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Internal anatomy of an erg sequence from the aeolian-fluvial system of the De La Cuesta Formation (Paganzo Basin, northwestern Argentina)

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ABSTRACT

Permian red beds of the De La Cuesta Formation in the Sierra de Narváez (Paganzo Basin, northwestern Argentina) are essentially composed of sandstones associated with mudstones and subordinate conglomerates. Facies distributions and stacking patterns indicate that these sediments resulted from the interaction between aeolian and ephemeral fluvial systems, and are represented by aeolian dune, dry aeolian interdune and aeolian sand sheet, mudflat, wet aeolian interdune, and fluvial deposits. The De La Cuesta Formation is characterised by aeolian (erg) sequences alternating with non-aeolian (terminal alluvial fan – mudflat) sequences. Each erg sequence is bounded at its base by a regionally extensive sand-drift surface and at the top by an extinction surface. A number of architectural elements, including aeolian dunes limited by interdunes, grouped crescentic aeolian dunes, longitudinal dunes, and draa with superimposed crescentic dunes are recognised in the erg sequences. The sand sea developed during phases of increasing aridity, whereas non-aeolian deposition might have occurred during more humid phases. Thus, the styles of aeolian-fluvial interaction are considered to result from cyclical climatic changes. Within the drier hemicycles, the rhythmic alternation between draa deposits and aeolian dune and interdune deposits indicates higher frequency cycles that could be attributed to subtle climatic oscillations and/or changes in sand supply and availability. The development of the Permian sand sea in the inland Paganzo Basin seems to be related to the growth of a volcanic chain to the west. This topographic barrier separated the Paganzo Basin from the Chilean Basin, located along the western margin of Gondwana and characterised by shallow marine carbonate sedimentation. The correlation between the Permian erg and the shallow marine carbonates suggests a regional warming period during the Middle Permian in western Gondwana.

KEYWORDS **Erg sequence. Permian. Argentina. Western Gondwana.**

INTRODUCTION

One of the most important sedimentary records of the Upper Palaeozoic of South America is found in the Paganzo Basin, which extends over an area of nearly 150,000 km^2 in northwestern Argentina (Salfity and Gorustovich, 1983; Azcuy et al., 1999; Tedesco et al., 2010).

During the Permian, the Paganzo Basin was characterised by the deposition of continental red beds, which were documented by the pioneer works of Bodenbender (1911, 1912) and Frenguelli (1944, 1946). From a lithostratigraphic perpective, these deposits are known as the De La Cuesta, Patquía, La Colina and Del Salto formations based on the areas of geographic occurrence (Turner, 1962; Cuerda, 1965; Azcuy and Morelli, 1970; Quartino et al., 1971). These red beds form thick siliciclastic sequences that include important deposits of aeolian origin which have been analysed by Spalletti (1979), Limarino (1984, 1985), López and Clérici (1990), Limarino and Spalletti (1986), Sessarego (1986), Limarino et al. (1993) and López Gamundí et al. (1992). On the basis of micropalaeontological, ichnological and palaeomagnetic evidence, it has been determined that the sequences dominated by aeolian sedimentation, with associated ephemeral fluvial and lacustrine deposits, developed during the Middle to Late Permian (Aceñolaza and Vergel, 1987; Limarino and Césari, 1987; Limarino et al., 1993; Limarino and Spalletti, 2006; Krapovickas et al., 2010).

The present paper seeks to document the styles of aeolian-fluvial interaction within deposits of these Permian sequences that crop out in one of the northernmost areas of the Paganzo Basin (southwest of the Catamarca Province, Argentina) and to analyse their palaeogeographical-palaeoclimatic relevance.

GEOLOGICAL SETTING AND STRATIGRAPHY

The Late Palaeozoic Paganzo Basin (Salfity and Gorustovich, 1983), located in northwestern and central Argentina (Fig. 1), is composed of a mostly continental terrigenous clastic infill of about 4,500m formed as a response to basin-forming tectonic processess, sea-level fluctuations and climatic changes (Fernández Seveso and Tankard, 1995; Limarino et al., 2006). In the Paganzo Basin, sedimentation took place from the Middle Carboniferous to the Early-Late? Permian (Limarino and Césari, 1985; Archangelsky et al., 1996), and the Permian record is characterised by a widespread development of siliciclastic red-bed successions (Limarino et al., 2006; Limarino and Spalletti, 2006).

During the Permian, the Paganzo Basin was separated from the proto-Pacific active margin of western Gondwana by an important volcanic chain whose record is known as the Choiyoi Group (Groeber, 1946; Stipanicic et al., 1968; Yrigoyen, 1972). These magmatic rocks show changes through time. The older and basic rocks were formed under an Early Permian compressional orogenic phase linked to a shallowing episode of the palaeo-Benioff zone, while the acidic volcanic rocks of the younger Choiyoi Group were produced as a consequence of the cease of subduction and the gravitational collapse of the orogenic belt under an extensional regime (Martínez et al., 2006).

The study area is located to the north of the Paganzo Basin, in the eastern sector of Sierra de Narváez and to the west of the Fiambalá city (Fig. 1), at the northernmost end of the Famatina Range. This area was extensively studied by Turner (1958, 1967) who gave the name of the De La Cuesta Formation to a 1,600m thick Permian sedimentary succession. This unit rests indistinctly on Carboniferous deposits that belong to the Agua Colorada Formation or on Ordovician-Silurian granitoids of the Narváez Formation forming part of the Famatinian Magmatic Cycle (Rapela et al., 1999; Dahlquist et al., 2008; Castro et al., 2008) (Fig. 2). The De La Cuesta Formation is essentially composed of brick-red sandstones of variable grain-size which, according to Turner (1967), are associated with reddish and yellowish marls, conglomerate layers, and intercalations of basaltic agglomerates and tuffs.

López and Clérici (1990), whilst researching the Permian sequence in this region, recognised three sedimentary associations in vertical terms. The lower one is characterised by fluvial meandering and ephemeral stream deposits; the middle section is characterised by a range of aeolian-fluvial system interactions (the subject of study of this research), and the upper association is interpreted as a lacustrine succession which includes siliciclastic and evaporitic facies. In the last interval, Aceñolaza and Vergel (1987) found Permian microflora which can be correlated with the *Cristatisporites* biozone.

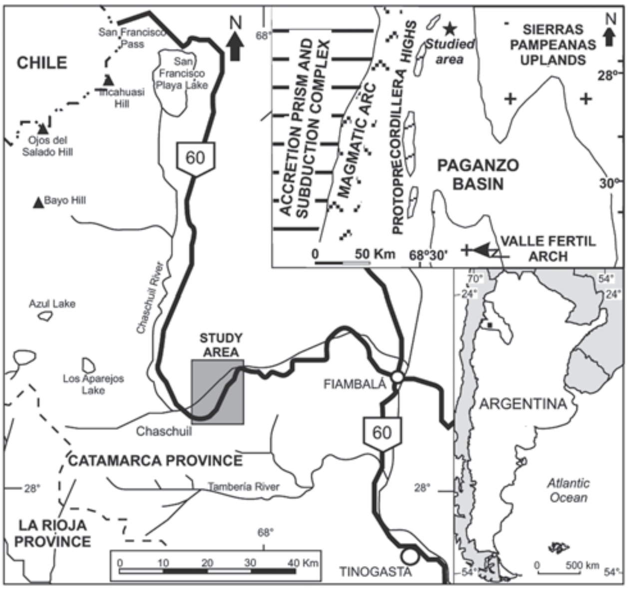

FIGURE 1 | **Location map of the study area. In the insert, main Upper Palaeozoic tectonic elements and location of the Paganzo Basin.**

METHODOLOGY

For this investigation, sedimentological studies were carried out in the area where the Sierra de Narváez is crossed by the Chaschuil River, between the places of Gallina Muerta to the southwest and Las Angosturas to the northeast, where excellent outcrops of Permian red beds are developed (Figs. 2 and 3). Methods included the analysis of texture, composition, sedimentary structures (including the orientation of directional structures) and lithosome geometry with the aim of defining observational facies, facies associations and architectural patterns. The synthetic profile of the studied succession is illustrated in Figure 4.

FACIES ASSOCIATIONS

Five facies associations have been defined in the De La Cuesta Formation: 1) aeolian dunes, 2) dry aeolian interdune and aeolian sand sheet, 3) mudflat, 4) wet aeolian interdune, and 5) ephemeral fluvial systems (Fig. 4).

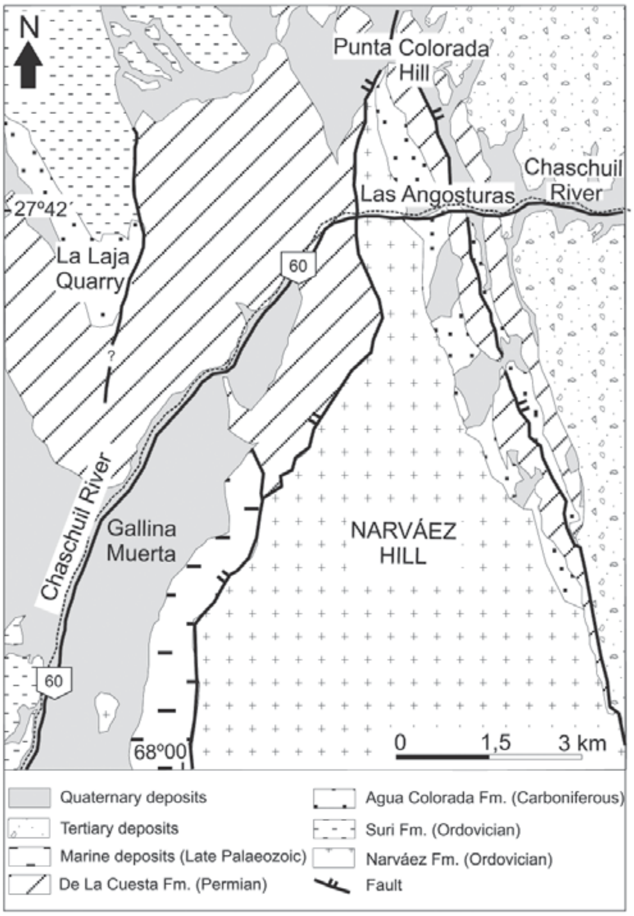

FIGURE 2 | **Geological sketch map of the Sierra de Narváez region. The study area is located to the west and southwest of Las Angosturas.**

Aeolian dunes

The presence of aeolian dune deposits in the Permian red beds of the Paganzo Basin is known from the works of Spalletti (1979), Limarino (1984), Limarino and Spalletti (1986), Sessarego (1986), López Gamundí et al. (1992) and Limarino et al. (1993). This facies association is made up of well sorted fine- to medium-grained sandstones with rounded to well-rounded grains and large scale cross-bedded sets, with variable thickness from 0.3m to 5m (2.3m mean thickness). When sections parallel to the transport direction are observed, two types of cross-bedded sets are recognised: one in which the cross-laminae show a strongly tangential base, and the other in which the cross-laminae are planar. Laminae developed by grain flow, grain fall and aeolian ripple migration have been identified in cross-bedded sets (Hunter 1977). Grain flow laminae have a steep inclination angle (20º to 24º), are relatively thick (5 to 30mm) and massive, and are composed of medium-grained sand (Fig. 5A). The grain fall laminae are made up of well sorted, very fine- to fine-grained sand, and they have a steep inclination angle and a much thinner thickness, which does not exceed 5mm (Fig. 5A). By contrast, the translatent ripple laminae are equally thin (1 to 3mm); they are composed of fine- to medium-grained sand and are preferably located in the lower sections of the cross-bedded sets with tangential geometry. Thus, it is common for cross-bedded strata to show a vertical trend in

FIGURE 3 | **General view of the Permian red beds (De La Cuesta Formation) at Sierra de Narváez. The cliff to the left is approximately 9m high.**

which there is a transition from a low-inclined lower section with translatent ripple laminae to an upper section in which grain flow and grain fall laminae alternate. In addition, cross-bedded sets with convolute lamination were randomly identified.

The development of texturally mature sandy deposits forming cross-bedded strata with grain flow, grain fall laminae, and translatent ripples suggests that they are residual deposits from aeolian dunes (Kocurek and Dott, 1981). Moreover, layers with synsedimentary deformation could have been caused by the collapse of the upper sectors of the dunes because of sand dampening and a consequent decrease in their internal friction angle (Mountney and Thompson, 2002).

Dry aeolian interdune and aeolian sand sheet

This association is composed of sandstones with fine to coarse textural variations and moderate sorting.

Individual layers, each 0.3 to 0.7m thick, show markedly tabular geometries with important lateral continuity and a characteristic horizontal inner lamination of even low angle. These laminae are less than 10mm thick (Fig. 5B) and commonly show an inverse graded structure in which there is a vertical change from very fine-grained sand to medium- and/or coarse-grained sand. Isolated cross bedded sandstone sets of relatively low angle (about 10º) and thickness between 0.1 and 0.2m usually appear in these sequences.

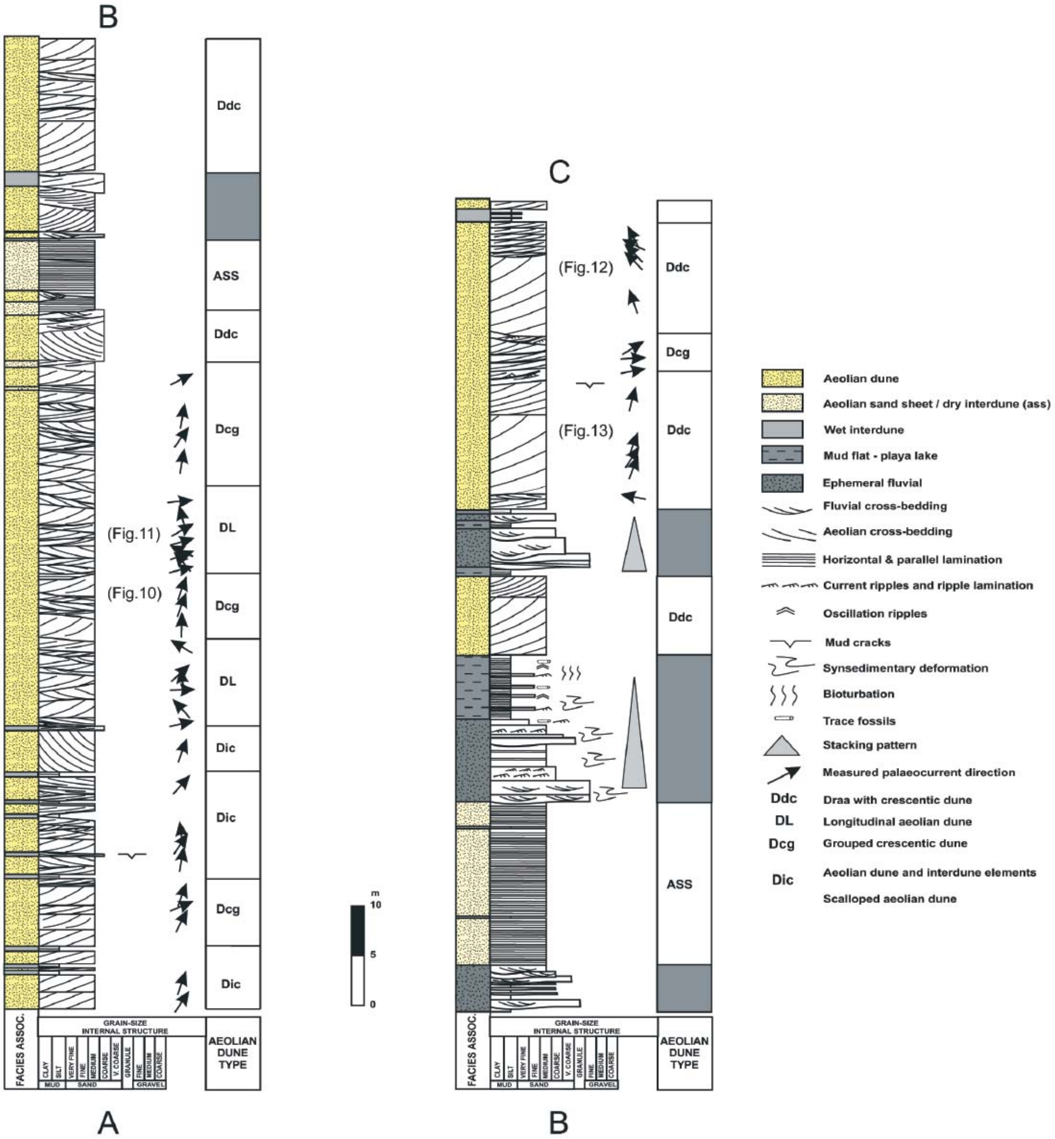

FIGURE 4 | **General sedimentolo–gical log of the aeolian-fluvial deposits. This figure also shows the vertical distribution of the main aeolian architectural elements.**

Inversely graded layers of low angle with horizontal laminae are interpreted as translatent strata with subcritical climbing formed by the migration of aeolian ripples (Hunter, 1977). The thin cross-bedded sandstone bodies that intercalate in these successions are interpreted as residual or truncated deposits from protodunes and/or isolated aeolian dunes of limited lateral extent (Trewin, 1993; Mountney et al., 1999).

Thin sedimentary bodies of this facies association are intercalated and show transitional passages to cross-bedded strata which are attributed to the aeolian dunes association (Fig. 5C). This is why they are regarded as dry interdune and/or interdraa deposits formed in areas in which development of aeolian dunes was inhibited (Kocurek and Nielson, 1986; Kocurek and Havholm, 1993). In addition, similar facies have been previously described in Permian red bed sequences from the Paganzo Basin by Limarino (1984), Limarino and Spalletti (1986), López Gamundí et al. (1992) and Limarino et al. (1993).

It is worth noting that in only one case does this association constitute a succession of more than 4m thick, in which there is amalgamation of tabular sandstone bodies (Fig. 5D). Despite the fact that the sandstones show characteristics very similar to those described above, the presence of bioturbation, especially horizontal traces, should be emphasised. There are also irregular laminations of less than 10mm thick, which are regarded as adhesion structures caused by the adherence of sand grains on humid surfaces (Kocurek and Fielder, 1982; Crabaugh and Kocurek, 1993). Furthermore, it is common to observe water-escape structures and bedding surfaces with linguoid current ripples which represent the local reworking of aeolian sands by ephemeral streams (Fig. 6A). This deposit is interpreted as an aeolian sand sheet (Fryberger et al., 1979; Scherer et al., 2007; Delorenzo et al., 2008), which develops when there is a decrease in the contribution of sand to desert systems (Fryberger et al., 1979; Clemmensen and Abrahamsen, 1983; Kocurek and Nielson, 1986; Clemmensen and Dam, 1993), or a decrease in sand availability due to a rise in the water table and consequent sand dampening (McKee, 1979; Mountney et al., 1998; Veiga et al., 2002).

Mudflat

This association is composed of red mudstones related to thin sandstone layers and heterolithic intervals of the same colour that constitute successions exceeding 2.5m in thickness. Mudstone intervals are mostly internally massive although, in some cases, horizontal and convolute laminations are developed. Mud cracks are common, whereas symmetrical ripple forms are less so. Sandstone and heterolithic intercalations constitute thin and laterally continuous layers. The most prominent structures are cross-laminations attributed to linguoid ripple migration and horizontal laminations (at times distorted by water escape)

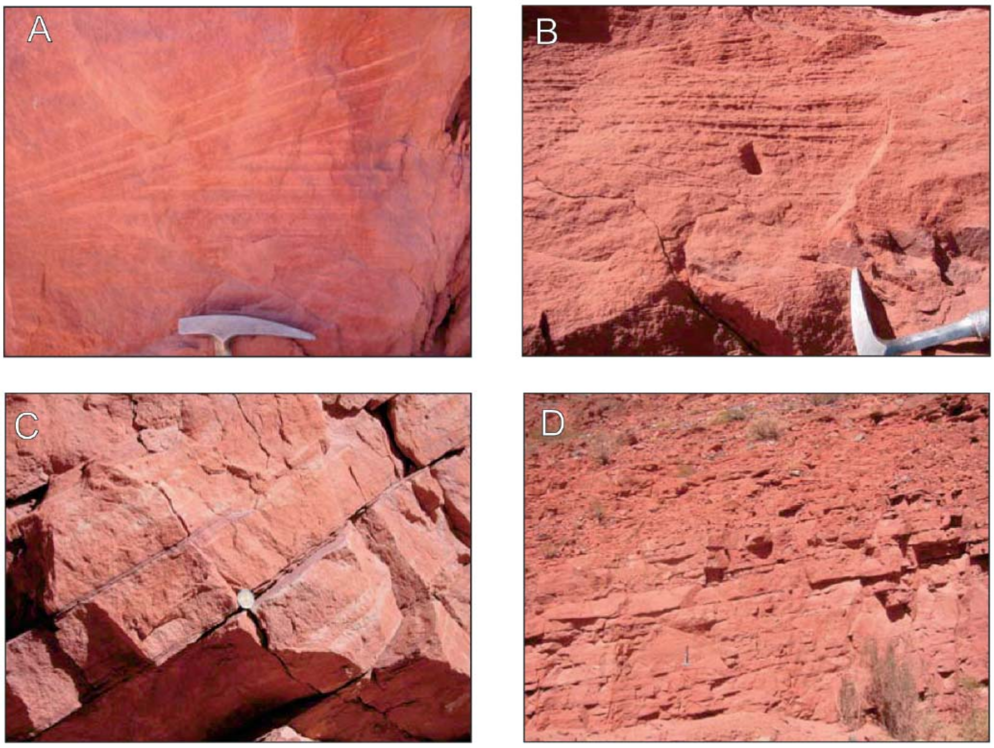

FIGURE 5 | **A) Grainflow and grainfall cross-lamination in aeolian dune deposits. B) Horizontal lamination formed by climbing translatent strata in dry interdune. C) Interbedded dry interdune deposits and isolated medium-scaled cross-bedded sets (protodunes). D) General view of the aeolian sand sheet deposits.**

defined by textural alternations of fine- and very fine-grained sand as well as fine-grained sand and mudstone.

Fine-grained deposits are considered as the product of suspension fall-out from water bodies lately subjected to desiccation processes. Their deposition could be ascribed to very shallow water bodies that developed during periods of episodic flooding in mudflat environments (Kelly and Olsen, 1993; Sadler and Kelly, 1993; Spalletti and Colombo, 2005). Sandstone bodies and heterolithic pairs formed by thin alternations of mudstones and fine-grained sandstones are attributed to the spasmodic non-channelised flooding of an ephemeral fluvial system (Williams, 1971; Picard and High, 1973; Tunbridge 1981, 1984).

Wet aeolian interdune

The deposits in this facies association are very similar to those of the mudflat association, with the peculiarity that they are thinner deposits (maximum thickness of 0.6m) intercalated between aeolian dune deposits (Fig. 6B). These intervals are characterised dominantly by massive or laminated mudstones associated with thin intercalations of siltstones and very fine- to fine-grained sandstones with horizontal and ripple cross-lamination. Some intervals of this facies association are composed of thin layers (0.3 to 0.5m) of fine-grained sandstones with trough cross-stratification produced by the stream reworking of aeolian deposits.

Ephemeral fluvial systems

Fluvial channel deposits have been widely recognised and described in the Permian red beds of the Paganzo Basin (Spalletti, 1979; Limarino, 1985; López Gamundí et al., 1989; Pérez et al., 1993, among others). However, they are not predominant in the studied sections. They consist of texturally heterogeneous beds, ranging from medium-grained clast-supported conglomerates (with rounded pebbles of up to an average size of 30mm) to very fine-grained sandstones. The conglomerate beds are thick (over 1.5m) and show the common imbrication as well as horizontal laminations and low-angle cross-bedded sets (Fig. 6C). Sandstones vary in grain size from coarse- to fine-grained. They show the amalgamation of internally massive thick layers (0.8 to 1.7m) followed by beds with horizontal lamination and/or low angle cross-stratification (Fig. 6D). Trough and planar cross-bedded strata are very scarce. These coarse-grained deposits show two architectural patterns: a more frequent one which has a significant lateral continuity of tabular layers, and a less frequent one characterised by a strong lenticular (channelised) geometry. In both cases, they are limited by sharp surfaces over which thin muddy intraconglomerates usually appear. Furthermore, a mudstone level with mud cracks is usually preserved at the top of many sandstone strata.

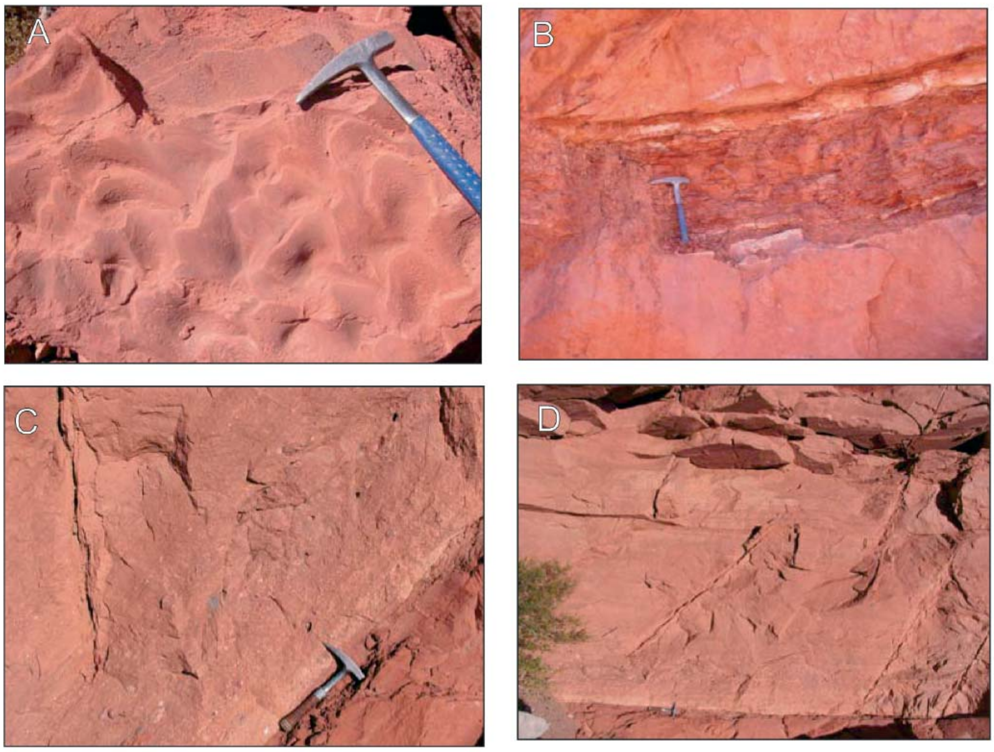

FIGURE 6 | **A) Linguoid ripples at the surface of reworked dry interdune deposits. B) Massive mudstones in wet interdune deposits. C) Close view of coarse-grained sheetflood deposits (ephemeral fluvial facies association). D) General view of gravelly and sandy non-channelised ephemeral fluvial deposits.**

The most regionally continuous bodies are interpreted to be the deposits of unconfined sheet splays or poorly confined fluvial flows (Picard and High, 1973; Olsen, 1987; North and Taylor, 1996; Mountney et al. 1998), whereas the most lenticular ones result from channel fills, suggesting greater incision and avulsive abandonment. Intraconglomerates composed of muddy chips indicate erosive processes of fine-grained overbank deposits which accumulated in interchannel areas. Although inner textural variations are not observed in sandstone strata, mudstone levels preserved towards the top of some of these units reflect a marked upward fining trend in these fluvial deposits. This gradual vertical evolution indicates the waning stage of flooding and decreasing velocity of flows towards lower flow-regime conditions. The development of massive strata is interpreted as the product of hyperconcentrated flows with sand overload and turbulence suppression, whereas gravels and sands with horizontal and low angle laminations reflect transportation processes of high-regime flow rates. Both features suggest that the sedimentary processes were produced by high capacity, fast and episodic currents (Bordy and Catuneanu, 2002; Scherer et al., 2007).

Medium scaled trough cross-bedded sets are more common in sandstone lenticular bodies. They are interpreted as the deposits of very shallow sandy bedload channels, typical of the distal portions of the braided plains that characterise the fluvial systems of arid regions (Miall, 1996; Talbot et al., 1994; Scherer et al. 2007).

Aeolian deposits consist of low-relief bedforms (zibars, sand shadows ?) and protodunes commonly intercalated in fluvial deposits. These associations have been identified by Langford (1989) and Tripaldi and Limarino (2008) in aeolian-fluvial interaction sequences.

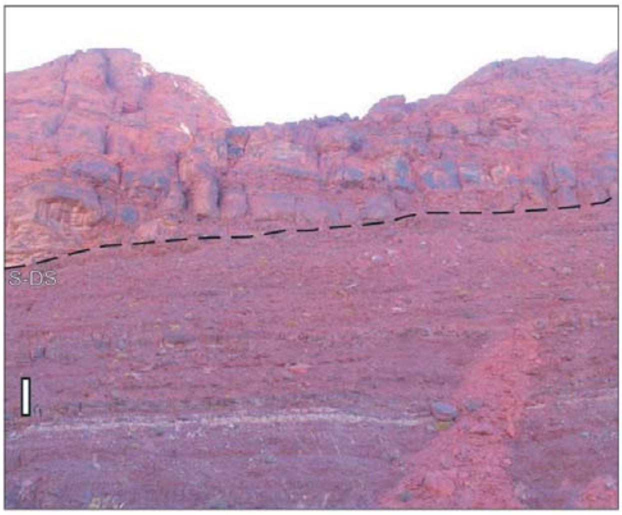

FIGURE 7 | **Sand-drift surface (S-DS) separating playa lake deposits below from aeolian dune deposits above. The white bar is 1m thick.**

ARCHITECTURE OF AEOLIAN DEPOSITS

In the study area, aeolian deposits constitute sedimentary sequences alternating with non-aeolian sediments. Such aeolian sequences have been referred to by Wilson (1973) as erg sequences. Such sets are limited at the base and on the top by sharp and subhorizontal surfaces, which can be followed laterally over great distances. According to Clemmensen and Tirsgaard (1990), the basal bounding surfaces are known as sand-drift surfaces (Fig. 7) and their origin is attributed to regional scale deflation processes (Rodríguez López et al., 2008). The presence of bioturbation, intense cementation areas and mud cracks suggest aeolian deflation down to the level of the capillary zone (Loope, 1988; Havholm and Kocurek, 1994; Mountney and Howell, 2000) in inland continental areas (Kocurek et al., 2001; Mountney, 2006). The surface developed on top of the erg sequences constitutes another significant discontinuity, marking the decline or disappearance of the sand sea, which is referred to as the extinction surface in this work.

The De La Cuesta Formation erg sequences consist of several architectural elements whose schematic representation is illustrated in Figure 8. These sedimentary bodies are defined in accordance with the following characteristics: relationship between dune and interdune facies associations, scale and degree of amalgamation of cross-bedded units, characteristics of cross-stratification foresets, orientation of these structures and characteristics of bounding surfaces of varied hierarchy.

Aeolian dune and interdune elements

These are characterised by cross-bedded units ranging in thickness from 1 to 3m, which generally alternate with 0.2 to 0.5m intervals that correspond to the dry aeolian interdune association. The cross-bedded bodies display forms that range from nearly tabular to wedge-like with a crescentic geometry in which a progressive increase in set thickness can be observed in a paleaeowind direction. This particular morphology arises where groups of cross-bedded sets are bounded at their base by a surface with a smooth but persistent inclination opposed to that of the cross-bedded structures. According to Kocurek (1981, 1996) and Mountney and Howell (2000), these surfaces are attributed to the migration of primary bedforms and are know as interdune surfaces. Cross-bedded layers show different geometries, ranging from planar foresets to tangential ones with maximum inclination angles of 20° to 25° which constitute lee-side slipfaces of aeolian bedforms.

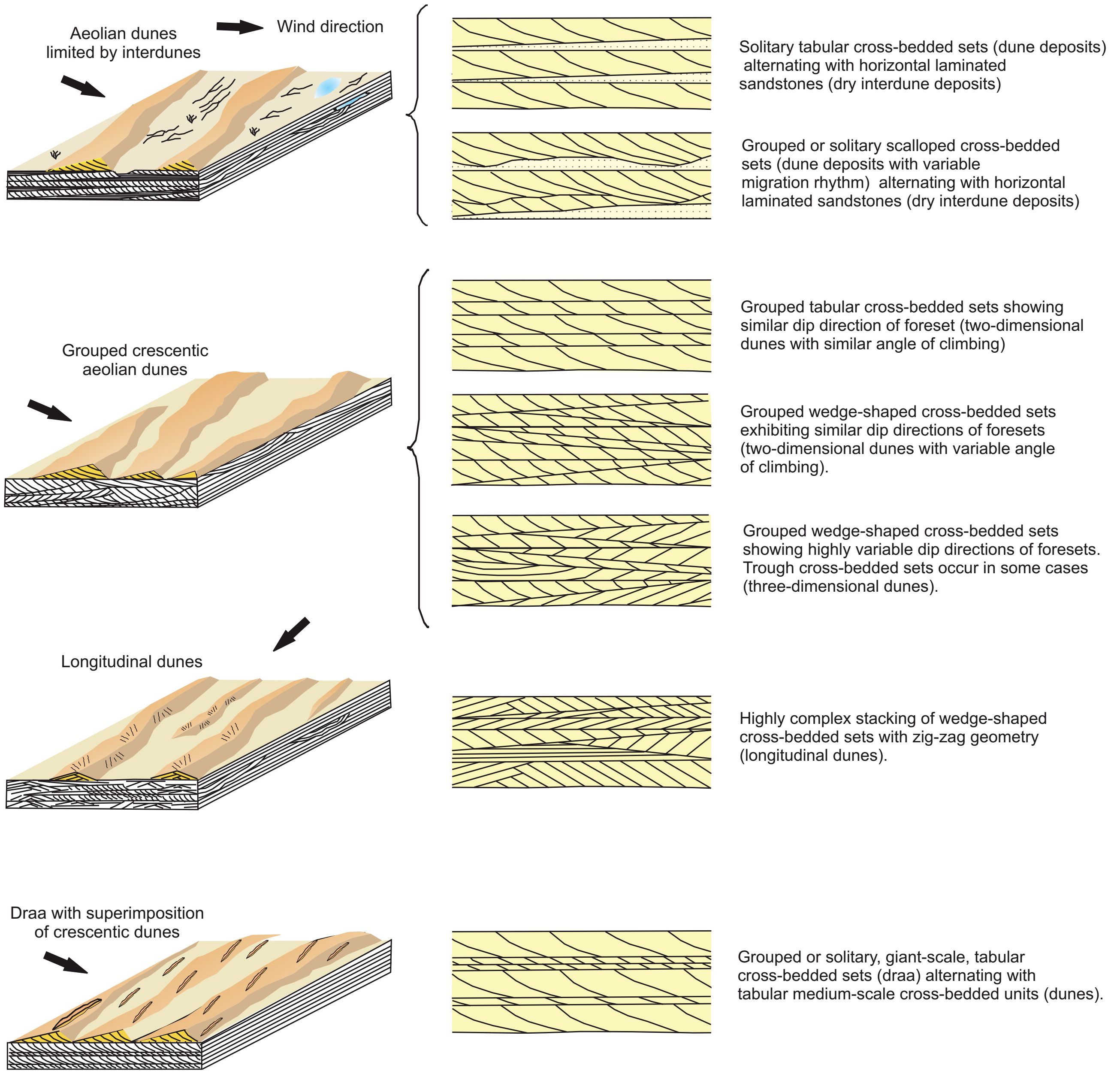

FIGURE 8 | **Schematic sketches of the main aeolian architectural elements defined in the De La Cuesta Formation.**

A very special type of aeolian dune, which belongs to this architectural style, is the one made up of cross-bedded strata with important internal reactivation surfaces (Brookfield 1977) developed over dune slipfaces. Within these strata, foresets constitute packages limited by concave-up internal surfaces, which define subsets and are inclined towards the net sand transport direction with variable angles (Fig. 9). Their presence in aeolian deposits has been attributed to important changes in wind orientation and/or dune migration rhythm (Kocurek, 1988; Mountney and Jagger, 2004). The resultant aeolian deposits (Fig. 9) are characterised as scalloped dunes (Kocurek, 1991; Kocurek et al., 1999).

Grouped crescentic aeolian dunes

This architectural element corresponds to overlapping cross-stratified sets of aeolian origin. Some of these bodies, especially those with planar cross-laminae, show a highly persistent orientation of the internal structures (Figs. 4 and 10). For this reason, they are considered to result from the migration and stepping of transverse aeolian dunes. The surfaces limiting the sets define two main geometries. In the first and more common one, the surfaces are parallel or subparallel, indicating that the stepping angle is nearly constant (Fig. 10). In the second and less common one, the surfaces that limit

FIGURE 9 | **Cross-bedded sandstones formed by migration of scalloped dunes.**

the sets intersect frequently, which suggests that the stepping angle varies in accordance with changes in wind speed or sand supply rate (Rubin and Hunter, 1983; Mountney and Howell, 2000; Tripaldi and Limarino, 2005).

Conversely, other aeolian bodies are characterised by a greater variability in foreset azimuths (Fig. 4), which normally have a three-dimensional architectural pattern with tangential laminae in sections parallel to the palaeowind and trough laminae in transverse sections. These features are interpreted to be the depositional product of aeolian dunes that had curved crestilines (Rubin, 1987; Mountney 2006) which is why they are attributed to barchanoid ridges.

The surfaces bounding each cross-bedded layer can show different geometries. The most frequent surfaces are those that dip slightly towards the direction of the cross-laminae. They can be regarded as a variety of superimposition surfaces (Fig. 10) formed in response to changes in the migration of successive crescentic aeolian dunes. Cross-bedded sets limited by concave-up surfaces on top are uncommon, suggesting out of phase stepping of aeolian dunes (Rubin, 1987) or deflation effects in the stoss-face of migrating dunes.

Longitudinal dunes

This architectural element has a very complex pattern as it consists of the overlapping of a series of cross-bedded sets that reach a thickness of up of 10m and are associated with sandy levels formed by low angle layers due to the migration of aeolian ripples. One distinct feature is that adjacent or overlapped cross-bedded strata have fairly discontinuous wedged and lenticular geometries. Front layers are inclined in two preferential directions with a 100º separation (Fig. 4) and they create a very typical zig-zag pattern in the outcrop. They also present a diverse morphology, including slightly tangential, trough, and wedge laminae (Figs. 8 and 11). The last features are limited by a lower bounding surface with a steep inclination angle, internal layers whose dip matches that of the basal surface, and an upper stratification plane with a marked truncation (Fig. 11).

Consequently, these deposits are due to the migration and vertical accretion of small-scale longitudinal (Bagnold, 1941) or linear (Tsoar, 1989; Bristow et al., 2000) aeolian dunes. The zig-zag pattern and marked bimodality of foreset orientation are ascribed to deflection of aeolian currents oblique to crest orientation in seif linear dunes (Tsoar, 1982, 1983; Chakraborty, 1993; Bristow et al., 2000).

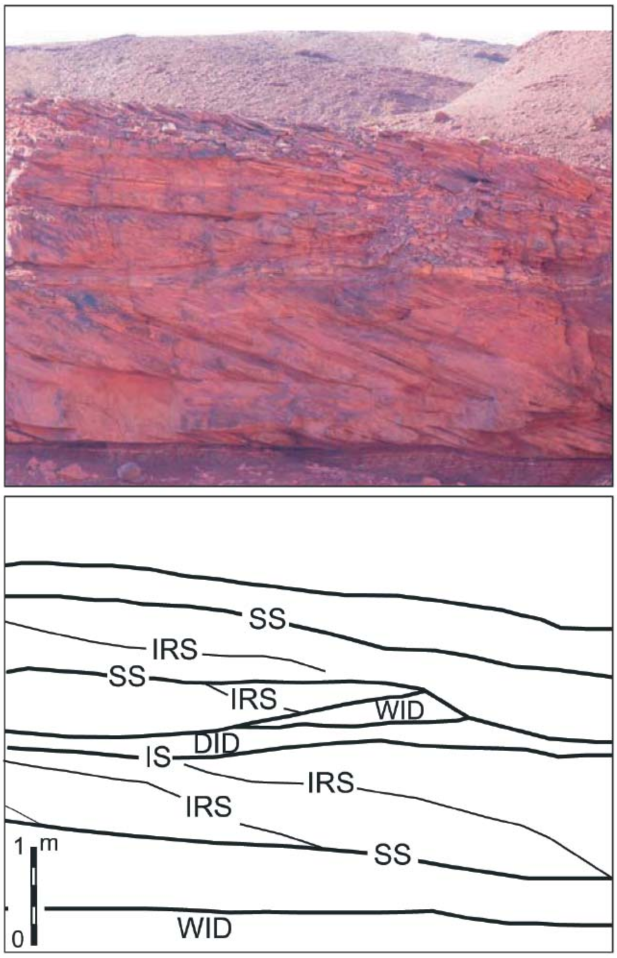

FIGURE 10 | **Superimposed cross-bedded sets representing grouped crescentic aeolian dunes. SS: superimposition surface; IRS: internal reactivation surface; IS: interdune surface; WID: wet interdune deposits; DID: dry interdune deposits. (See Fig. 4 for location).**

Draa with superimposed crescentic dunes

These sedimentary deposits are characterised by 6 to 20m thick sequences composed of two elements. The lower one corresponds to tabular cross-bedded megasets of up to 8m thick, consisting of more than 2cm thick tangential foresets (Fig. 12). The upper element is composed of an amalgamation of aeolian cross-bedded strata of smaller scale (no greater than 1m) and tabular geometry (Fig. 12). The cross-laminae are consistently oriented in the same direction and they also coincide with that of the underlying cross-bedded megaset (Figs. 4 and 12). From the foregoing discussion it follows that they result from the stepping of crescentic aeolian dunes similar to the ones described by Rodríguez-López et al. (2008). However, there are also small isolated cross-bedded intercalations (0.2-0.3m) that present an opposite or oblique orientation (protodune) and that step over draa leeward faces.

The surfaces bounding each cross-bedded set can present different geometries (Figs. 12 and 13). The most frequent ones are surfaces that are inclined downwind with variable angles (Figs. 12 and 13). Kocurek (1996) has characterised such surfaces as superimposition surfaces, and attributes them to aeolian dune migration towards the lee-side of aeolian macroforms (draa), with poor development of slipfaces. However, the fact that the same effect could be achieved when aeolian dune trains migrate in a sense that is oblique to the forward direction of draa should be borne in mind (Tatum, 2007). It should be pointed out that, in some cases, these superimposition surfaces show a steep inclination angle (over 20º), which is why it is assumed that they represent the direct migration of aeolian draa and/or dunes over an inactive avalanche face of a previous draa (Fig. 13).

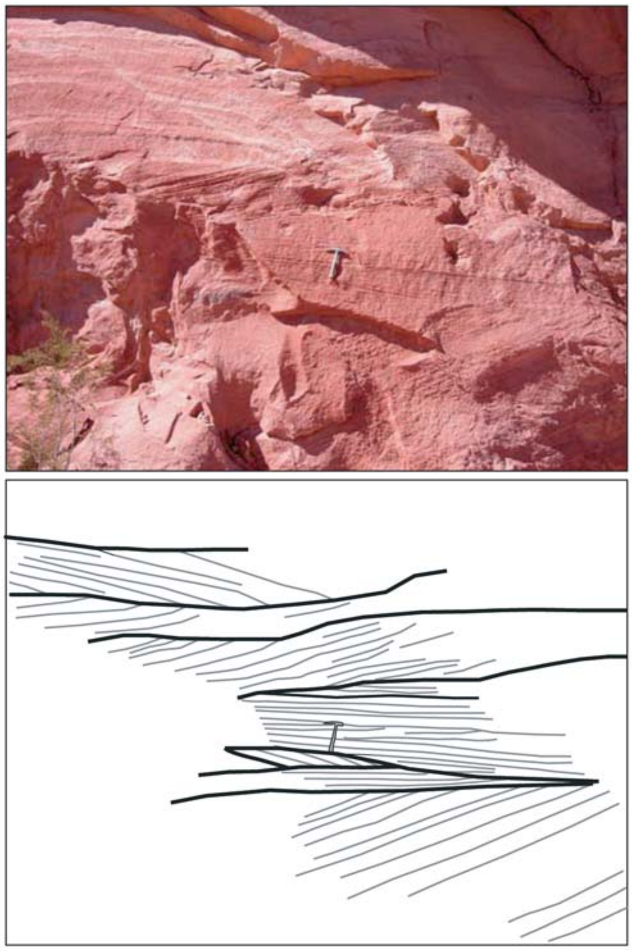

FIGURE 11 | **Zig-zag cross-stratified sets representing the deposit of a longitudinal (linear) aeolian dune. (See Fig. 4 for location).**

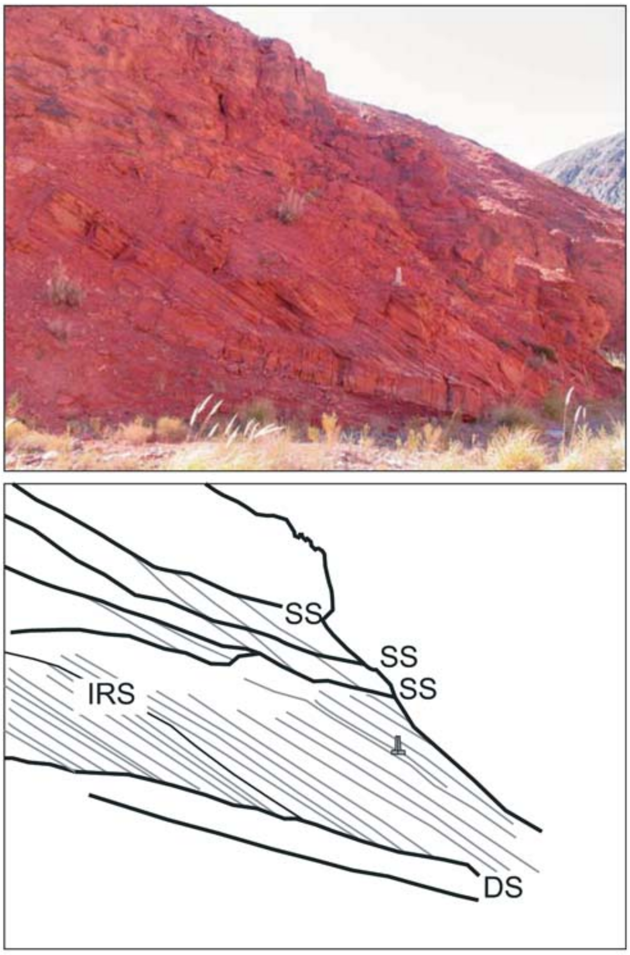

FIGURE 12 | **Draa deposit showing a lower giant-scaled cross-bedded set covered by thinner aeolian cross-bedded units formed by migration of superimposed aeolian dunes. The monolith is 1m high. DS: deflation surface; IRS: internal reactivation surface; SS: superimposition surface. (See Fig. 4 for location).**

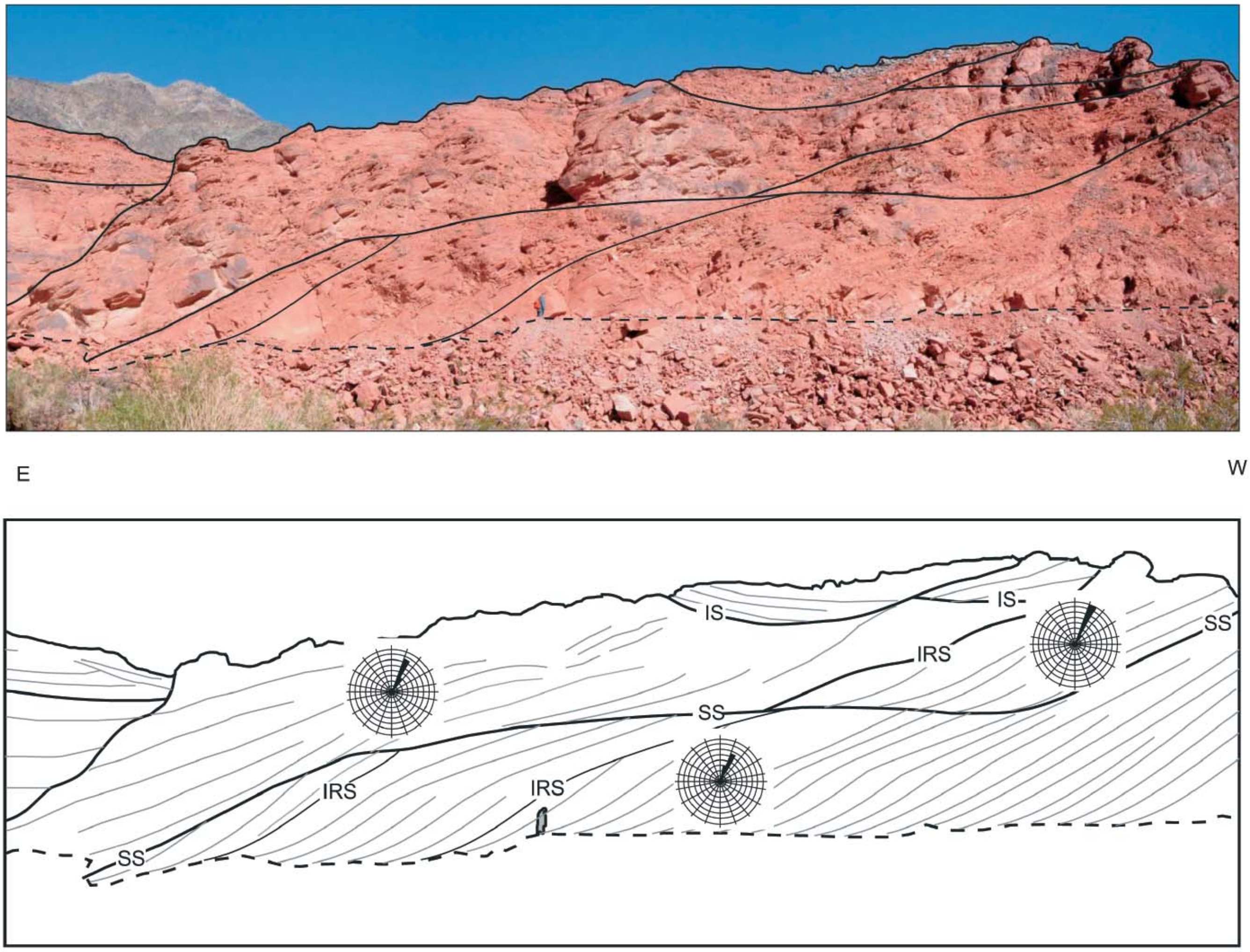

FIGURE 13 | **Wind-perpendicular section showing superimposed giant-scaled cross-bedded sets interpreted as draa deposits, covered by thinner aeolian cross bedded units. SS: superimposition surface; IRS: internal reactivation surface; IS: interdune surface. (See Fig. 4 for location).**

DISCUSSION

Two major depositional systems can be defined in the analysed Permian sedimentary sequence of the Sierra de Narváez. These systems show closely related vertical relationships. On the one hand, a set of aqueous sediments suggests the development of an ephemeral system of a terminal alluvial fan type which ended in a shore or mudflat environment (Olsen, 1987; Kelly and Olsen, 1993; Collinson, 1996; Bull, 1997; Bourke and Pickup, 1999; Tooth, 2000). On the other hand, large aeolian sand deposits constitute strong evidence of sand sea system formation, i.e. ergs (Glennie, 1970; McKee, 1979; Loppe, 1985).

The interaction between aeolian and fluvial systems can respond to cyclical changes in climatic conditions, accommodation space and location of the water table (Mountney et al., 1999; Veiga et al., 2002; Mountney, 2006). They may also represent several locations within the sedimentary basin with dominance of fluvial deposits in up-wind sections and aeolian deposits within the erg (Mountney and Jagger, 2004; Veiga and Spalletti, 2007).

It seems that the Permian aeolian deposits of Sierra de Narváez were most likely conditioned by temporal variations in climatic conditions (Kocurek, 1998; Swezey, 2003) in a markedly arid context. In this regard, a progressive increasing aridity at regional scale has been cited for the Middle to Upper Permian in several areas of south-western Gondwana (López Gamundí et al., 1992; Scherer, 2000; Limarino and Spalletti, 2006; Nardi Dias and Scherer, 2008).

The development of deflation sand-drift surfaces that overlie ephemeral fluvial and playa lake deposits, and of extinction surfaces, located on top of sand sea records constitutes significant evidence of the aforementioned climatic variability. As shown in Figure 10, the location of key surfaces and the vertical stacking of facies associations allow us defining large scale cycles that attain several meters in thickness (Fig. 14). More humid hemicycles, with a shallow water table position, contributed to the development of extinction surfaces and the dominance of terminal fan - mudflat deposits, associated with marginal aeolian facies or aeolian sand sheets (Swezey, 2003; Mountney and Jagger, 2004; Mountney, 2006). The hemicycles represented by the onset and development of erg systems correspond to drier and windier environmental conditions. The decrease in the water table position during these periods may be related to a relative eustatic fall (Soreghan et al., 2002) or to overfeeding conditions (high value in the relationship between sand supply and basin subsidence). Thus, the development of drier climatic conditions could have led to flat sand-drift surfaces and to a greater availability of fluvial sands to be mobilised by the wind whilst vegetation coverage decreased in density (Kocurek, 1998; Mountney and Howell, 2000; Veiga et al., 2002; Swezey, 2003; Mountney, 2006). The establishment of the aeolian system over the above mentioned surfaces could have been essentially determined by sand supply and availability, and by the capacity of the wind to transport the sand (Kocurek and Lancaster, 1999). An important sand supply provided by ephemeral fluvial systems could therefore have been the main source of texturally mature materials for the Permian erg development.

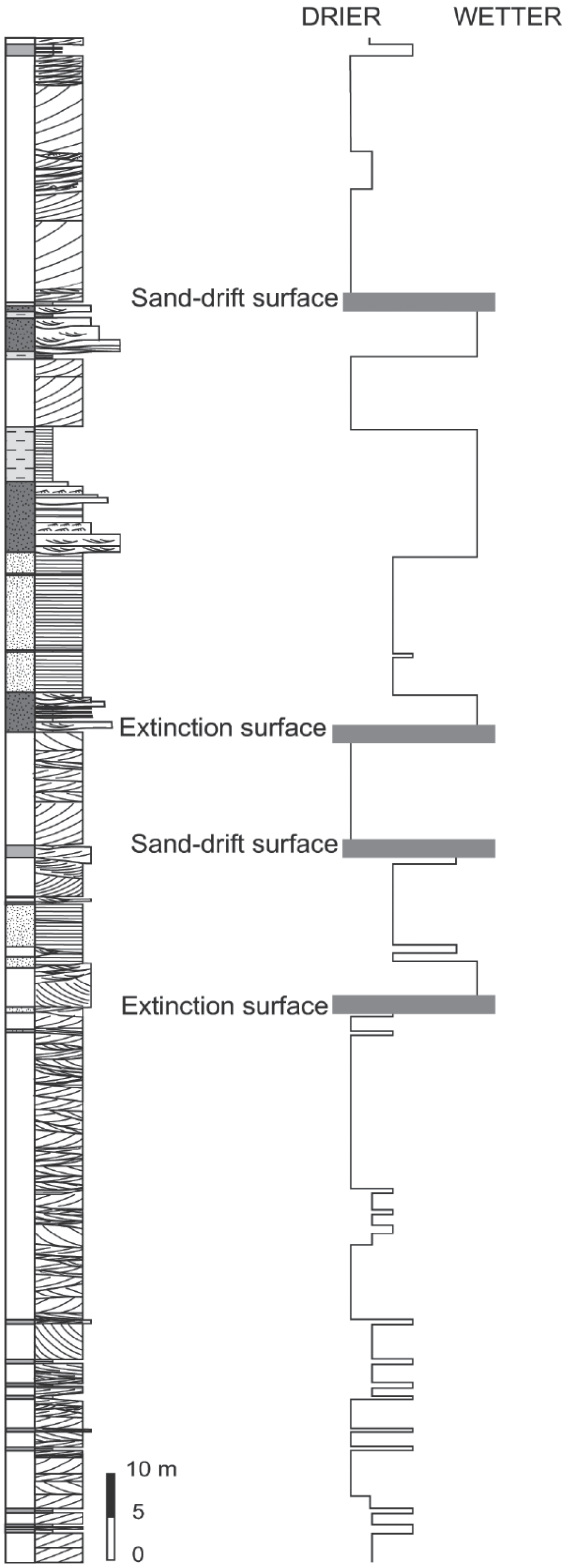

FIGURE 14 | **Schematic representation of the sedimentary log showing the main bounding surfaces (sand-drift surfaces and extinction surfaces). Note hemicycles resulting from alternation of wetter and drier periods.**

It is also worth noting that, especially in drier hemicycles, shorter-term rhythms are defined, in which there is a dominant element of draa deposits alternating with one another in which dune and interdune deposits are characteristic (Fig. 14). Although these higher frequency cycles could be attributed to subtle climatic changes, they could also be due to variations in sand supply and availability.

As regards the Paganzo Basin and neighbouring areas, the significant episode of environmental desiccation with conditions that favoured the development of aeolian deposits seems to be closely related to the growth of the important volcanic chain represented by the Choiyoi Group (Groeber, 1946; Stipanicic et al., 1968; Yrigoyen, 1972). This barrier, which was palaeogeographically significant, divided the western margin of Gondwana into two areas (Fig. 15A). The western area (Chilean Basin) received a strong marine influence that gave rise to milder conditions; and the eastern area (Paganzo Basin) had a marked inland-style with a much drier climate, related to the rain shadow effect produced by the growth of the volcanic chain (Fig. 15A). Furthermore, this topographic highland isolated the Paganzo Basin from marine transgressions during the Late Early Permian despite the persistence of a relatively high sea level position (Haq and Schutter, 2008) during this period.

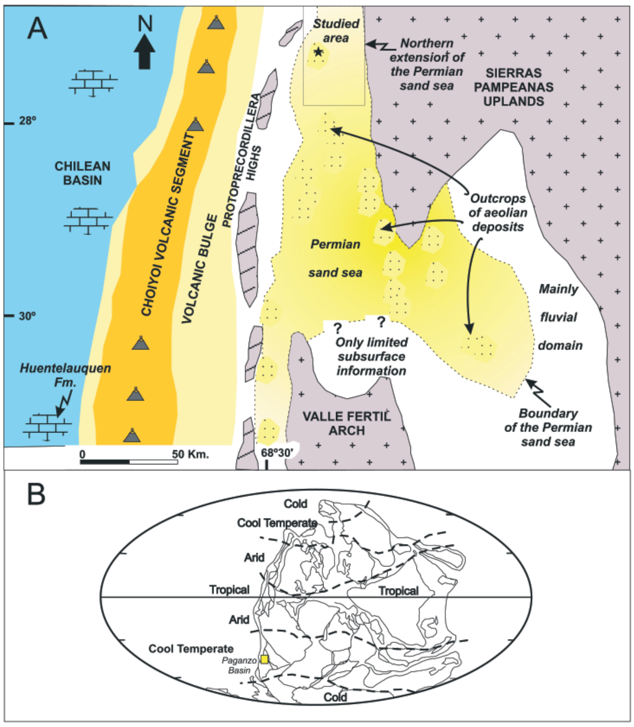

FIGURE 15 | **A) Palaeogeographic sketch of the Paganzo Basin and neighbouring areas during the Lower-Middle Permian. B) Lower Permian (Cisuralian) global palaeogeography and climatic belts (Tabor and Poulsen, 2008). Note the location of the Paganzo Basin in the Cool Temperate Belt.**

As accounts with many present day world deserts, another possibility is that the development of the Permian sand sea of the Paganzo Basin would be related to a high-pressure system. These systems and the correlative arid belts form at low latitudes, between 20 and 40 degrees from the equator; however, the palaeogeographic reconstruction of the Permian Pangea (Fig. 15B) clearly shows that the Paganzo Basin was located at higher latitudes, in the cool temperate palaeoclimatic belt (Tabor and Poulsen, 2008).

The aeolian outcrops of Sierra de Narváez area play a major role in estimating the regional extension of the aeolian sand sea, and in establishing the regional relationships with non-aeolian sequences located to the west (Chile) and northwest (northern Argentina). The location of the outcrops of the Sierra de Narváez enables us to extend the aeolian sand sea towards the northernmost sector of the Paganzo Basin. Thus, the aeolian sand sea could have covered a minimum area of 85,000 km^2. As shown in Figure 15A, only the eastern flank of the Paganzo Basin seems to have been dominated by fluvial deposits, probably because of the humid conditions owing to the proximity to the Sierras Pampeanas upland.

From a palaeogeographic viewpoint, the Permian outcrops of Sierra de Narváez link the aeolian deposits of the Paganzo Basin to those located to the west, in the volcanic segment (Choiyoi arc) and in the Chilean Basin. The aeolian succession studied in this paper is located to the southeast of the Arizaro Formation (Aceñolaza et al., 1972), which crops out in the north of Argentina close to the boundary with Chile (along the Choiyoi volcanic segment). The aeolian deposits seem to be contemporaneous with the Upper Member of the Arizaro Formation, which consists of marine fossil invertebrate bearing limestones. Moreover, the Permian aeolianites could be correlated with marine carbonates of the Chilean Basin known as the La Cantera Member of the Huantelauquén Formation (Muñoz-Cristi, 1973). Thus, the aeolian sand sea deposits of the Paganzo Basin and the shallow marine carbonates accumulated to the west suggest the existence of warm arid/semiarid conditions along the western margin of Gondwana during the Middle Permian.

CONCLUSIONS

As a result of the sedimentological study of the Permian De La Cuesta Formation outcrops in Sierra de Narváez it is possible to recognise facies associations belonging to aeolian dunes, dry aeolian interdune and aeolian sand sheet, mudflat, wet aeolian interdune and ephemeral fluvial systems.

Aeolian deposits, which constituted erg sequences dominated by dune facies associations, were limited at the base by sand-drift surfaces, and at the top by extinction surfaces.

The main architectural elements recognised in the erg sequences are aeolian dune and interdune deposits, grouped crescentic aeolian dunes, longitudinal dunes, and draa with superimposed crescentic dunes.

Two main deposition systems: a terminal alluvial fan - mudflat, and a sand sea or erg are defined in the De La Cuesta Formation. These systems are ascribed to temporal variations in climatic conditions that led to considerable changes in the water table position and, hence, in the accommodation and supply of sands susceptible to aeolian mobilisation.

Climatic changes are evident in large scale cycles in which hemicycles bounded by deflationary sand-drift surfaces and extinction surfaces are recognised. Ephemeral fluvial and mudflat deposits prevailed in more humid hemicycles, and erg sequences developed during drier hemicycles.

It is possible to recognise alternation between grouped dune (draa) accumulations and simple dune sets separated by interdune elements in drier hemicycles. These lower scale cycles are attributed to less intense and shorter climatic variations and also to changes in sand contribution and to its availability for aeolian transportation and deposition.

The positive relief represented by the Choiyoi Group volcanic chain would have played a critical palaeogeographical role not only in the generation of arid conditions in the continental inland, but also in the development of a Permian erg even in conditions of high global sea level positioning. Palaeocurrent data indicate that wind transport direction was mainly towards the NNE and NE, therefore the volcanic chain would have controlled the characteristics of the air flow, acting as an effective climatic barrier for storm systems. The presence of deposits characterised by various styles of aeolian - fluvial interaction to the southwest of the province of Catamarca (northwest Argentina) enables us to estimate an approximate area of 85,000 km^2 for the Permian desert of the Paganzo Basin.

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