 2a), presents an irregular and low relief sandy landscape (aeolian sand sheet; Pye and Tsoar, 2009). Field survey shows the presence of small mounds, without lee faces and covered by bushes, resembling coppice dunes (Melton, 1940; Pye and Tsoar, 2009). Remote sensing analysis of this area reveals a series of parabolic dunes with different degree of development. These parabolic dunes have very thin (<100 m-width) and relatively long (tens of meters to few kilometers) arms, some of them can reach up to 2.5 km in width.

Some stabilized parabolic dunes are also associated to the low area between the arms of the parabolic megadunes (Figs. 7c, 8). This pattern is better identified in aerial photographs or satellite images than in the field, especially the images taken during humid periods when elongated lakes developed between the arms.

4.3. Distribution of the dunes along the Utracán-Argentino valley

The described complex dune pattern of the Utracán paleo-dune field, with parabolic megadunes and superimposed blowout and barchanoid dunes, is concentrated where the Utracán-Argentino valley is confined and forms a well-defined topographic depression, limited at both sides by the structural plain. This configuration is illustrated by topographic profiles from the SRTM-C elevation data (transect T2 and T3, Fig. 2c). This segment starts about 25 km westward of T2 and ends about 10 km eastward of T4.

From the surroundings of the Chacharramendi locality, where the valley is partially confined (transect T1 in Fig. 2), the aeolian deposits become perceptible, associated with a poorly sorted colluvial cover of silty sand to gravel. Eastward, the aeolian sand cover gets progressively

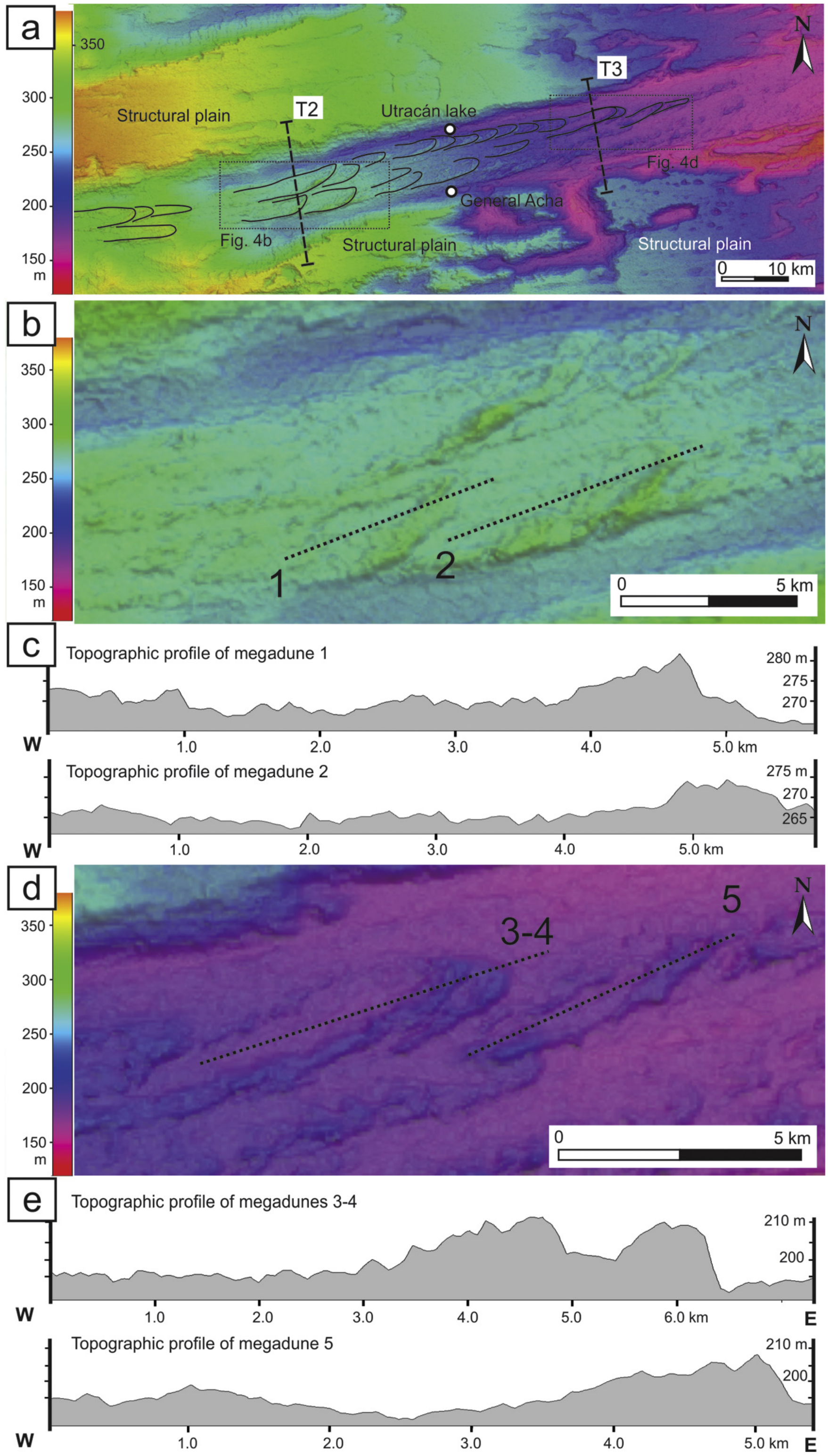

Fig. 5. a) Parabolic megadunes (outlined in black) of the Utracán paleo-dune field in the MDE-Ar digital elevation model; T2 and T3 are transects indicated in Fig. 2; b) detail of parabolic dunes at transect T2; c) topographic profiles of megadunes 1 and 2 of panel b; d) detail of parabolic dunes at transect T3; e) topographic profiles of megadunes 3–4 and 5 of panel d. Heights in m, based on SRTM-C data.

more continuous, with sand sheets and, from about the location of transect T1 (Fig. 2a), simple parabolic and blowout dunes appear.

On the eastern tip of the Utracán-Argentino valley, roughly coincident with the area where the valley loses depth (transect T4 in Fig. 2), the paleo-dune field grades into a low-relief aeolian mantle with small blowout dunes. In this region, the aeolian component of the landscape does not completely disappear but the environment becomes a mixed fluvial-aeolian-lacustrine plain and the sand deposits spread northeasterly to other aeolian unit with linear and parabolic dunes (CPD unit in Fig. 1; Zárate and Tripaldi, 2012).

A main aeolian transport from west to east, along the Utracán-Argentino valley, is suggested by the transport direction of the analyzed

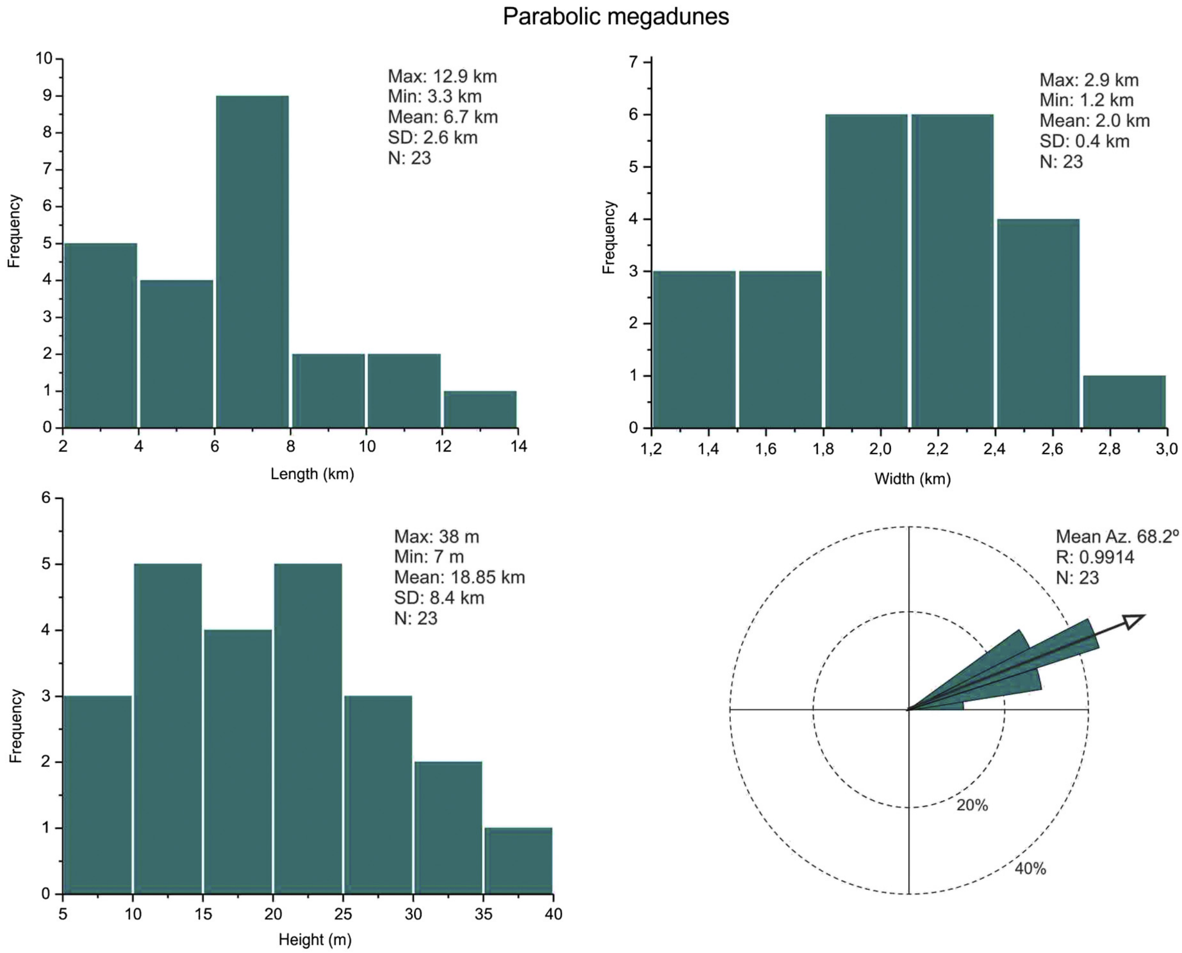

Fig. 6. Morphometric values (length, width, height and transport direction in azimuth) of the parabolic megadunes of the Utracán paleo-dune field (Max: maximum value; Min: minimum value; SD: standard deviation; N: number of measurements).

dunes: parabolic megadunes facing to azimuth 69°, superimposed compound blowout dunes to azimuth 58°, and barchanoid dunes to azimuth 28°; Figs. 6, 9). This transport direction coincides with the resultant drift direction (RDD 35.4°, Figs. 3c), obtained from the vectorial analysis of present (data for the period 1985–1989 CE) daily wind at General Acha weather station (location in Fig. 2a,b).

5. Discussion

5.1. Aeolian dynamics

The complex dune pattern of the inland Utracán paleo-dune field, formed by parabolic megadunes with superimposed compound blowout and barchanoid dunes, raise several questions related to the controlling factors of their formation and the relative chronology of the different dunes.

The existence of an adequate sand supply and the dominance of unidirectional winds have been pointed out as the main controls of parabolic dunes, together with a moderate vegetation cover (Yan and Baas, 2015, and references therein). The pivotal role of vegetation in parabolic dune formation is documented by their ubiquitous association. Even when vegetation causes some limitation in the capacity of winds to transport sand, the presence of a partial vegetation cover inhibits neither the migration nor the growth of these dunes. On the contrary, parabolic dunes always develop in relationship to some vegetation (Pye and Tsoar, 2009: p. 230) that anchors the arms while the noses move downwind (Hack, 1941), and determines the typical U-shape in plan-view. It is generally indicated that sand deflated from the central part is deposited along the arms, and the nose, but a further sand input from outside the dune field should not be ruled out (Pye and Tsoar, 2009).

Parabolic dunes are considered to result from the modification of a previous aeolian cover, either from the stabilization of barchan and transverse dunes or by the transformation of blowouts (Yan and Baas, 2015, and references therein). In the Utracán paleo-dune field simple parabolic and blowout dunes are common bedforms, whereas barchanoid dunes are less frequent and appear only above the parabolic megadunes. The Utracán parabolic dunes may be developed from blowout dunes, as it was reproduced by numerical simulations (Duran et al., 2008) and, among others, reported in the Canadian prairies (Barchyn and Hugenholtz, 2013).

By means of computer models, Werner (1995) finds dune fields are complex systems where dunes emerge due to a self-organizing behavior, and the different dune morphologies are dynamical attractors, representing steady states of broad range of initial conditions. Both properties, emergent behavior and existence of attractors, are characteristic of non-linear conditions like the transport of aeolian sand (Werner, 1995). We hypothesize that parabolic and blowout dunes may be the basic bedforms that emerged under the boundary conditions of the Utracán dune field, related to a high sediment supply coupled with a moderate vegetation cover and the wind deceleration, with the addition of adequate accommodation space due to the topographic configuration of the valley

In this sense, parabolic and blowout dunes are considered the main attractors of the Utracán paleo-dune field. Our conceptual model of dune field construction proposes that the aeolian system develops large-scale bedforms (compound blowout dunes and parabolic

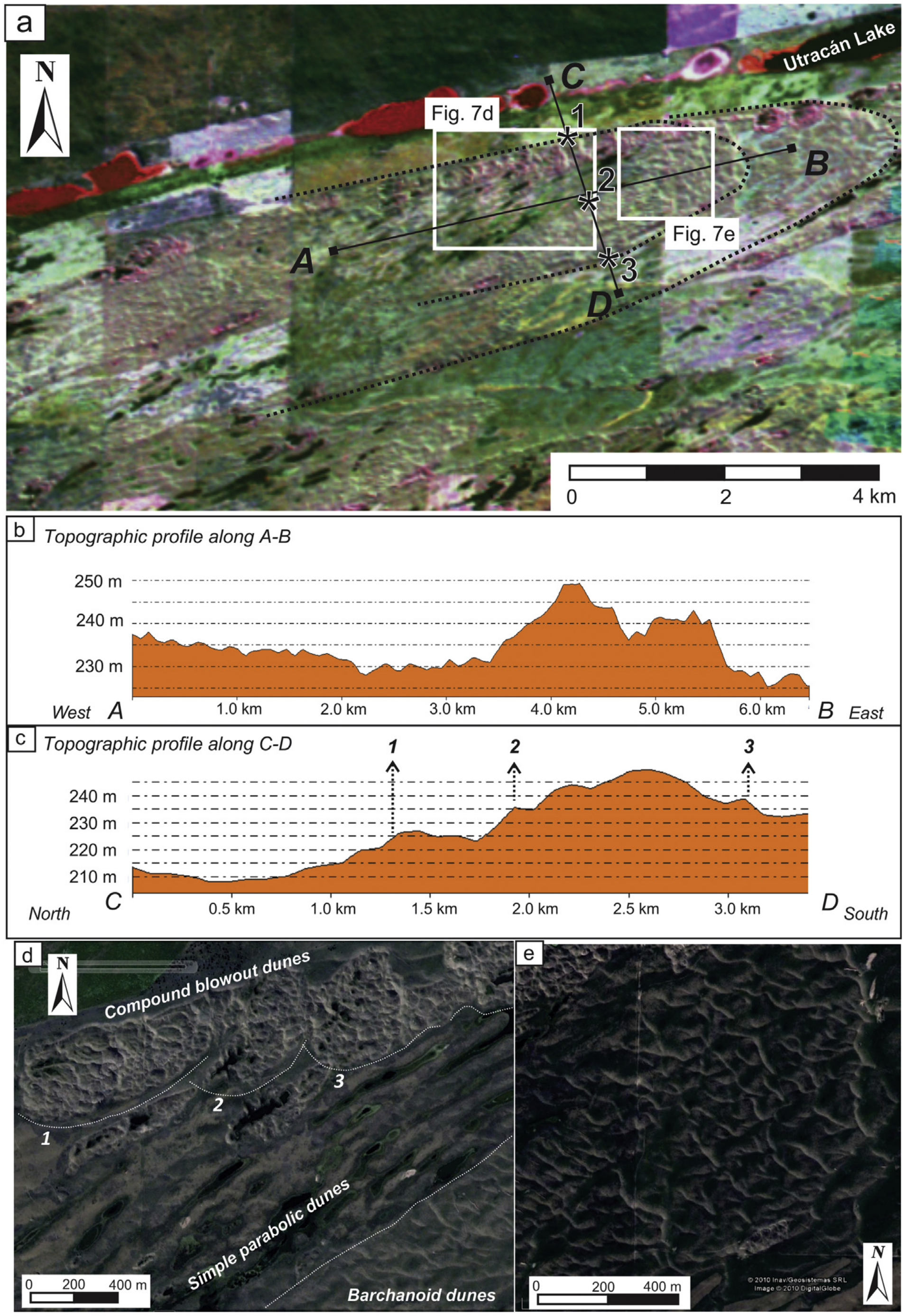

Fig. 7. Parabolic megadunes with superimposed dunes: a) semi-transparent Landsat ETM image (RGB 357 with Gaussian filter, date 2005-03-09) overlaid on SRTM-C digital elevation data showing a train of megadunes (outlined by black dotted lines) near the area of the Utracán lake and other saline lakes (in red) at the northern margin of the valley; b) longitudinal topographic profile across a parabolic megadune, in m based on SRTM-C data (A-B in panel a) showing the nose area; c) transverse topographic profile of this parabolic megadune, in m based on SRTM-C data (C-D in panel a), illustrating a thinner and lower northern arm and a wider and higher southern arm of the parabolic megadune; d) three compound blowout dunes at the northern parabolic arm, barchanoid dunes at the southern arm, and simple parabolic dunes between the arms (image courtesy of Google Earth®); e) detail of the barchanoid dunes.
(Image courtesy of Google Earth®).

megadunes from hundreds of metres- to kilometers-long, respectively) following these original dune attractors. In addition, the development of megadunes and large blowouts would have been promoted by dune merging (Kocurek and Ewing, 2005) and vertical growth of existing dunes (Lancaster, 1988b).

The topography is another factor to consider. At the western tip of the valley, the emergence of parabolic megadunes roughly coincides, at about 65° 5′W, with the beginning of the Utracán-Argentino valley (Fig. 10a,c). This depression determines an accommodation space for aeolian sedimentation, which occurs preferentially within the valley where we find the thickest sand cover and the largest bedforms (Figs. 5, 10).

Accommodation, defined as the space available for sedimentation, is one of the main factors that allow the accumulation of sediments in a basin and, potentially, the creation of a stratigraphic succession (Miall, 2010: p.49). Accommodation is, also, a key element for the preservation

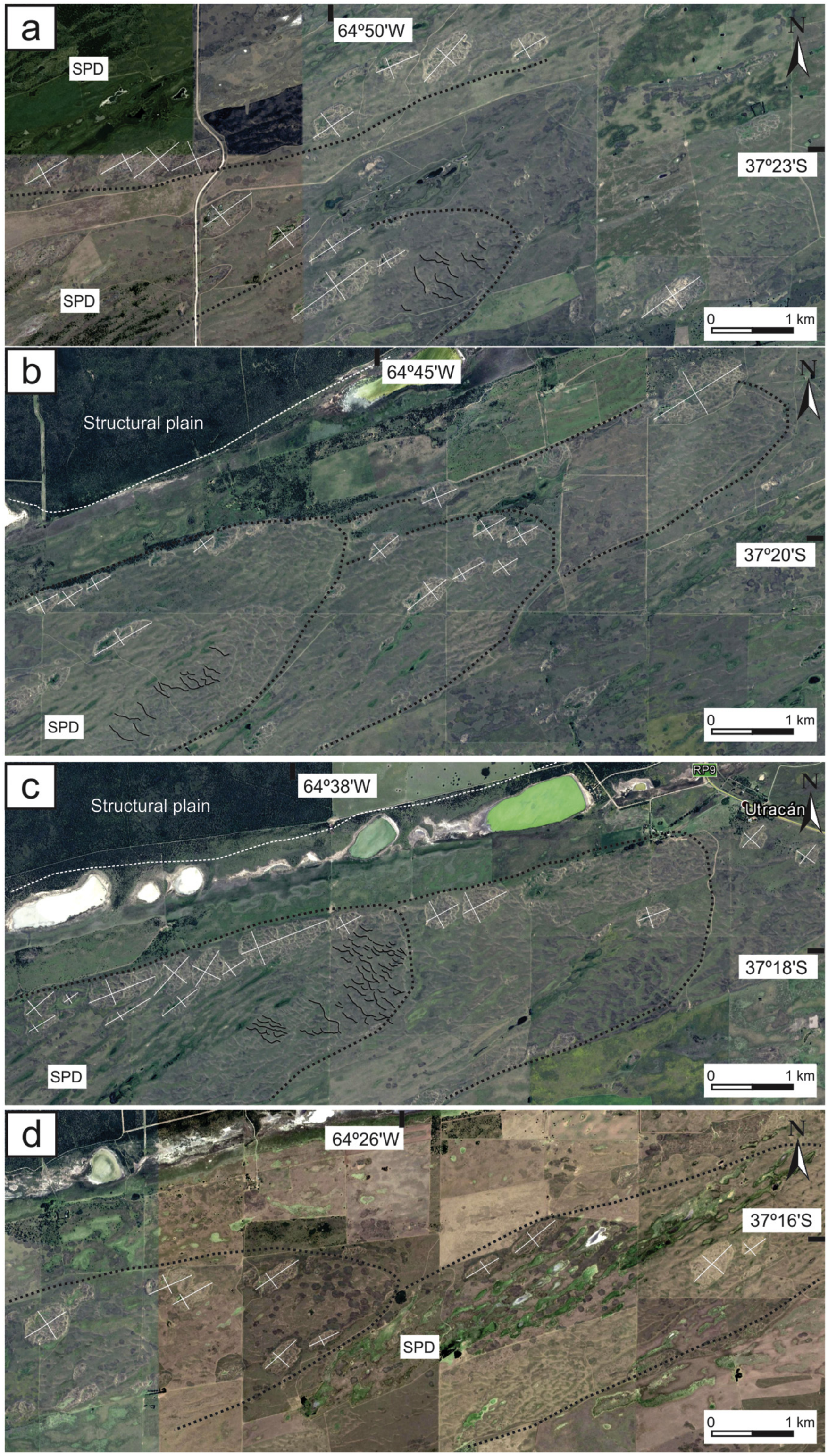

Fig. 8. Satellite images showing the measured compound blowout dunes (outlined in white) and barchanoid dunes (outlined in black), superimposed on the parabolic megadunes (outlined in dotted lines). Morphometric parameters according to Fig. 4.
Image courtesy of Google Earth®.

of the aeolian record which responds to spatial and temporal changes in the availability of accommodation space (Mountney and Howell, 2000).

Among the mechanisms for the formation of aeolian systems, there is the wind deceleration due to the presence of a topographic depression and/or a topographic barrier (Fryberger and Ahlbrandt, 1979; Kocurek and Havholm, 1993). In the Utracán-Argentino valley, the lateral confinement coincides with a change in the longitudinal valley slope direction (Fig. 10a, d). We suggest this topographic configuration promotes wind deceleration and accommodation space for aeolian sedimentation. It is worthy of mention that the parabolic megadunes only appear after that break in the slope and, also important, within the valley. There are no megadunes over the structural plain. We hypothesize

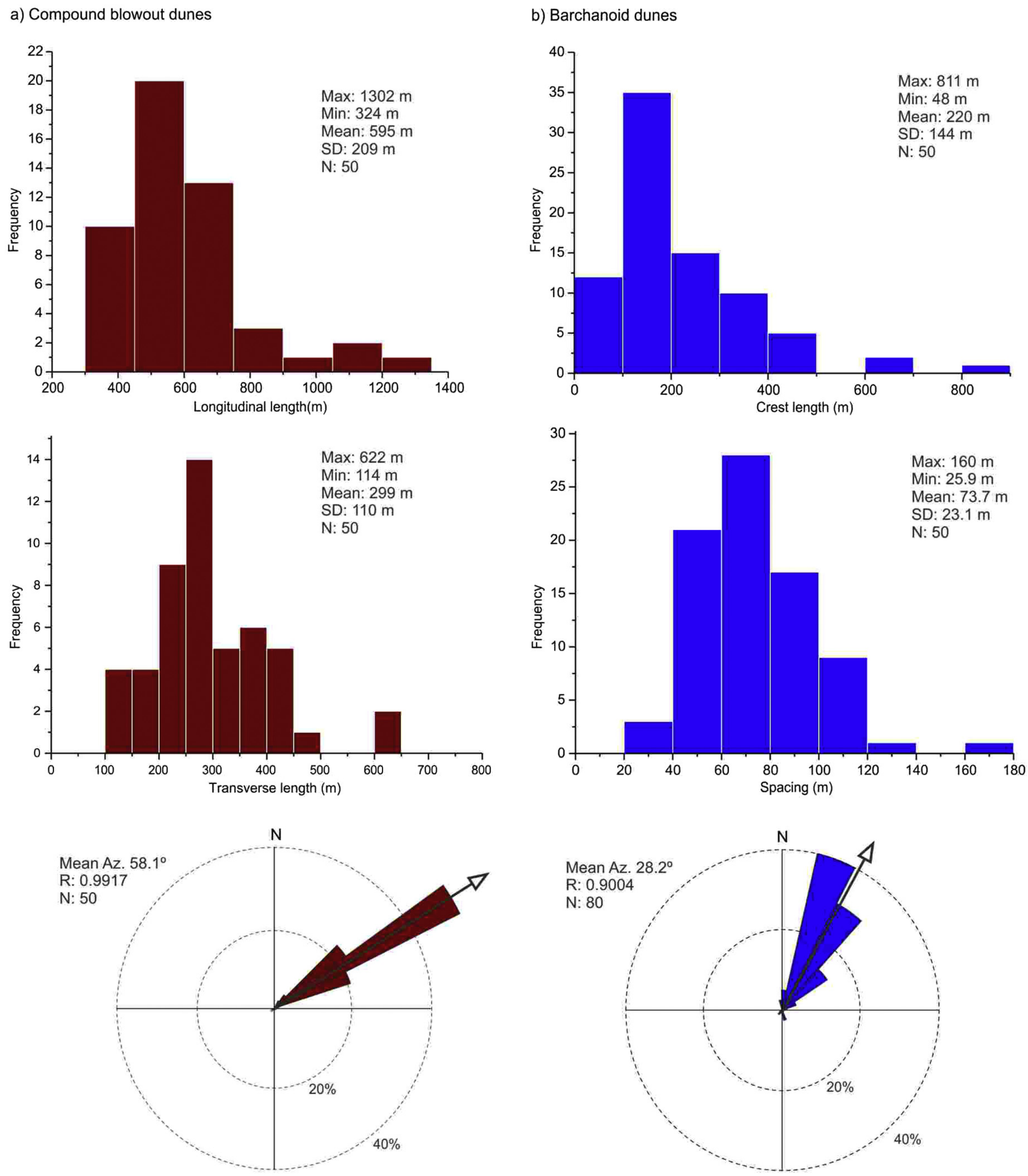

Fig. 9. Morphometric values of the compound blowout dunes (longitudinal length, transverse length and transport direction by azimuth) and barchanoid dunes (crest length, spacing and transport direction by azimuth), superimposed on the parabolic megadunes of the Utracán paleo-dune field (Max: maximum value; Min: minimum value; SD: standard deviation; N: number of measurements).

that the development of megadunes at the confined segment of the valley is related to this topographic control together with a high sediment supply.

The superimposition of dunes above the megadunes might correspond to contemporary bedforms (e.g. Havholm and Kocurek, 1988) or either to successive episodes of dune field construction (dune generations after Lancaster, 1992).

Parabolic dunes described in different localities worldwide have migration rates of tens of meters per year (Yan and Baas, 2015, and references therein), which indicate significant aeolian morphogenesis, while any aeolian disturbance of a vegetated sandy surface may cause blowout dunes (Barchyn and Hugenholtz, 2013). We speculate the Utracán parabolic dunes-megadunes might represent episodes of more active aeolian conditions than blowout dunes, due to a reduced vegetation cover and/or a higher sediment supply in comparison to the context during the formation of simple-compound blowout dunes.

At a first approximation, we infer the parabolic dunes-megadunes were developed during a first episode of dune field construction, likely during the late Pleistocene in accordance to the regional aeolian record of central Argentina (Tripaldi et al., 2011; Tripaldi and Forman, 2007, 2016; Tripaldi and Zárate, 2016) and the proposed long history of dune fields showing megadunes and/or several dune generations (Wilson, 1972; Lancaster, 1992; Beveridge et al., 2006; Mason et al., 2011). In addition, aeolian activity during the early-mid Holocene is not ruled out considering the regional evidence (Forman et al., 2014). We interpret the simple-compound blowout dunes were later developed by deflation

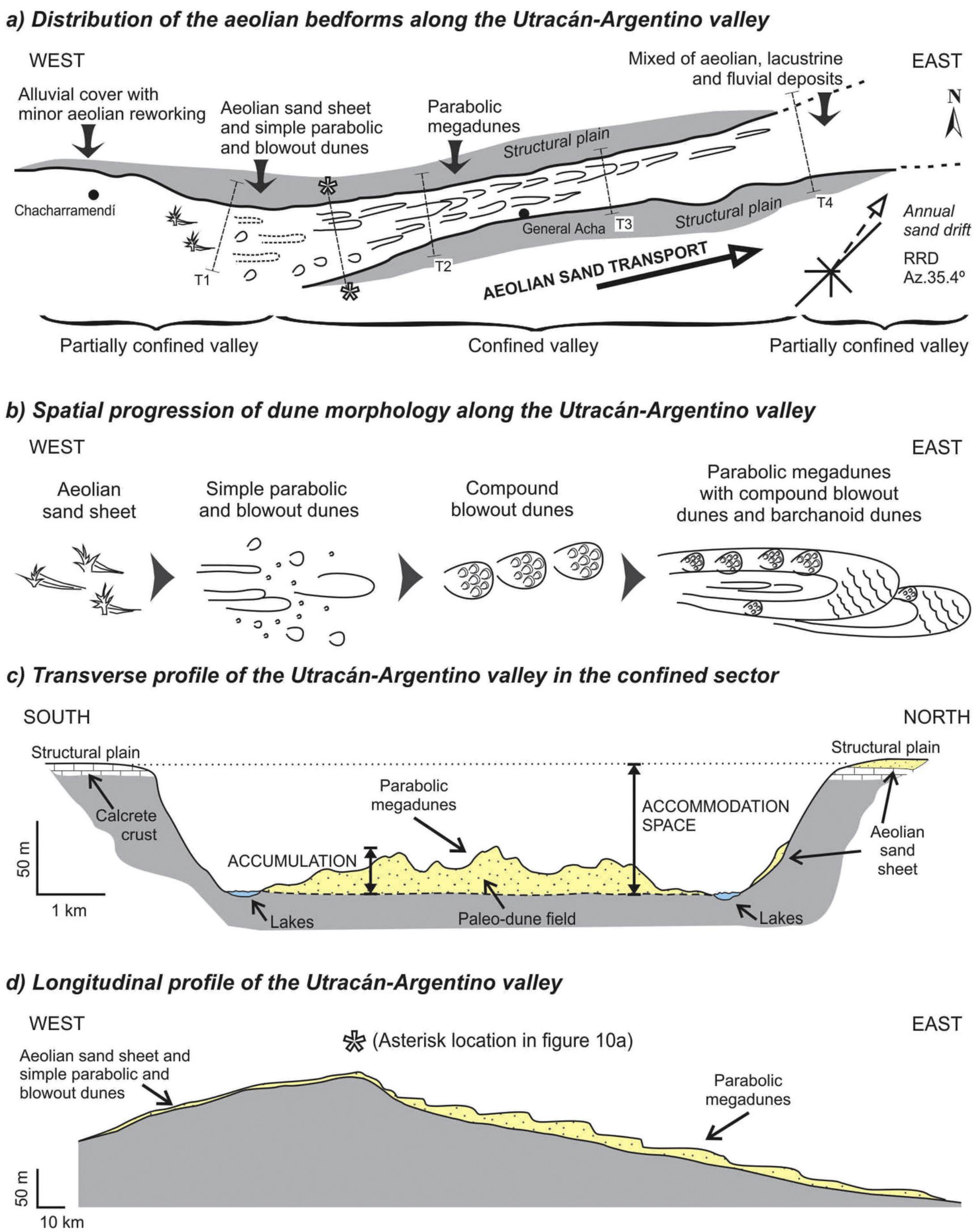

Fig. 10. a) Schematic diagram of the distribution of the aeolian bedforms along the Utracán-Argentino valley, with unconfined and confined valley segments, illustrating the inferred aeolian sand transport. T1 to T4 indicate the location of transects of Fig. 2, the asterisk-line marks the location of the change of the longitudinal valley slope direction. Annual sand drift (RDD: resultant drift direction) to azimuth 35.4° (see Fig. 3); b) Spatial progression of the dune morphologies along the Utracán-Argentino valley; c) The largest and more complex aeolian bedforms are concentrated where the valley is limited on both sides by the structural plain what creates an accommodation space for aeolian accumulation (scheme based on the aeolian sequence stratigraphy concepts of Kocurek and Havholm, 1993); d) Longitudinally along the valley, the parabolic megadunes arise to the east of the change of the longitudinal valley slope direction.

of the previous aeolian landscape and they would respond to boundary conditions of, either, a more extended vegetation cover and/or a lower sand supply compared to the previous conditions.

5.2. Sand transport pathway

The presence of a sand sheet at the western sector of the Utracán-Argentino valley, passing eastward to simple parabolic and blowout dunes, and then to the largest and most complex pattern (parabolic megadunes with superimposed compound blowout dunes and barchanoid dunes), evidence a west-east spatial progression of bedforms (Fig. 10b). The dunes grow along the valley with a transport direction to the east (Figs. 6, 9, 10),in agreement with the resultant drift direction (azimuth 35.4°) obtained by vectorial analysis of present wind velocity (Figs. 3, 10a).

The west-to-east spatial progression of dunes is thought to be related to a sediment supply west of the Utracán paleo-dune field, in the Andean piedmont. The aeolian deposits of central Argentina are mostly of Andean provenance (Iriondo, 1990; Zárate and Blasi, 1991, 1993; Zárate, 2003; Tripaldi et al., 2010). The Desaguadero-Salado-Curacó fluvial system, and associated distributary fluvial systems (Lorenzo et al., 2017), collecting the drainage of the Andes Cordillera (Fig. 1), is the main source area. The sand deposits of the Utracán dunes have an Andean provenance along with local inputs from Permian-Triassic volcanic outcrops situated nearby (Szelagowski et al., 2004).

The paleo-dune fields located along the transverse valleys of La Pampa Province allows us to explain the presence of the extensive sandy aeolian cover in the central Pampean plain (the CPD aeolian unit in Fig. 1; Zárate and Tripaldi, 2012). The sand of this aeolian unit shows a high proportion of volcanic rock fragments and plagioclase (Tripaldi et al., 2018), similar to the composition observed in the aeolian deposits of La Pampa Province (Szelagowski et al., 2004).

The aeolian drift direction (Figs. 6,9), the west-to-east dune spatial progression along the valley (Fig. 10b), and the sand composition suggest that the transverse valleys of La Pampa Province behave as aeolian sand transport pathways. The well sorted, fine to very fine sand was then transferred eastward, through the valleys, from the Andes piedmont to the Pampean plain (Figs. 1, 2).

The existence of a sediment transport pathway is mentioned as a key element in several large ergs (Wilson, 1973; Breed and Grow, 1979; Fryberger and Ahlbrandt, 1979; Mainguet et al., 1980; Corbett, 1993). The development of intermontane dune fields in southwestern United States is also related to the presence of transport pathways delivering sand (Zimbelman et al., 1995; Ramsey et al., 1999; Muhs et al., 2003). Similarly, the paleo-dune fields of the transverse valleys of La Pampa Province are hypothesized to be part of regional Quaternary sand transportation paths that cross the central region of Argentina from west to east and promote the formation of dune fields in the central Pampean plain.

6. Conclusions

The geospatial analysis of the Utracán paleo-dune field (La Pampa Province, Argentina) shows a complex pattern of parabolic megadunes with superimposed compound blowout dunes and barchanoid dunes. We interpret the parabolic and blowout dunes as the main attractors of this dune field, which emerged under particular boundary conditions at the transverse valleys of La Pampa Province. The generation of the Utracán paleo-dune field was likely the result of the combined effect of mainly three factors: a high sediment supply and significant wind deceleration plus the presence of an adequate accommodation space due to the topographic configuration of the valley. Our conceptual model of dune field construction proposes that this aeolian system develops large-scale bedforms (compound blowout dunes and parabolic megadunes from hundreds of meters- to kilometers-long, respectively) following the original dune attractors.

The petrographic composition of the dune sand allows us to infer that the Utracán-Argentino valley, and likely the other transverse valleys of La Pampa Province, worked as aeolian sand transport pathways that transferred well sorted, fine to very fine sand from the Andean piedmont eastward to the Pampean plains, likely during the Quaternary in accordance to the chronology of other aeolian units of central Argentina.

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