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Hierarchy of bounding surfaces in aeolian sandstones of the Jurassic Tordillo Formation (Neuquén Basin, Argentina)

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ABSTRACT

The Tordillo Formation is a continental clastic unit deposited in the Neuquén Basin during the Late Jurassic. This paper discusses the stratigraphy of the succession outcropping at the Quebrada del Sapo, with emphasis on the origin, dimensions and hierarchy of bounding surfaces of aeolian deposits. Field survey, supported by the measurement of three detailed stratigraphic sections and line drawings of photographic panels allow the identification of four unconformity bounded units within the succession, informally named as T1, T2, T3 and T4. Units T1 and T3 are composed of conglomerates and pebbly sandstones deposited by density flows in a lacustrine environment. Paleocurrents indicate a source area located in the northeast while the presence of angular sandstone blocks suggests resedimentation processes. T2 and T4 units are composed of fine to medium grained sandstones of aeolian origin, characterized by large scale dunes and minor dry interdunes. Both units have sharp bases, and overlie a deflation surface characterized by the presence of ventifacts. Paleocurrents suggest a paleowind direction from the southwest. Internal bounding surfaces show a hierarchy of at least four discrete surfaces which were numbered according to their crescent extension. Type 1 surfaces are related to the normal advance of the dune front. Type 2 are reactivation surfaces within a single dune set. Type 3 surfaces relate to set superposition. Type 4 surfaces are related to extensive deflation of the dune complex, and define at least nine elementary aeolian sequences in the T4 unit.

KEYWORDS **Aeolian deposits. Tordillo Formation. Neuquén Basin. Argentina. Jurassic.**

INTRODUCTION

The Kimmeridgian Tordillo Formation is a mainly clastic unit broadly developed in the Neuquén Basin, western Argentina (Fig. 1). It is composed of reddish and greenish conglomerates, sandstones and mudstones, deposited in different non-marine environments, ranging from alluvial fans to lacustrine and aeolian systems (Peroni et al., 1984; Gulisano, 1988; Arregui, 1993; Vergani et al., 1995). The formation displays an irregular thickness

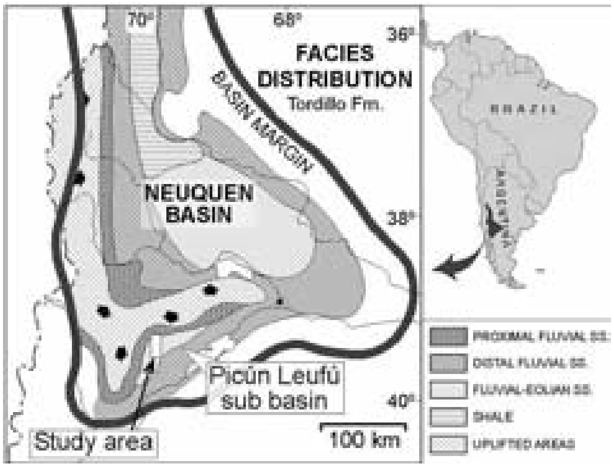


FIGURE 1 | **Location map of the Neuquen Basin with indication of the distribution and main facies types of the Tordillo Formation. Modified from Vergani et al. (1995).**

which can exceed 700 metres, and was accumulated as a consequence of a temporary disconnection of the Neuquén Basin from the paleo-Pacific Ocean (Mutti et al., 1994a; Legarreta, 2002), occurred at the beginning of the sedimentation of the Mendoza Group (Fig. 2). Aeolian deposits are extensively developed in the central part of the basin (Fig. 1), where in appropriate conditions can contain large hydrocarbon accumulations (i.e. Loma La Lata field; Fig. 3).

Despite its extension in the subsurface, outcrops of aeolian deposits of the Tordillo Formation are scarce, and only recognized southward of the Huincul Arch (Picún Leufú Sub-basin, Figs. 1 and 3) as part of an equivalent clastic unit known as Quebrada del Sapo Formation (Parker, 1965; Digregorio, 1972). The outcrops of the Quebrada del Sapo Formation constitute a narrow fringe along the southern flank of the Picún Leufú anticline with a variable thickness ranging between 0 and 60 m (Freije et al., 2002).

The present contribution is focused on the study of the origin, stratigraphy, facies changes and internal hierarchy of aeolian clastic bodies of the Tordillo Formation outcropped at the Quebrada del Sapo (Fig. 4). The final goal of this research was to contribute to a better understanding of the dimensions and internal characteristic of oil-bearing sandstone bodies interpreted as aeolian deposits in the central part of the basin, using interpretations and data derived from field studies in equivalent strata.

Field studies included a detailed mapping of the locality, complemented by the description of three detailed stratigraphic sections. The existence of continuous exposures permitted the construction of photographic panels to trace the shape and internal geometrical features recognized within these aeolian clastic bodies. The last procedure was to estimate the hierarchy and continuity of internal bounding surfaces. These bounding surfaces were also

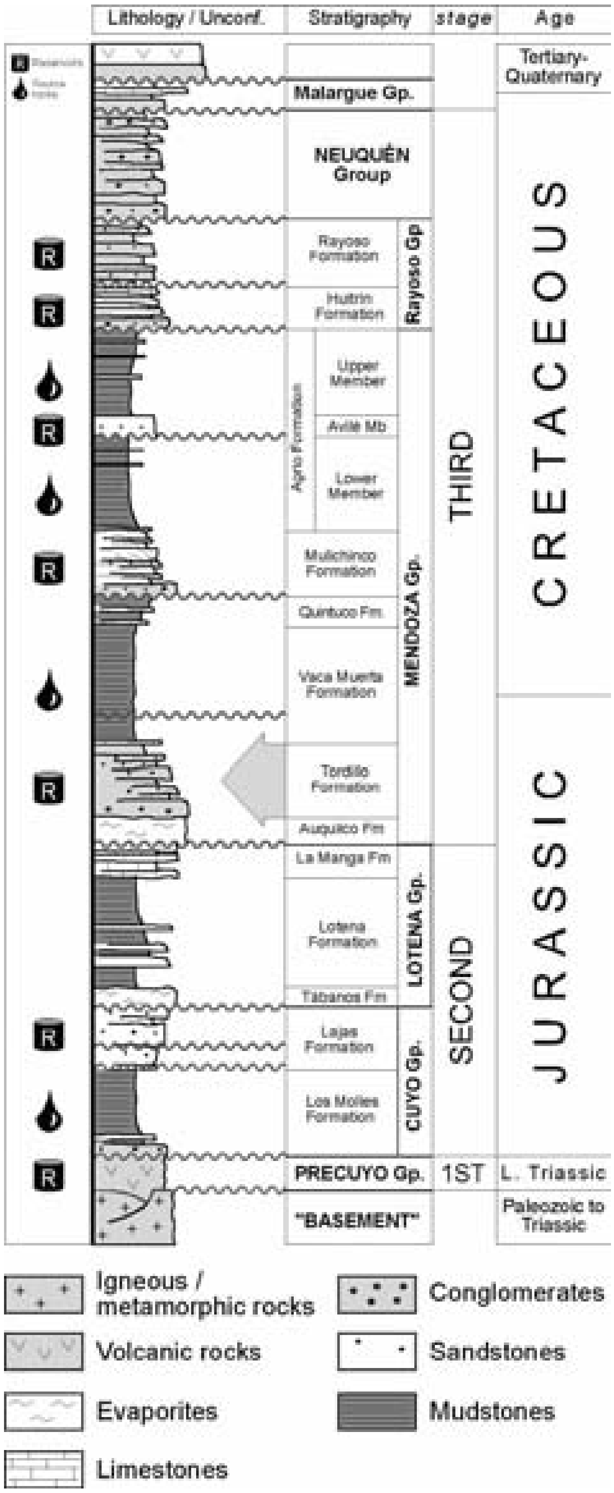


FIGURE 2 | **Schematic stratigraphic column of the Neuquén Basin (not to scale) with indication of the main souce and reservoir hydrocarbon rocks. The grey arrow indicates the stratigraphic position of the Jurassic Tordillo Formation.**

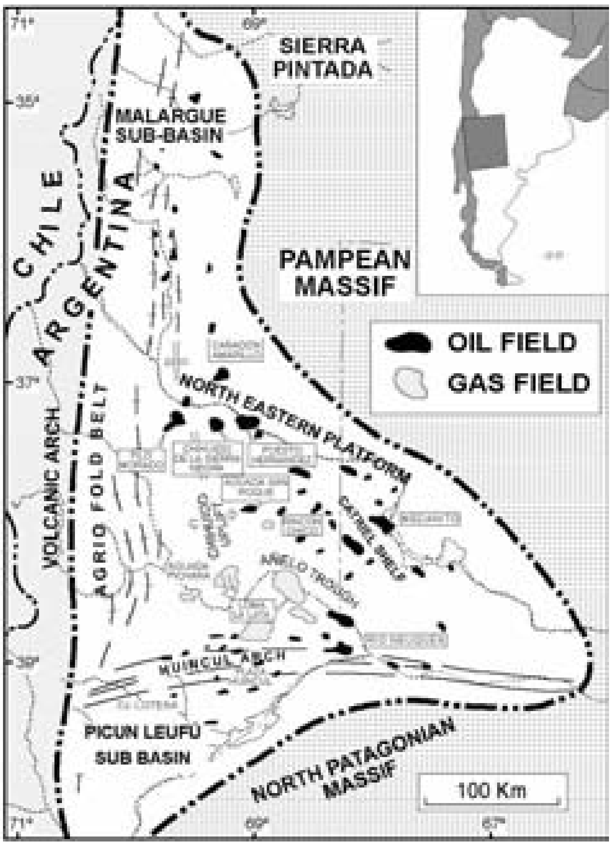


FIGURE 3 **Main geologic features of the Neuquén Basin. The location of major oil and gas fields is indicated (Modified after Hogg, 1993).**

sampled in different positions to evaluate the possible existence of physical barriers for migrating fluids along their extension.

GEOLOGICAL FRAMEWORK AND STRATIGRAPHY

Located in the Southern Andes, the Neuquén Basin is the main oil-bearing basin of Argentina. This basin was defined as a Late Triassic back-arc basin developed over continental crust and generated by thermal-tectonic collapse behind a stationary magmatic arc (Mpodozis and Ramos, 1989). Their sedimentary infill took place mainly during the Jurassic and Cretaceous with a clastic succession up to 7000 m thick (Fig. 2). During the accumulation of this succession, three main depositional stages can be recognized (Zavala and González, 2001): The first stage (Late Triassic - Early Jurassic) is syn-rift and characterized by the deposition of volcanic and volcanoclastic materials (Precuyo Group) along half-graben depocenters where they show a high variable thickness (Gulisano, 1981). The second stage (Early-Late Jurassic) is represented by a mainly clastic prograding continental to marine succession (Cuyo and Lotena groups), deposited over a tectonically-induced irregular relief. Several tectonic episodes and sea level changes occur during its deposition, resulting in a pronounced control on facies changes and geometry of their corresponding units. The third stage (Late Jurassic - Late Cretaceous) is integrated by an up to 6 km thick marine to continental succession (Mendoza, Rayoso and Neuquén groups). These deposits have the most extensive geographical occurrence in the basin, and their thickness changes more regularly.

Gas and oil production in the basin (Fig. 3) is mainly concentrated in three areas: 1) The basin center, which is a mainly gas-bearing zone, 2) the north-eastern platform, and 3) the Huíncul Arch (Hogg, 1993). Main source rocks belong to the third stage (Vaca Muerta and Agrio formations), although the Los Molles Formation (first stage) has some oleogenetic potential (Fig. 2). Reservoirs are relatively common in the three stages (Fig. 2), but their optimum characteristics frequently depend on structural, stratigraphic and diagenetic factors.

THE TORDILLO FORMATION AT THE QUEBRADA DEL SAPO

Previous studies of the Tordillo Formation performed on outcrops located in the surroundings of the bridge of the 40 road over the Picún Leufú stream (Zavala and Freije, 2001a; 2002) suggest the existence of two sub-units (or sequences). The lower unit (or sequence 1) is composed of conglomerates and coarse grained sandstones deposited in a fluvio-lacustrine environment. These coarse grained strata show diverse paleocurrents generally oriented towards the Southwest, thus suggesting an origin related to Jurassic clastic wedges developed at the southern side of ancient exposures of older strata along the Huincul Arch. The sequence 1 is sharply overlaid by fine to medium grained sandstones assigned to sequence 2 that are interpreted to have been deposited in an aeolian

FIGURE 4 **Location map of the Quebrada del Sapo area.**

environment characterized by dune and dry interdune facies. At the boundary between sequences 1 and 2 a regional deflationary surface with ancient serir deposits has been identified.

In the Quebrada del Sapo area (Fig. 4) the Tordillo Formation uconformably overlies reddish and greenish mudstones with plant debris assigned to the Lotena Formation (Fig. 5). Here the Tordillo Formation is composed of conglomerates and coarse grained sandstones interbedded with fine to medium grained gray sandstones. The Tordillo Formation is in turn sharply covered by well stratified black shales containing ammonoids, which characterize the base of the Vaca Muerta Formation. Field survey in strata of the Tordillo Formation at the Quebrada del Sapo identified four unconformity bounded units of regional extent informally named T1, T2, T3 and T4 (Fig. 5). The four unconformity bounded units are interpreted to have been deposited in fluvio-lacustrine (T1 and T3 units) and aeolian (T2 and T4 units) environments. The detailed description of the exposures at the Quebrada del Sapo allowed also the identification of 11 clastic facies. A synthesis of the main characteristics of these facies is presented in Fig. 6, where they were grouped according to their relation to aeolian or fluvio-lacustrine environments.

Unit T1

This unit is up to 12 m thick and unconformably overlies greenish and reddish mudstones with plant debris of the Lotena Formation (Fig. 5). Unit T1 is composed of: conglomerates and coarse grained sandstones, which appear massive (facies HCF in Figs. 6 and 7A and RCg in Fig. 9B) or laminated with traction carpets (facies CT in Figs. 6 and 7A); medium to coarse grained sandstones with anisotropic hummocky cross stratification (in the

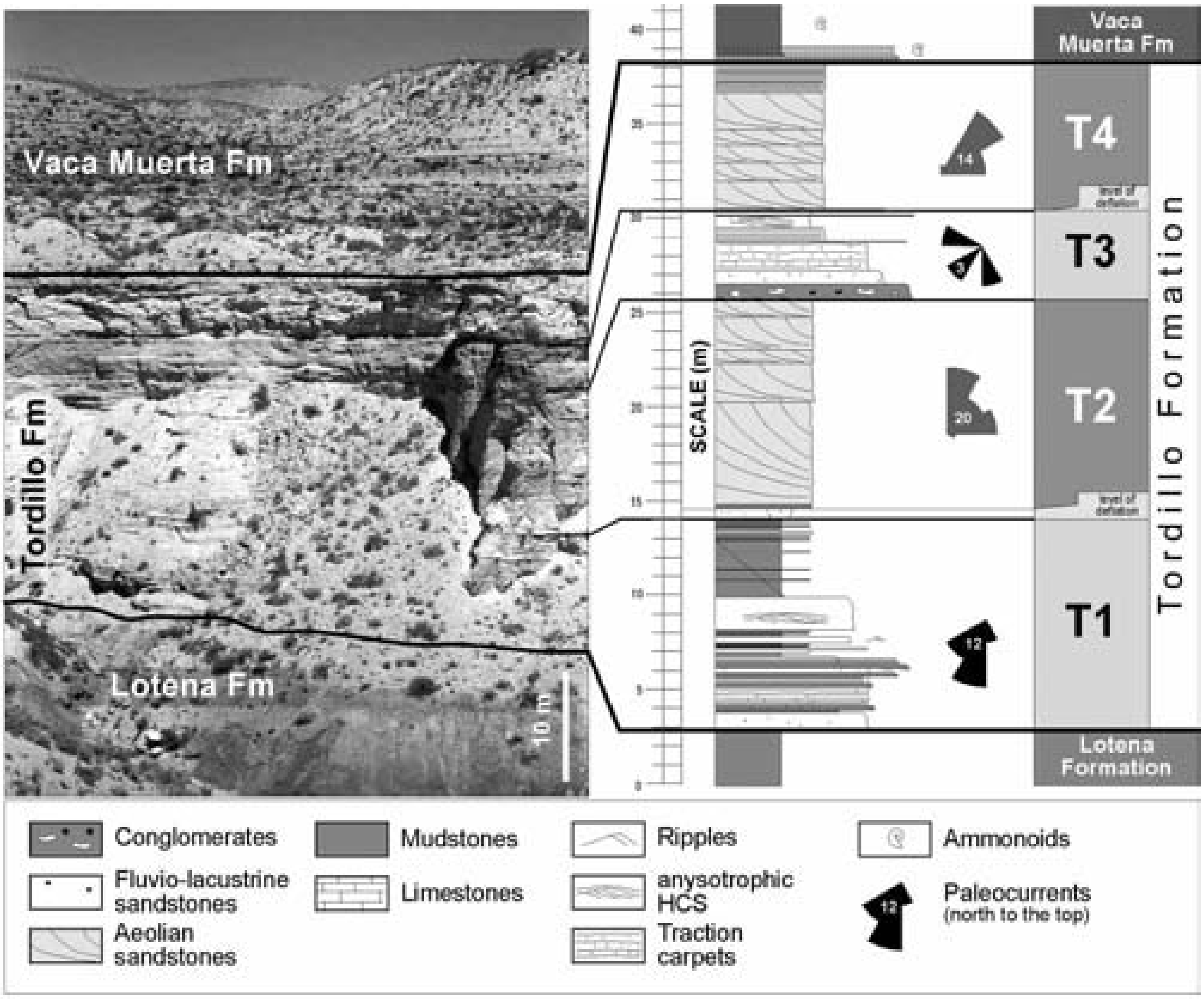
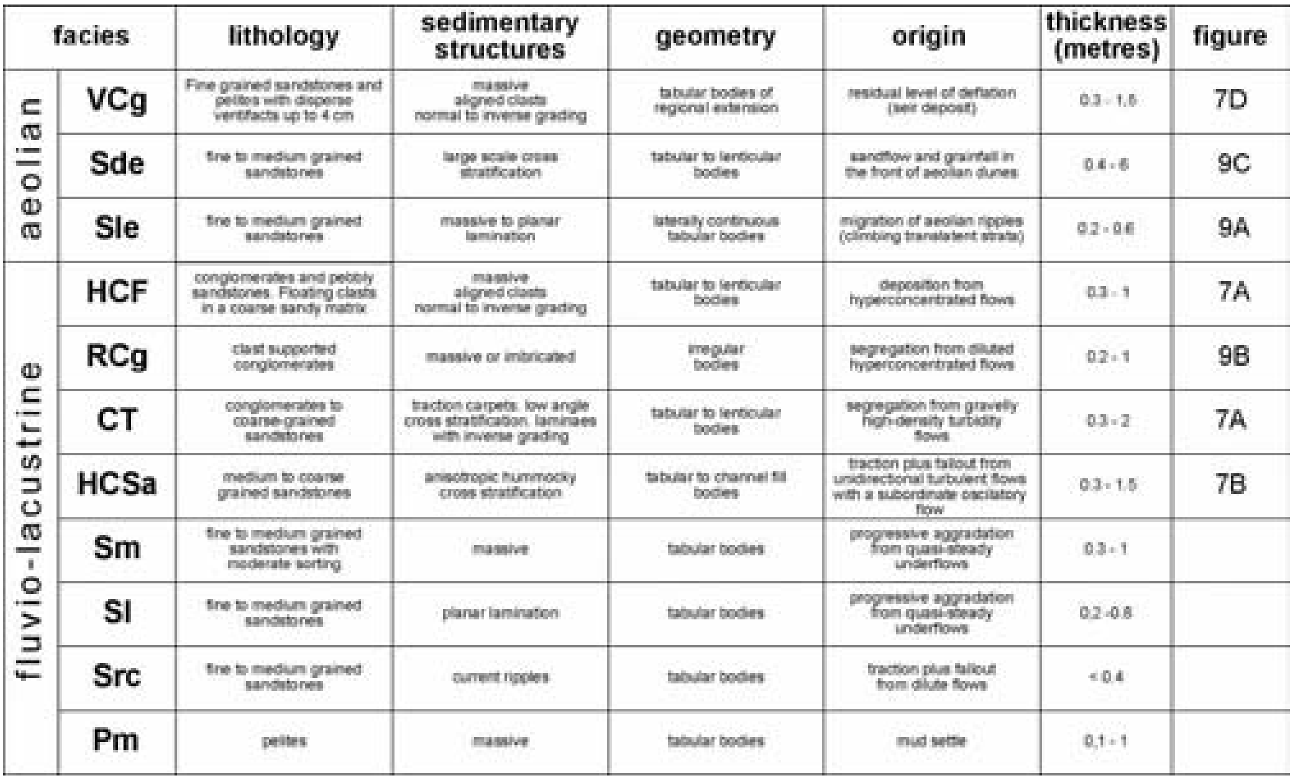


FIGURE 5 | **Panoramic view and stratigraphic scheme with the measured paleocurrent directions of the Tordillo Formation outcropping at the Quebrada del Sapo. Note that units T1 and T3 show paleocurrents toward the Southwest whereas units T2 and T4 are directed toward the Northeast.**



facies		lithology	sedimentary structures	geometry	origin	thickness (metres)	figure
aeolian	VCg	Fine grained sandstones and pelites with disperse ventifacts up to 4 cm	massive aligned clasts normal to inverse grading	tabular bodies of regional extension	residual level of deflation (seir deposit)	0.3 - 1.5	7D
	Sde	fine to medium grained sandstones	large scale cross stratification	tabular to lenticular bodies	sandflow and grainfall in the front of aeolian dunes	0.4 - 6	9C
	Sle	fine to medium grained sandstones	massive to planar lamination	laterally continuous tabular bodies	migration of aeolian ripples (climbing translatent strata)	0.2 - 0.6	9A
fluvio-lacustrine	HCF	conglomerates and pebbly sandstones. Floating clasts in a coarse sandy matrix	massive aligned clasts normal to inverse grading	tabular to lenticular bodies	deposition from hyperconcentrated flows	0.3 - 1	7A
	RCg	clast supported conglomerates	massive or imbricated	irregular bodies	segregation from diluted hyperconcentrated flows	0.2 - 1	9B
	CT	conglomerates to coarse-grained sandstones	traction carpets. low angle cross stratification. laminaes with inverse grading	tabular to lenticular bodies	segregation from gravelly high-density turbidity flows	0.3 - 2	7A
	HCSa	medium to coarse grained sandstones	anisotropic hummocky cross stratification	tabular to channel fill bodies	traction plus fallout from unidirectional turbulent flows with a subordinate oscilatory flow	0.3 - 1.5	7B
	Sm	fine to medium grained sandstones with moderate sorting	massive	tabular bodies	progressive aggradation from quasi-steady underflows	0.3 - 1	
	Sl	fine to medium grained sandstones	planar lamination	tabular bodies	progressive aggradation from quasi-steady underflows	0.2 -0.8	
	Src	fine to medium grained sandstones	current ripples	tabular bodies	traction plus fallout from dilute flows	< 0.4	
	Pm	pelites	massive	tabular bodies	mud settle	0,1 - 1	

FIGURE 6 **Synthesis of main characteristics of clastic facies types recognized in the Tordillo Formation.**

sense of Mutti et al., 1994b; facies HCSa in Figs. 6 and 7B); and minor structured or structureless fine grained sandstones (facies Sm, Sl and Src in Fig. 6). The common occurrence of ventifacts among the lithic clasts evidences a previous aeolian abrasion in the surroundings. Individual beds display a thickness up to 1.5 m and contain thin intercalations of red and green mudstone levels on top (facies Pm in Fig. 6).

Both paleocurrents and facies changes (Fig. 8) indicate a source area located in the NNE. Facies analysis (Fig. 6) suggests that this unit was likely deposited by dense flows (hyperconcentrated and concentrated flows) of fluvial origin. The lack of evidences of subaerial exposure (like mud cracks or paleosols) or clear water stage facies, suggests a deposition in a subaqueous environment, probably lacustrine.

Unit T2

This unit is up to 15 m thick and unconformably overlies Unit T1 (Fig. 7C), starting above a regional level of deflation with ventifacts (facies VCg in Figs. 6 and 7D). Unit T2 is composed of laminated (facies Sle in Figs. 6 and 9A) to cross-stratified (meter scale) fine grained sandstones (facies Sde in Figs. 6 and 9C). The laminated sandstones often show inverse grading within the single lamina, which is characteristic of climbing translatent strata (Fig. 9A), a sedimentary structure diagnostic of aeolian processes (Hunter 1977).

Two distinctive successions can be recognized within Unit 2, which are informally indicated as “a” and “b” (Fig. 8). The lower one, succession “a”, is integrated by laminated sandstones partially cemented with carbonates and interbedded with rare thin mudstone layers. These characteristics suggest an aeolian deposition close to the water table. This succession has only been recognized in sections 2 and 3 (Fig. 8). The upper succession (“b”) is more widely distributed and entirely composed of fine grained sandstones with large-scale cross stratification related to aeolian dunes. Paleocurrents measurements on cross-stratified sandstones indicate that dominant paleowinds were from the southwest with a dispersion up to 120°. The last relatively small dispersion may suggest the existence of barjanoid or transverse type aeolian dunes (Glennie, 1970; Reineck and Singh, 1980).

Unit T3

This unit is up to 9 m thick and it is composed of conglomerates and pebbly sandstones, that unconformably overlie the aeolian deposits of unit T2 (Figs. 8 and 9D). The conglomerates in proximal areas (towards the north) contain large angular blocks of light gray sandstones up

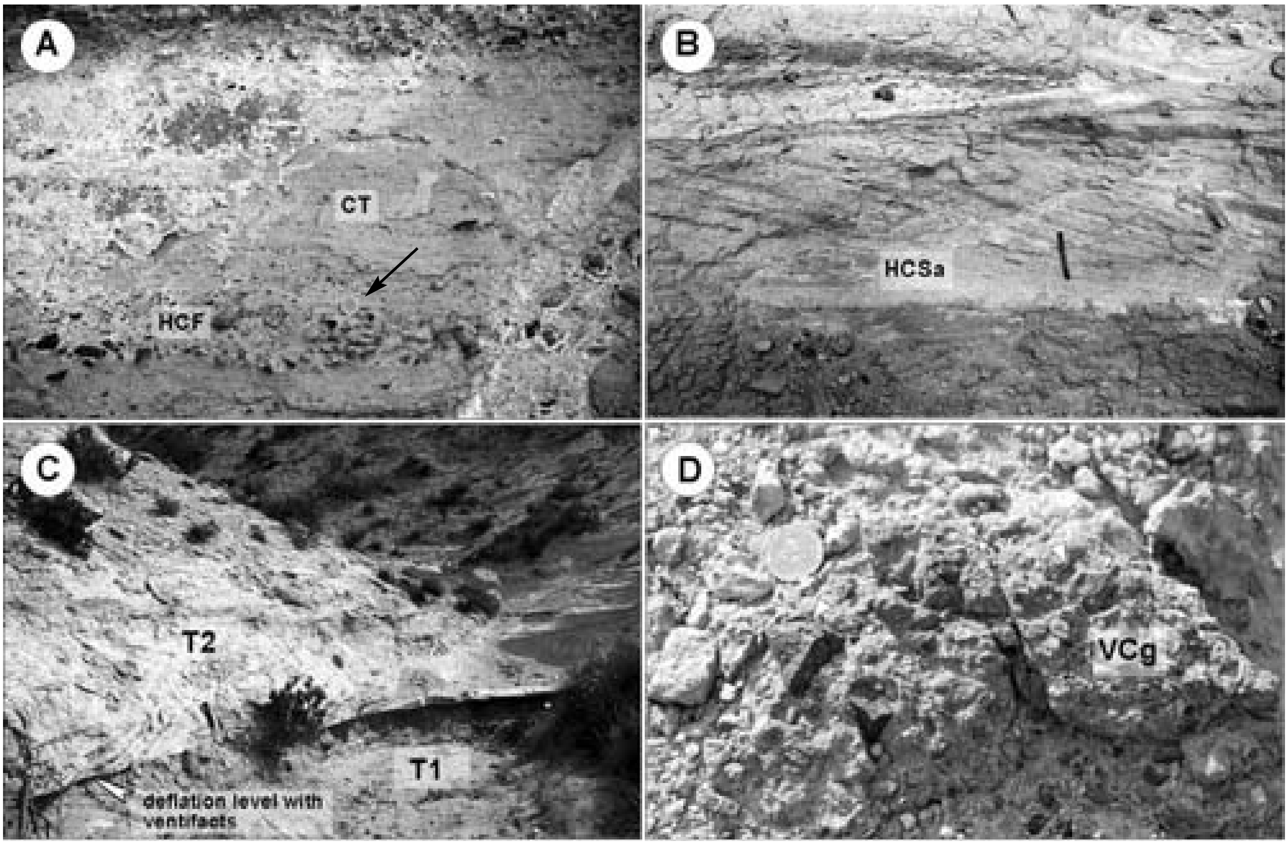


FIGURE 7 **Clastic facies of the Tordillo Formation. A) Graded beds related to hyperconcentrated flows (HCF) and pebbly sandstones with traction carpets (CT), coin 2.3 cm. B) Coarse grained sandstones with anisotropic hummocky cross-stratification (HCSa, paleocurrent to the right). C) Close up of the boundary between units T1 and T2. The position of the deflation level is indicated with a white arrow. D) Detail of the deflation level with ventifacts (white arrows) of facies VCg., coin 2.3 cm.**

to 40 cm in diameter. The existence of rounded fractured lithic clasts (Fig. 9B) strongly suggests an origin related to the redeposition from older deposits exhumed and eroded from adjacent areas. Paleocurrents measurements on cross-bedding and facies changes (Fig. 8) give evidence of a source area located between the North and East. Facies analysis suggest an environment similar to that of Unit T1, characterized by dense flows of fluvial origin accumulated in a subaqueous environment, probably lacustrine.

Unit T4

Unit T4 sharply overlies Unit T3 with a residual (deflationary) level of regional extent characterized by the presence of ventifacts. Unit T4 is up to 11 m thick and is almost entirely composed of fine to medium grained sandstones which display distinctive large scale cross stratification (facies Sde in Fig. 6) with individual sets that can exceed 6 m (Figs. 9C and 9D). Other minor facies include laminated and massive sandstone beds. These sedimentological features together with the occurrence of sedimentary structures diagnostic of aeolian processes (like climbing translatent strata) suggests that this unit was probably deposited in an aeolian environment characterized by extensive dune fields. Paleocurrent measurements on large-scale cross bedding indicate a dominant paleowind direction from the southwest, which is generally similar to that of Unit T2. Nevertheless, the low dispersion (less that 90°) suggests the existence of transverse dunes (Glennie, 1970; Reineck and Singh, 1980).

From a more regional point of view, Unit T1 could probably be correlated with Sequence 1 of Zavala and Freije (2002), while units T2 to T4 could be equivalent to Sequence 2 of these authors. This interpretation is supported by the recent discovery (Gazzera, pers. comm.) of relatively thin intercalation of conglomerates with ventifacts within the aeolian deposits of Sequence 2 in the surroundings of the 40 road.

ORIGIN AND HIERARCHY OF BOUNDING SURFACES IN THE AEOLIAN DEPOSITS OF THE TORDILLO FORMATION

The use of line drawing techniques over photographic panels constructed from oblique photographs permits the

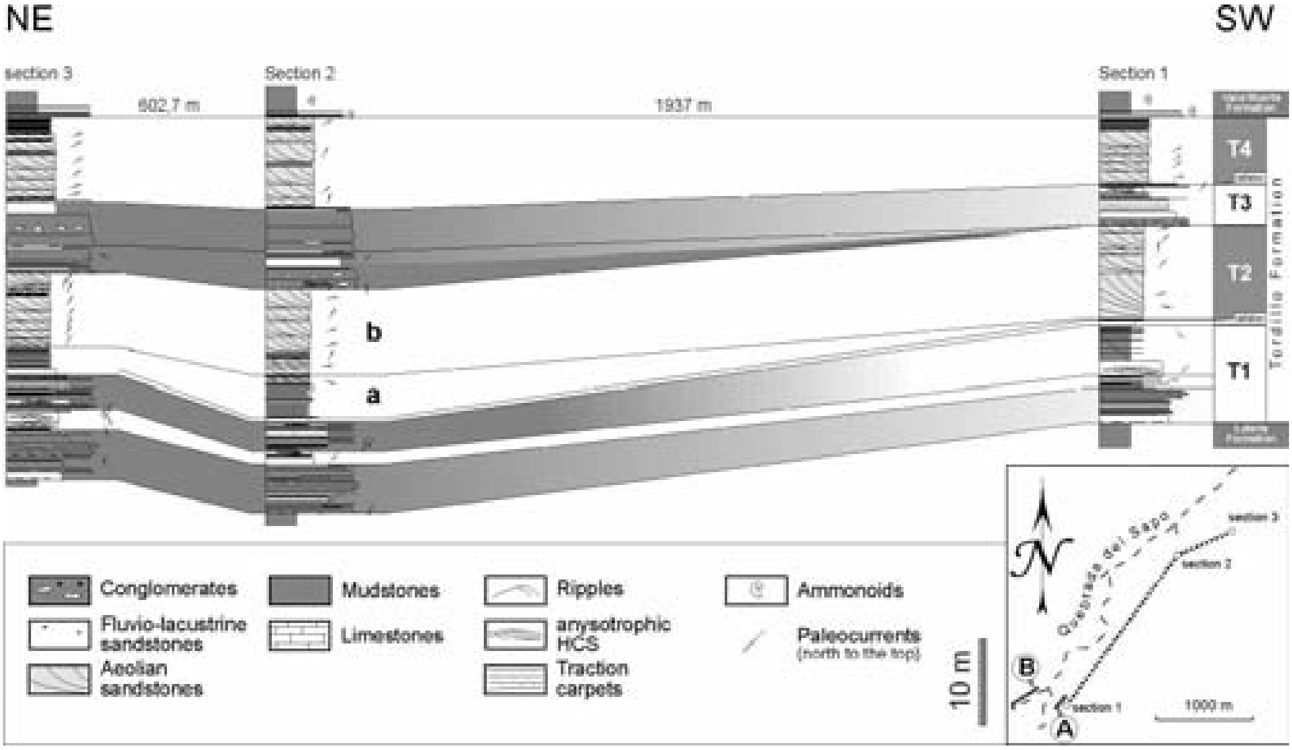


FIGURE 8 **Stratigraphic panel of the Tordillo Formation at the Quebrada del Sapo, flattened at the base of the overlying Vaca Muerta Formation. Note the existence of two distinct successions (a and b) within Unit T2. Units T1 and T3 show facies changes (fining) towards the southwest, which is consequent with the paleocurrents. In the detailed map on the lower right, A and B show the position of the line drawings of Figs. 10 and 11 respectively.**

measurement and detailed description of the internal characteristics of ancient dune fields (facies Sde) recorded in the T2 and T4 units. The existence of relatively continuous vertical cliff exposures of the Unit T4 in the Quebrada del Sapo provided two photographic panels extending 46 and 162 m respectively (Figs. 10 and 11). The detailed analysis of these panels revealed the existence at least of four categories of bounding surfaces, which can be classified according to their crescent degree of stratigraphic significance (Fig. 12).

Type 1 surfaces

These surfaces are parallel to subparallel and concave upward, displaying gentle dips near the base of the dune set and increasing angles towards the top. As can be noted in Fig. 13, the more common dip angles range from 19 to 27º, this is substantially less than the natural repose angle of fine to medium grained sand (34° approx.). The type 1 surfaces correspond to those developed as a consequence of a normal advance of the dune front (Fig. 12). Its origin relates to a punctuating advance, probably as a consequence of a discontinuous sand supply and the combined effect of sandflow and grainfall in the dune lee side. The maximum extension of this surface is directly related to the maximum thickness of a single dune set, which in the case considered can reach 20 m (Fig. 11).

Type 2 surfaces

These surfaces typically truncate type 1 surfaces at low angles (usually less than 10º) within a single dune set, and can be concave or convex upward (Fig. 12). The maximum observed extent of these surfaces is of 32 m. The origin of this surface is probably related to the action of episodic and reverse aeolian flows, which erode and modify the normal profile of the dune front.

Type 3 surfaces

They are commonly parallel to subparallel, and bound different and successive dune sets (Fig. 12), showing an extent up to 150 m. The surfaces could be slightly concave or convex upward and often lie subhorizontally, with dip angles between 2 and 10º in a direction roughly contrary with respect to that of the paleowinds. This inclination probably corresponds to the angle of climb between successive dune sets, and related to the passage of the dune trough (deflation zone) over the deposits of a pre-existent dune front (deposition zone). The final preserved thickness of the dune front depends on this angle of climb.

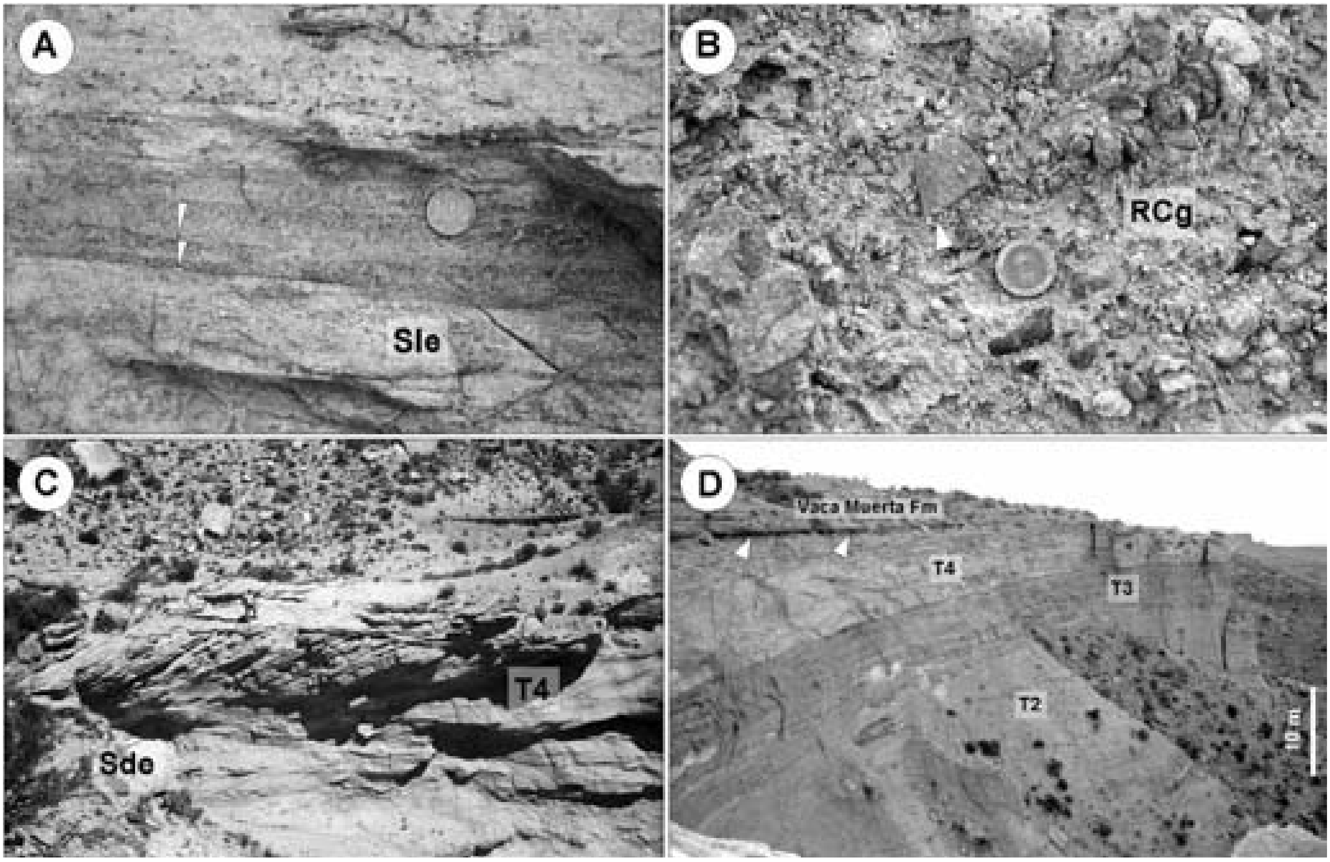


FIGURE 9 | **A) Close up of laminated sandstones of facies Sle, related to the migration of climbing translatent strata (Unit T2), a sedimentary structure diagnostic of aeolian processes. Note the inverse grading, which is characteristic, coin 1.8 cm Ø. B) Detail of the massive conglomerates (facies RCg) of Unit T3. Note the presence of fractured rounded clasts (white arrow), coin 2.3 cm Ø. C) Particular of dune facies (Sde) of the T4 Unit. Person 1.72 cm tall. D) Close up of the boundary between the Tordillo and the Vaca Muerta Formation (arrows).**

Type 4 surfaces

These surfaces are the more widely extended along the study area. Type 4 surfaces commonly are quite irregular, forming an erosional relief that can involve the whole thickness of the aeolian unit (in the case shown in Fig. 11, more than 8 m). The lateral continuity of the surfaces are often greater than 100 m, and can exceed the length of the exposures. For the upper aeolian unit (T4), the discrimination and mapping of type 4 surfaces (Fig. 11) allows the identification of at least nine elementary aeolian sequences (Table 1), each one having a variable extent, with general good lateral continuity and wide/depth relationships between 10 – 30. The type 4 surfaces could correspond to super surfaces (Talbot, 1985; Kocurek, 1988) related to allocyclical erosional processes, which bound genetic units of deposition (Fig. 12).

Discussion

The presence of a hierarchy of bounding surfaces of different origin and lateral extent in aeolian deposits has been documented before in several papers and attributed to different processes. Thus, Stokes (1968) relates the origin of horizontal erosional surfaces to deflation processes controlled by the proximity of the water table whereas Mckee and Moiola (1975) concluded that the existence of subparallel erosional surfaces bounding different sets of dune deposits could correspond to the lateral migration of different bodies of dunes and interdunes. The first attempt to introduce a hierarchy was done by Brookfield (1977) who proposes three different orders of bounding surfaces, each one related to the lateral migration of bedforms of different scales. In recent years additional efforts have concentrated on the identification of aeolian sequence boundaries (or super surfaces) and the understanding of the internal organization of aeolian sequences and their relationships with eustatic and climatic changes (Kocurek, 1988; 1996; Zavala and Freije, 2001b; Mountney and Thompson, 2002).

The hierarchy described in this paper differs from that proposed by Brookfield in that here the first category was used to name surfaces having small extent and duration, and where the following and more relevant categories progressively acquire crescent numbers. In a similar way used by Miall (1988) for fluvial deposits,

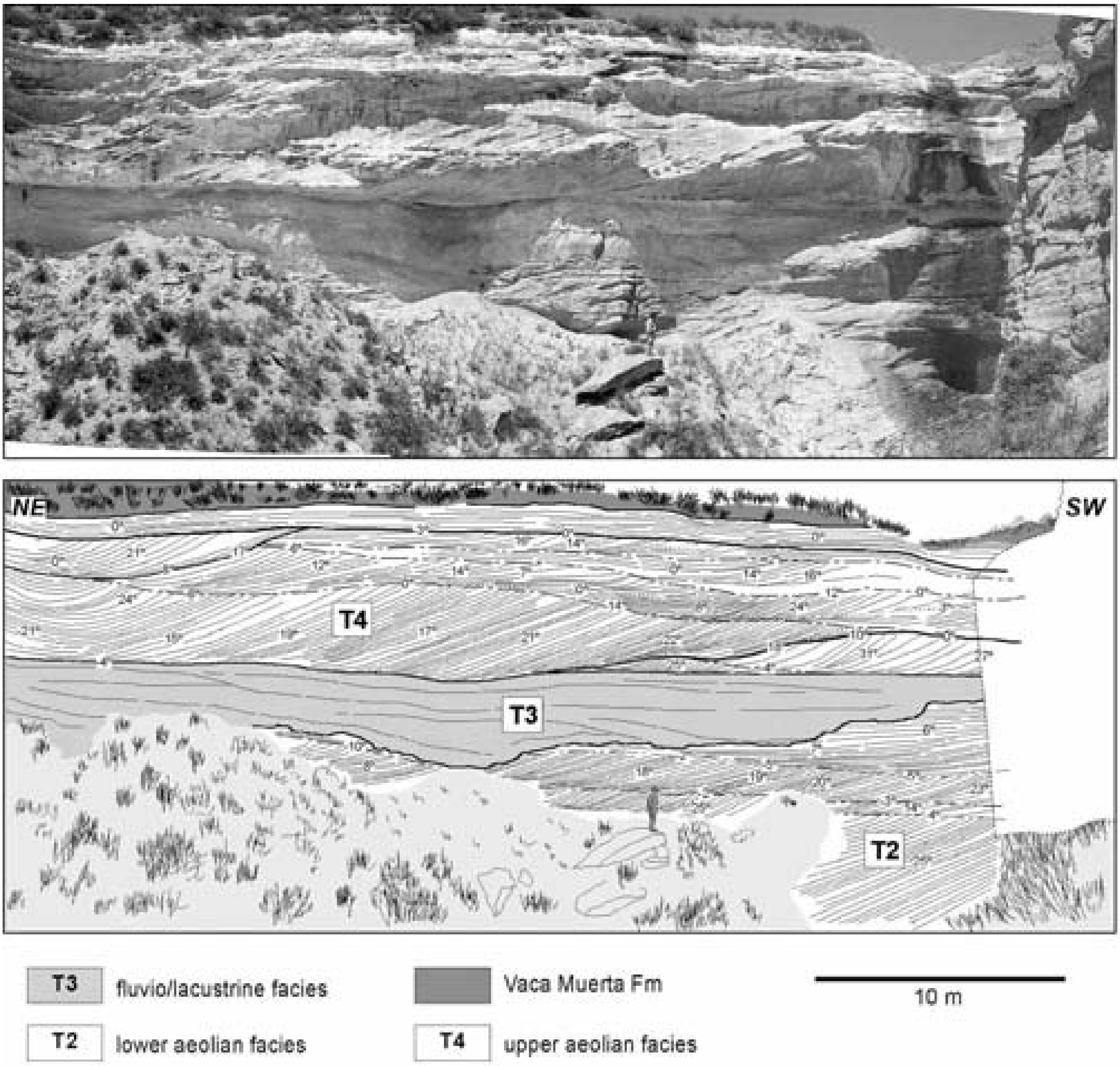


FIGURE 10 **Panoramic view and line drawing of main recognizable surfaces within the clastic bodies of the Tordillo Formation in the Quebrada del Sapo, in the surroundings of section 1. Lines with different traces reflect the hierarchy of bounding surfaces in aeolian strata. See "A" in the map of Fig. 8 for location.**

the use of a crescent nomenclature allows the incorporation of new and more regional surfaces of great relevance. The other fundamental difference resides in the fact that the three smallest categories recognized here are related to the lateral migration of dunes, while the more regional surfaces of category 4 are the result of deflation processes. This detailed characterization permits the identification of meter scale aeolian units that form the primary building blocks. An illustration of the main characteristics and lateral relationships among the four hierarchical orders of bounding surfaces recognized herein is presented in Fig. 12. Generally a bounding surface of certain order is only truncated by another surface of similar or higher hierarchy.

CHANGES IN THE PETROPHYSICAL PROPERTIES OF AEOLIAN DEPOSITS AT BOUNDING SURFACES

Due to the fact that an aeolian bounding surface represents a time-gap in sedimentation, its occurrence is often accompanied by early diagenetic changes with consequences in the petrophysical properties of the rocks involved along its extension. Since the time-gap in sedimentation seems to be proportional to the hierarchy of the bounding surface, diagenetic changes are expected to be more severe according to the crescent importance of the surface hierarchy. As an example, while type 1 surfaces often are only characterized by a subtle change in grain-

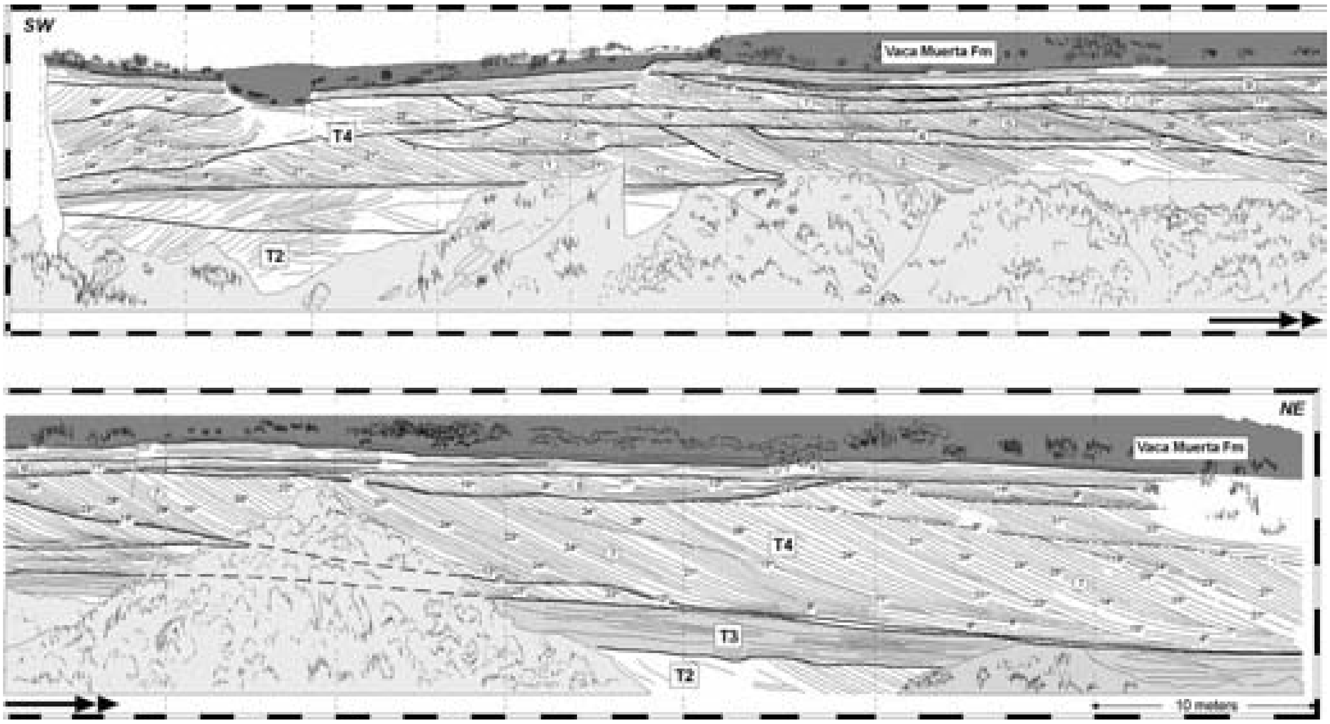


FIGURE 11 | **Line drawing along a highly continuous outcrop (162 m). Numbers indicate the distinguished elementary aeolian sequences. The scale is variable. For references of the bounding surface hierarchy see Fig. 12. The location is indicated as "B" in the map of Fig. 8.**

size and sorting, type 4 surfaces commonly display a slight oxidation and diagenetic alteration related to a more prolonged exposition to weathering. Consequently, the adequate identification of the hierarchy and extension of each bounding surface is of great importance because they create a heterogeneous framework that provides an internal anisotropy to the flow characteristics within a reservoir. The last understanding is fundamental for the planning of new strategies of hydrocarbon recovery from strata accumulated in aeolian environments.

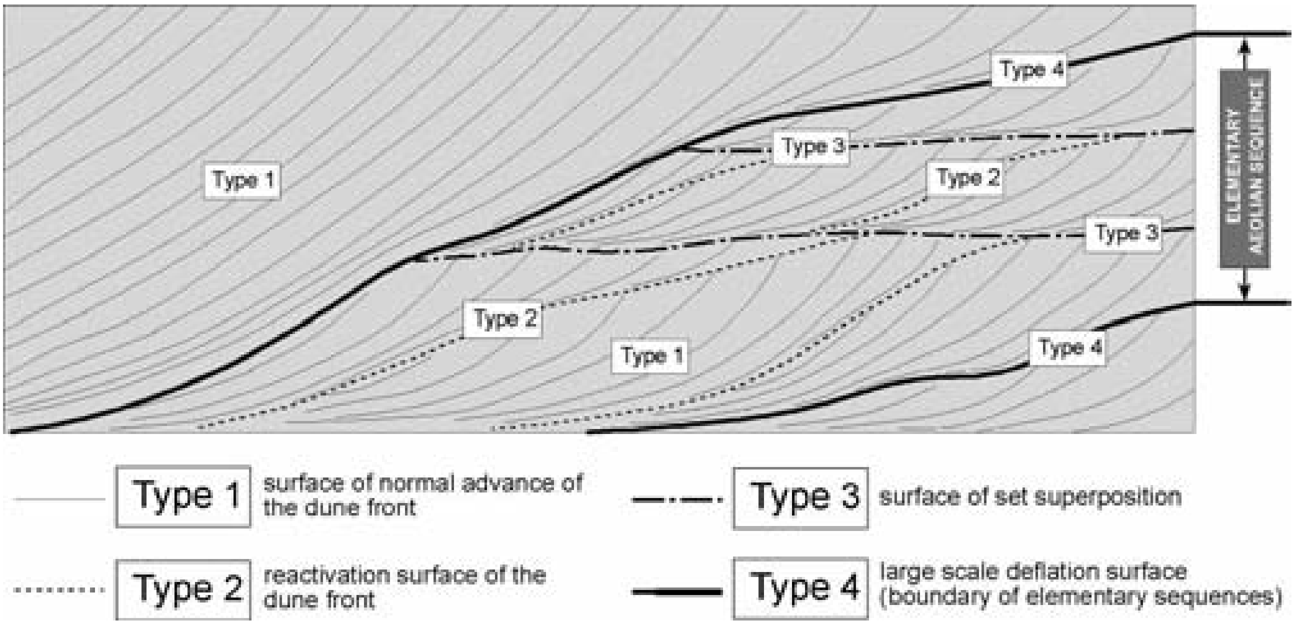


FIGURE 12 | **Conceptual diagram of the types, hierarchy and lateral relationships of bounding surfaces recognized within dune deposits of the Tordillo Formation.**

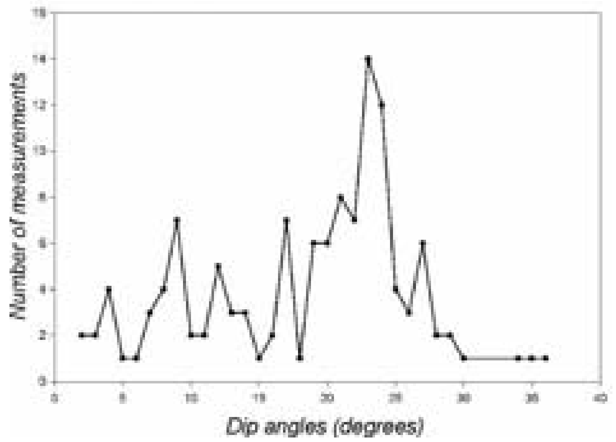


FIGURE 13 **Plot of the dip angles in type 1 surfaces vs. the number of measurements. Note that the most common dip angles range from 19 to 27º.**

To characterize the directional petrophysical properties of aeolian rocks across different types of bounding surfaces, petrophysical studies were performed over eight field samples (A, B, C, M1, M2, T1, T2 and T3) . This study was carried out by RCLAB (Argentina), and the main results are summarized in Table 2. In this table, "-V" in each sample indicates that the petrophysical properties were measured in a direction roughly perpendicular to the bounding surface, whereas "-H1" and "-H2" means that the values were obtained in a plane parallel respect to the considered surface, but at 90º angle amongst them. Samples A and T1 were obtained across type 3 and type 4 bounding surfaces, while samples B and T2 corresponds to type 1 bounding surfaces (Fig. 14). Sample C was taken in sandstone deposits located between two consecutive type 1 bounding surface. Additionally, samples M1 and M2 belong to fluvio-lacustrine deposits, and sample T3 was obtained in interdune sandstones located close to the boundary with the Vaca Muerta Formation. Although the limited number of samples does not provide a through analysis, preliminary data suggests some relevant characteristics.

TABLE 1 **Main dimensions and geometric characteristics of the nine elementary aeolian sequences defined for the upper aeolian unit (T4).**

Sequence	Length (metres)	Thickness (metres)	lenght/ thickness	maximum angle	bounding surface
1	56	4	14	21°	
					5°
2	24	2.8	8,5	20°	
					20°
3	84,8	2.9	29.2	27°	
					4°
4	34	1	34	23°	
					3°
5	50,66	2,13	23,78	26°	
					10°
6	33,6	3,36	10	29°	
					12°
7	>136	5,73	23,73	34°	
					14°
8	41,4	1,43	28,95	17°	
					16°
9	80	0,96	83,33	27°	

TABLE 2 **Table showing the directional petrophysical analysis performed in this study. In the table, "-V" indicates that the petrophysical properties were measured in a direction roughly perpendicular to the bounding surface, whereas "-H1" and "-H2" means that the values were obtained in a plane parallel respect to the considered surface, but at 90º angle amongst them. See Fig. 14 for a schema with the location of most samples.**

Sample	apparent density (gr/cm3)	grain density (gr/cm3)	porosity (%)	gas permeability (mD)	Klinkenberg permeability (mD)
A-H1	2,47	2,61	5,03	0,0024	0,0011
A-H2	2,41	2,61	7,75	0,0093	0,0048
A-V	2,42	2,59	6,81	0,0027	0,0013
B-H1	2,38	2,76	13,77	2,9860	2,1682
B-H2	2,51	2,74	8,18	5,6653	4,2749
B-V	2,45	2,74	10,66	0,2695	0,1694
C-H1	2,09	2,56	18,26	1,1729	0,8052
C-H2	2,08	2,52	17,64	1,5718	1,0983
C-V	2,14	2,55	16,07	1,5699	1,0968
M1-H1	2,31	2,68	13,83	3,1487	2,2937
M1-H2	no data				
M1-V					
M2-H1	2,30	2,61	11,70	0,0151	0,0080
M2-H2	2,26	2,60	13,03	0,1253	0,0752
M2-V	2,25	2,60	13,60	0,0956	0,0565
T1-H1	2,38	2,56	7,37	0,0079	0,0040
T1-H2	2,41	2,58	6,61	0,0095	0,0049
T1-V	2,37	2,58	7,84	0,0025	0,0012
T2-H1	2,23	2,65	15,92	0,2331	0,1452
T2-H2	2,22	2,66	16,47	0,3697	0,2368
T2-V	2,21	2,66	16,83	0,0726	0,0422
T3-H1	2,38	2,74	12,92	0,0082	0,0042
T3-H2	2,38	2,73	12,82	0,0091	0,0047
T3-V	2,36	2,73	13,63	0,0147	0,0077

Samples of aeolian sandstones at type 3 and 4 surfaces show porosities close to 7 % and standard permeabilities less than 0.01 mD. These values are similar in all directions (both parallel and perpendicular with respect to the bounding surface) thus suggesting the possible existence of a barrier (seal) along the extension of the surface.

On the other hand, samples of sandstones on type 1 and 2 bounding surfaces indicate permeabilities 100 to 1000 times greater with respect to those of type 3 and 4 surfaces. Nevertheless, these samples show some hetero-

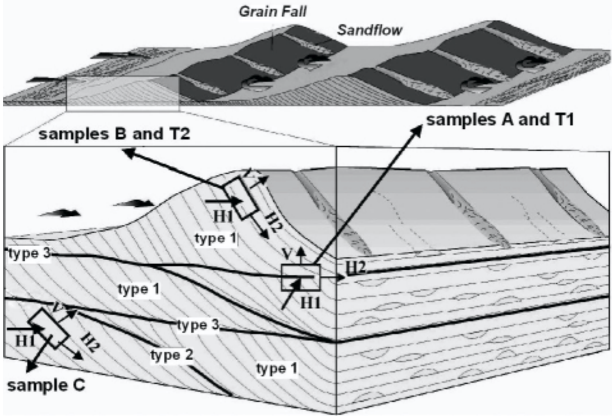


FIGURE 14 **Depositional schema for an aeolian system showing the location of samples A, B, C, T1 and T2. Not to scale.**

geneity when analyzing parallel *vs*. perpendicular-to-plane-bed permeability, with the first being 10 times greater. Although vertical permeabilities are not lesser enough to constitute true barriers, these surfaces could provide some anisotropy and act as a baffle to the flow distribution.

CONCLUDING REMARKS

The Tordillo Formation in the Quebrada del Sapo displays a total thickness up to 50 m, and is internally composed of four unconformity bounded units, informally called T1, T2, T3, and T4. These units are followed in paraconcordance, without apparent transition.

Units T1 and T3 are composed of coarse grained clastic deposits, deposited by fluvio-derived dense flows in a subaqueous environment, probably lacustrine. Paleocurrents and facies changes suggest a source area located in the Northeast.

Units T2 and T4 are characterized by fine to medium grained sandstones that overlie regional deflation surfaces. These units were probably deposited in an aeolian environment, by migrating transverse to barchan dunes. Paleocurrents suggest paleowind directions from the southwest.

The aeolian deposits of units T2 and T4 show at least four kinds of internal bounding surfaces of different hierarchy, related to (1) migration of the dune front, (2) reactivation of the dune front (3) superposition of different sets and (4) deflation. The mapping of type 4 surfaces permits the identification of at least nine elementary aeolian sequences.

Elementary aeolian sequences show a maximum thickness of 5.73 m, with a lateral continuity that can exceed 130 m. The wide/depth relationships of these sequences often round between 10 and 30.

Petrophysical studies performed over the bounding surfaces suggests that type 3 and 4 surfaces could constitute flow barriers along their extension (porosities close to 7 % and standard permeabilities less than 0.01 mD) in contrast to type 1 and 2 surfaces which, with a 100 to 1000 times greater permeability, only appear to provide some anisotropy to the flow distribution and do not constitute a true barrier.

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