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From Alluvial Fan to Playa: An Upper Jurassic Ephemeral Fluvial System, Neuquén Basin, Argentina

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Abstract

The Upper Jurassic fill of the back-arc Neuquén Basin includes a lowstand wedge known as the Tordillo Formation. The studied deposits crop out along a N-S oriented belt that runs parallel to the Andean magmatic arc. They are limited to the south by the east-west oriented positive structure of the Huincul arch formed as a result of Upper Jurassic tectonic inversion. The Tordillo deposits were formed in an arid fluvial-dominated system characterised by systematic downstream changes in architectural style. A gravelly and sandy bedload fluvial system is recognised in the southern upstream sector. The reduced thickness and the coarse grain size suggest steep gradients, excess of bedload supply and a low subsidence rate. Thicker and finer-grained deposits prevail to the north and northeast. They were formed under arid conditions in a wadi-sand flat-playa fluvial system. This distal facies association indicates increased accommodation owing to high rates of subsidence relative to coarse siliciclastic sedimentation rates. These low-gradient deposits are characterised by cyclic alternations of mud-dominated and sand-dominated packages interpreted as high- and low-accommodation systems tracts. The overall fining upward stacking pattern of the Tordillo Formation suggests a change towards higher accommodation rates. This is accompanied by frequent development of soil horizons and darker primary and reworked pyroclastic deposits. These attributes indicate a stronger explosive volcanic activity associated with increased precipitation and high water table emplacement towards the end of the Tordillo lowstand wedge.

Key words: Argentina, Neuquén Basin, Jurassic, fluvial sedimentology, facies models.

Introduction

Over the last three decades, the development of facies models and the description of case studies have improved our understanding of fluvial systems, and those which developed under arid to semiarid conditions have been extensively described (Tunbridge, 1984; Olsen, 1987, 1989; Clemmensen et al., 1989; Kelly and Olsen, 1993; Sadler and Kelly, 1993; Blum et al., 1998). However, less attention has been paid to the manner in which stratal architecture responds to tectonism, climate, sea level, and regional and temporal variations in accommodation and sediment supply (Howell and Mountjoy, 1997; Sweet, 1999).

The well exposed Upper Jurassic Tordillo Formation contains examples of fluvial sediments that formed under arid/semiarid conditions along the western edge of the Neuquén Basin (west central Argentina). The aim of this paper is fourfold: (1) to describe and interpret the sedimentary facies and depositional systems of the Tordillo Formation; (2) to relate the fluvial dynamics to sediment yield and fluvial transport characteristics; (3) to discuss the palaeogeography of the region; and (4) to evaluate the controls exerted by tectonic regime, climate and sediment supply.

Geological Setting

The Neuquén Basin is located in west central Argentina and eastern Chile between 36° and 40°S (Fig. 1). It is limited to the NE, S and SE by cratonic areas, and to the west by the Andean volcanic arc. The basin fill is more than 4,000 m thick, and is composed of continental and marine siliciclastic deposits, carbonates and evaporites that range in age from Late Triassic to Early Tertiary (Gulisano and Gutiérrez Pleimling, 1994; Vergani et al., 1995). The stratigraphy of the Neuquén Basin is summarised in figure 2. It has been interpreted as an ensialic back-arc basin associated with the easterly oriented subduction along the proto-Pacific margin of

Gondwana (Digregorio et al., 1984; Macellari, 1988; Legarreta and Uliana, 1991). A generalised extensional stress regime due to steep subduction angle and negative roll-back velocity (Ramos, 1999) occurred in the arc and in the back-arc settings. However, Vergani et al. (1995) and Veiga et al. (2001) demonstrated that regional subsidence was interrupted by several episodes of structural inversion.

Since the pioneering study by Groeber (1946) two major cycles (Jurásico and Ándico) composed of several transgressive-regressive subcycles are recognised in the sedimentary record of the Neuquén Basin (Fig. 2). Several authors (e.g., Gulisano et al., 1984; Legarreta and Gulisano, 1989; Legarreta and Uliana, 1991, 1996a, 1996b) interpreted these cycles in terms of eustatic changes under a regime of thermal subsidence. However, according to Vergani et al. (1995), Veiga et al. (2001) and Pángaro et al. (2002) tectonic inversion controlled and/or intensified sea-level drops favouring the development of regional unconformities and subsequent lowstand wedges.

The Kimmeridgian Tordillo Formation is one of these clastic wedges located between the marine carbonates and evaporites of the uppermost Jurásico Cycle and the deep marine anoxic shales and marls of the lowermost Ándico Cycle (Fig. 2). Although Groeber (1946), followed by Digregorio (1972), Digregorio and Uliana (1980) and more recently by Legarreta and Uliana (1996a, b, 1999), considered that the Tordillo sediments represent the latest depositional event of the Jurásico Cycle, other authors (e.g., Groeber et al., 1953; Stipanicic, 1969; Leanza et al., 1977, 2000; Orchuela and Ploszkiewicz, 1984; Legarreta and Gulisano, 1989; Riccardi and Gulisano, 1990; Leanza and Zeiss, 1990; Cruz et al., 2000) demonstrated that the Tordillo deposits were developed after the Araucanian (Intramalmic) tectonic inversion, and unconformably rest upon the carbonates and evaporites of the Lotena Group (Jurásico Cycle). Thus, they represent the first depositional event of the Ándico Cycle (Fig. 2).

The first detailed sedimentological study of the Tordillo Formation (and coeval units) was carried out by Marchese (1971) who described the main facies based on sediment grain-size and primary sedimentary structures, and interpreted them as the deposits of proximal to distal fluvial systems. Legarreta and Gulisano (1989), Legarreta et al. (1993) and Legarreta and Uliana (1996a, b, 1999) described a general scenario of alluvial fans and fluvial systems related to playa-lake depressions and aeolian dune fields for the Tordillo Formation.

A general palaeogeographic sketch (Fig. 3A) for the Tordillo Formation was published by Vergani et al. (1995). This shows the relationship between the main depositional systems and the areas reactivated during the late Oxfordian and earliest Kimmeridgian (Araucanian) inversion (e.g., Huincul arch, Fig. 3A). This tectonic episode partially eroded over 2000 m of pre-existing volcanic and sedimentary units in the Huincul arch. According to Vergani et al. (1995) this positive land separated two main depositional areas. The area in the southern part of the

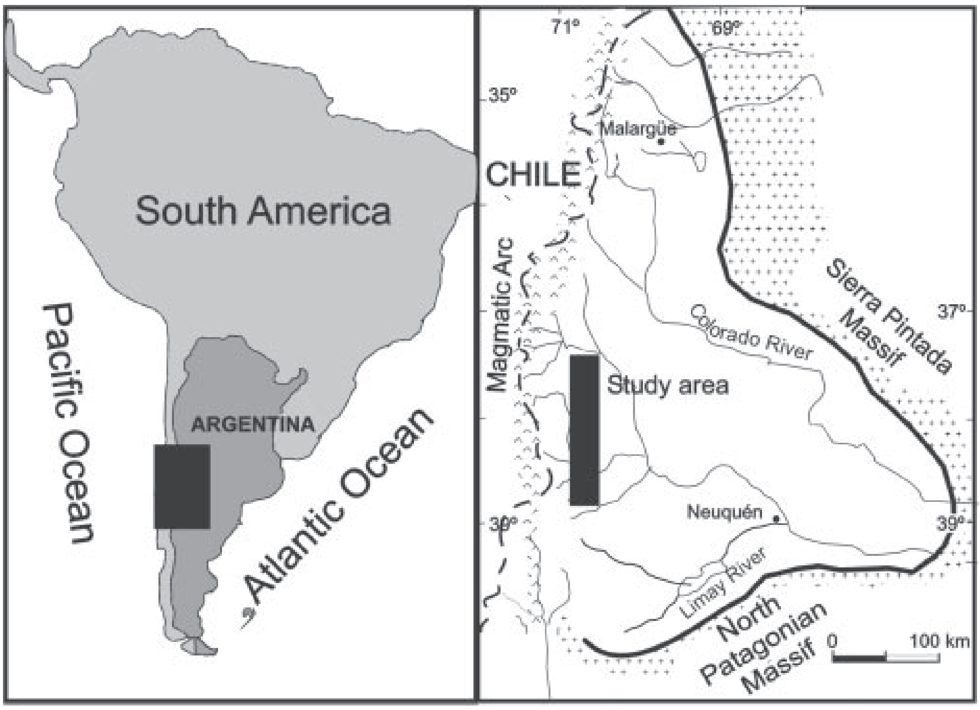

Fig. 1. Location map of the Neuquén Basin. The rectangle shows the study area.

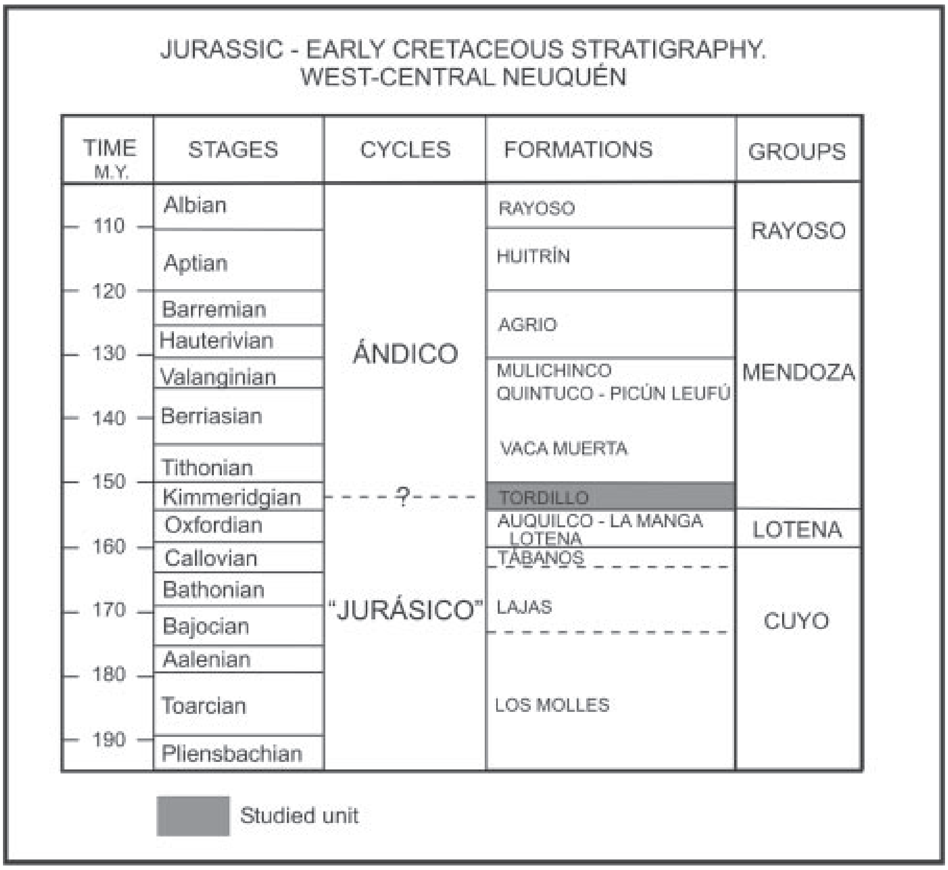

Fig. 2. Schematic stratigraphy of the "Jurásico" and "Ándico" cycles, showing the stratigraphic position of the Tordillo Formation.

basin consists of mixed aeolian-fluvial-playa deposits (Veiga et al., 2004). Thickness analysis of the Tordillo Formation (Fig. 3B) suggests the presence of two depocenters in the northern area: one to the west, characterised by the fluvial units studied in this paper, and the other to the east with thinner and finer deposits attributed to interactions between desert fluvial and aeolian systems (Orchuela and Ploszkiewicz, 1984; Peroni et al., 1984; Arregui, 1993; Boll and Valencio, 1996; Cruz et al., 2000; Cazau and Melli, 2002; Maretto et al., 2002).

Methods and Studied Localities

Six localities were studied in detail (Fig. 4). The selection was based on outcrop quality and on changes in stratigraphic architecture. A vertical section was measured with bed-by-bed logging in each locality (Figs. 5 to 10). Data collected included grain size, primary sedimentary structures and bounding surfaces. The palaeocurrent directions were recorded from all localities. Data were mainly obtained from cross-stratification, parting lineation and pebble imbrication, although additional information was collected from large grooves, current ripples and ripple cross-lamination. The bi-directionality inherent in parting lineation flow indications was resolved in favor of the direction indicated by associated cross-beds. Because structural dip in the project area is more than 10°, corrections for structural dip were necessary. Vector statistics were calculated using the method of Collinson and Thompson (1982). At Chenque Colorado and Loncopué (Fig. 4) photographic mosaics were taken to constrain the large-scale architecture of the depositional systems.

In the sections located to the south (Covunco, Chenque Colorado, Mallín Quemado, Figs. 5, 6 and 7) and to the northeast of the studied area (Puerta de Curacó, Fig. 10) the Tordillo Formation is entirely exposed. It typically rests on a significant unconformity with the Oxfordian La Manga carbonates and Auquilco evaporites and conformably underlies the black shales and marls of the Vaca Muerta Formation. The total thickness of the unit in these localities ranges from 85 m in Covunco to 188 m in Chenque Colorado.

To the west (Loncopué) and northwest (Neuquén River) of the study area, the lower levels of the Tordillo Formation are not exposed. However, these outcrops are thicker than those located to the south and northeast, and range from 250 m at Loncopué (Fig. 8) to more than 470 m in the Neuquén River section (Fig. 9).

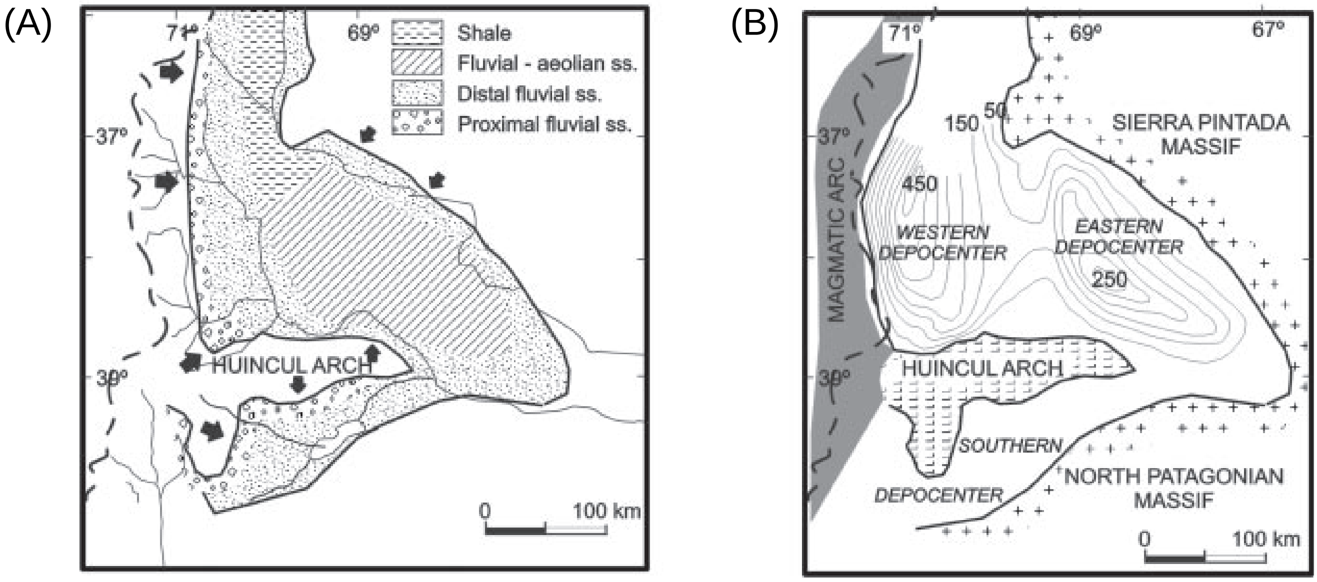

Fig. 3. (A) regional-scale palaeogeographic reconstruction of the Tordillo Formation (Vergani et al., 1995); (B) isopach map of the Tordillo Formation showing its main depocenters and major tectonic elements.

Lithofacies and Lithofacies Associations

Lithofacies in the Tordillo Formation were classified using the scheme of Miall (1978) with some modifications and additions (e.g., Spalletti, 1997, 2001; Veiga, 1997). Most lithofacies are common in fluvial deposits and are not described in detail. Individual lithofacies are listed in table 1.

Two main lithofacies associations are recognised in the study area: (1) proximal, and (2) distal. The proximal association occurs throughout the Tordillo Formation in the sections located to the south of the study area (Covunco, Chenque Colorado, Mallín Quemado, Figs. 5, 6 and 7) and in the basal 66 m of the Neuquén River section (Fig. 9). The distal facies association occurs throughout the Tordillo Formation at Loncopué and Puerta de Curacó, and in most of the Neuquén River section above its basal (proximal) 66 m (Figs. 8, 9 and 10). A detailed description of facies associations is presented in the following paragraphs.

Proximal lithofacies association

This is the coarsest facies association within the Tordillo

Table 1. Lithofacies types in the Tordillo Formation.

Structure	Gravel	Pebbly sand	Sand	Heterolithic	Mud	Other lithologies C: micritic carbonate T: tuff
Massive, matrix-supported	Gms					T
Massive, clast- supported	Gm	Gm	Sm		Fm	
Imbrication	Gi					
Wavy lamination (upper-stage flow-regime)			Swl			
Planar cross-bedding (ae = aeolian)			Sp, Sp(ae)			
Trough cross-bedding	Gt	SGt	St			
Low-angle cross-bedding	Gl	SGl	Sl			
Horizontal lamination (ae = aeolian)	Gh	SGh	Sh, Sh (ae)			
Current ripples			Sr	Hr	Fr	
Wave ripples			Sw	Hw		
Parallel lamination				Hh	Fh	
Convolute lamination and other syn-deformational features		SGcv	Scv	Hcv	Fcv	
Dessication cracks				Hc	Fc	
Palaeosols					Fs	Cs

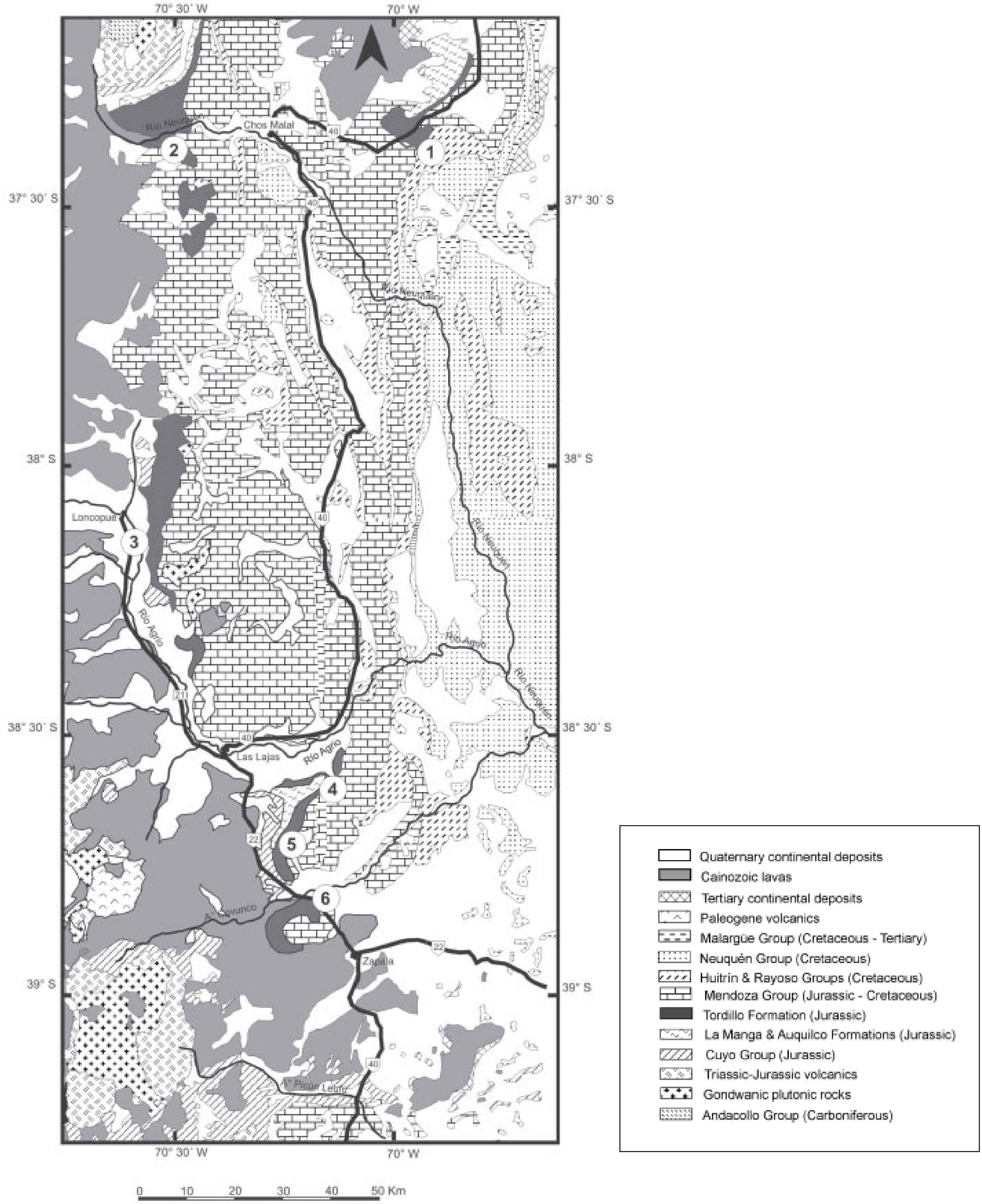

Fig. 4. Geological map of the western Neuquén Basin, showing the location of measured sections. 1–Puerta de Curacó, 2–Neuquén River, 3–Loncopué, 4–Mallín Quemado, 5–Chenque Colorado, 6–Covunco.

Formation. In the southern sections the deposits consist of multistorey, multi-lateral lenticular beds of imbricated clast-supported pebble to granule conglomerate and pebbly sandstone, and lenticular beds of trough cross-bedded and minor horizontally laminated medium- to very coarse-grained sandstone (Fig. 11). The clast populations in conglomerates are dominated by ignimbritic and rhyolitic clasts, and grain shapes range from subangular to rounded. A complex mosaic of erosion surfaces between sets can be traced laterally for up to 100 m. Set boundaries are generally concave up and horizontal with respect to depositional dip. Trough cross-bedding is present in most places, and sets range from 0.5 to 1.4 m-thick. The dip of foresets is slightly below the angle of repose in their uppermost parts and flattens somewhat in their lowermost parts. Trough cross-bedded storeys typically show low-angle reactivation surfaces oriented downdip (Fig. 11B). Lateral changes from conglomerate to pebbly sandstone and sandstone (or vice versa) along one single set are common. Scour and fill structures as well as clast-supported conglomerates and sandstones with horizontal bedding occur sporadically.

Set amalgamation compound large lenticular cosets of high angle cross-strata up to 3.5 m-thick extend up to

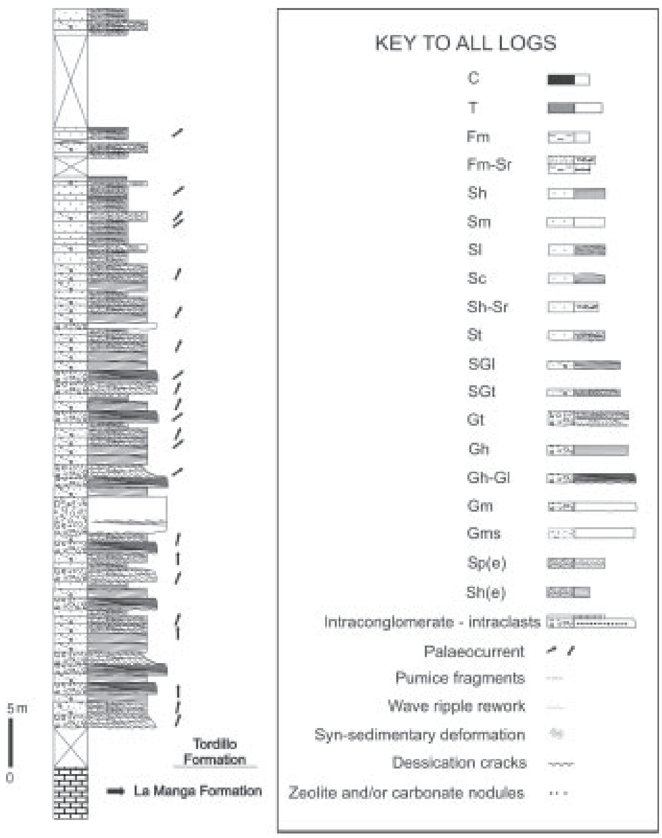

Fig. 5. Sedimentary log of the proximal facies association at Covunco (see Fig. 4 for location).

100 m laterally in a dip direction. Only some elements show a fining upward arrangement from trough cross-bedded pebble conglomerate to trough cross-bedded pebbly sandstone.

Three different packages can be defined in this facies association. One is composed of stacked cosets of cross-bedded lenticular conglomerates and pebbly sandstones (Gt, SGt). The second is formed by interstratifications of lenticular cross-bedded pebbly sandstones (SGt), trough cross-bedded very coarse-grained sandstones (St) and low-angle cross-bedded medium- to coarse-grained sandstones (Sl). The third package type, defined to the top of the Mallín Quemado section (Fig. 7), is composed of a medium- to coarse-grained sandstone dominated succession. It is characterized by lenticular and amalgamated trough cross-bedded units and subordinated horizontally bedded medium-grained sandstones. Cross-bedded pebbly sandstone lenses, and thin intercalations of mud-cracked siltstones and syneruption vitric-rich pyroclastic fallout deposits are less common.

The lenticular geometry of beds, abundant trough cross-bedding, scoured basal contacts, imbricated clasts, and clast-supported framework, coarse grain size, poor sorting and rarity of well developed horizontal stratification in these deposits indicate deposition from channelised fully turbulent bedload fluvial systems. The abundant reactivation surfaces and lack of fine-grained deposits suggest high channel mobility and a laterally unstable system. Architectural features, such as St sets and internal arrangement of accretion surfaces, and the consistent palaeocurrent direction of cross-bed relative to orientation of accretion surfaces, indicate that these deposits can be interpreted as downstream accreting compound bars (Miall, 1996; Miall and Jones, 2003).

Deeply incised channels are rare throughout the proximal facies association reflecting the strongly aggradational nature of these high-energy, sediment-laden streams. These conditions would develop in response to rising base levels of the main stream and very high sediment yield. Aggrading base levels and an over-all lack of perennial discharge apparently inhibited deep incision of the depositional surface (Blissenbach, 1954). Besides, the cyclicity of depositional packages suggests marked rhythmic variations in flow stage.

The lower levels of the Neuquén River section (Fig. 9) are composed of matrix-supported, unorganised conglomerates. They consist mainly of randomly dispersed, subrounded and rounded cobble to boulder sized basaltic, andesitic and rhyolitic clasts. Conglomerate beds are massive and range from 1.5 to 3.8 m-thick. Basal and upper contacts are sharp and planar. These deposits form laterally continuous, sheetlike bodies commonly interbedded with massive pebbly sandstones, cross

Fig. 6. Sedimentary log of the proximal facies association at Chenque Colorado (see Fig. 4 for location).

stratified sandstones and thin cross-laminated siltstone beds, showing very common mud-cracks on top.

The typical massiveness, very poor sorting of the deposits and chaotic distribution of upsized clasts within the bed suggest that the main sediment-support mechanism was the yield strength of a cohesive matrix (Lowe, 1982; Waresback and Turbeville, 1990; Blair and McPherson, 1994). Thus, the matrix-supported conglomerates suggest deposition *en masse* from subaerial viscous and cohesive debris flows (Iverson, 1997; Mulder and Alexander, 2001). High roundness values indicate that the material was deposited by a process that eroded pre-existing sediments. Intercalated deposits were formed by rapid deposition from fully turbulent, traction-dominated dispersions. Siltstone interbeds represent the fallout deposits of falling flood stage.

Above the described deposits, the association is dominated by sheetlike and multistorey packages of clast-supported conglomerates and pebbly sandstones. The sheets range in thickness from 0.6 to 1.8 m and extend tens of metres laterally. Internally they are either massive or horizontally bedded. These packages are separated by massive and/or trough cross-bedded coarse-grained sandstone lenses and mudcracked siltstone intervals. The dominance of crude stratification and evenly laminated gravel and pebbly sand together with the absence of deep scours suggest that these deposits resulted from unconfined high-energy bed-load currents (Nemec and Postma, 1993; Blair, 2000, 2001). Sandstone lenses and siltstone interbeds likely represent deposition from shallow waning flows.

Distal lithofacies association

This lithofacies association occurs throughout the Tordillo Formation at Loncopué and Puerta de Curacó (Figs. 8, 10 and 12). It also constitutes most of the thick section measured at in the Neuquén River section (Fig. 9). It is characterised by intercalations of mudstones, thin intraformational conglomerates and fine- to medium-grained sandstones. Light red to purple colours, indicating oxidizing conditions during deposition, prevail at Loncopué and in the Neuquén River section. At Puerta de Curacó and towards the top of the Tordillo Formation in the Loncopué and Neuquén River sections, the deposits are typically greenish gray, green and dark green. The distal lithofacies association consists of four elements: (1) laterally extensive fine-grained deposits, (2) major sandstone sheets, (3) sandstone ribbons and (4) amalgamated volcaniclastic deposits.

The *laterally extensive fine-grained deposits* are dominated by mudstones with subsidiary thin bedded sandstones and heterolithic intervals. Beds can be traced along–strike for about 1 km (Fig. 12A).

Mudstone beds range from sandy siltstones to silty claystones. The deposits range in thickness from about 0.3 m to over 3.5 m and most beds are internally structureless. Some beds exhibit faint lamination and fissility (Fig. 12B). The fine-grained textures are typical of suspension deposits. Periodic desiccation is indicated by frequent mud-crack horizons. However, the presence of invertebrate tracks and straight and anastomosed sharp-crested and symmetrical ripples also indicates periods in which the substrate remained moist after deposition. These deposits probably accumulated in shallow ephemeral ponds following periods of episodic low-energy flooding in mudflat and/or playa environments (Aigner and Bachmann, 1989; Kelly and Olsen, 1993; Sadler and Kelly, 1993).

Minor sandstone and heterolithic sheets and lenses also appear throughout the fine-grained laterally extensive deposits. Fining-upward trends are common, with the tops of the sheets and lenses grading into silt- and claystones.

Fig. 7. Sedimentary log of the Tordillo Formation at Mallín Quemado (see Fig. 4 for location).

These deposits are 0.3–0.7 m thick and laterally persistent for hundred of metres. Where these deposits are well developed, they contain three parts: (1) lower slightly erosional surface and basal intraformational conglomerate; (2) horizontally bedded medium- to fine-grained sandstone; (3) small scale trough cross-bedded and/or ripple cross-laminated fine-grained sandstone and siltstone, in which thin mudstone intercalations may appear. In plan view ripples are linguoid.The cycle is not complete in some examples; the deposits lack unit 2, and unit 3 lies directly upon the basal erosional surface and the intraformational lag.

Minor sheet sands are characteristic of non-channelised flooding especially in ephemeral systems (Williams, 1971; Picard and High, 1973; Tunbridge, 1981, 1984). They appear to record rapid inundation of an extensive mudflat. The lateral continuity of many of the sheets and lack of internal erosion or reactivation surfaces indicate that these deposits originated as unconfined sheet splays. Each package can be interpreted as the result of a single flood event. The basal erosional surface, commonly with mudstone intraclasts, as well as the subsequent horizontally-bedded sandstone interval is interpreted as a record of high-energy tractional flows, probably associated with rapid flooding and reworking of previously deposited muds. The gradual vertical evolution into small-scale troughs and cross-laminated facies indicates the waning stage of flooding and decreasing velocity of flows towards lower flow-regime conditions. Besides, small sandstone lenses are interpreted as minor feeder channels associated with sheet splays.

Isolated large-scale (up to 2 m) wedge-shaped sandstone sets intercalate between mud-dominated successions. They are composed of fine- to medium-grained, well-sorted sandstones arranged in cross-stratified sets with planar to tangential foresets. They dip less than 30° and show abundant reactivation surfaces. Foresets are characterised by alternations between wedge-shaped laminae and structureless fine-grained laminae. These large-scale well-sorted sand bedforms are interpreted as solitary slipfaced aeolian dunes in which foresets formed mainly as the result of grainflow and grainfall processes at the bottom of high-angle lee slopes (Hunter, 1977; Veiga et al., 2002).

Major sandstone sheets are the most common and prominent sandstone bodies in the distal facies association. They are particularly abundant at Loncopué and in the Neuquén River section where they form extensive resistant ledges (Figs. 12A, 13A). The deposits consist of an association of horizontally-bedded, subcritical cross-laminated, planar low-angle and trough cross-bedded sets (Fig. 13B). They are laterally continuous for at least

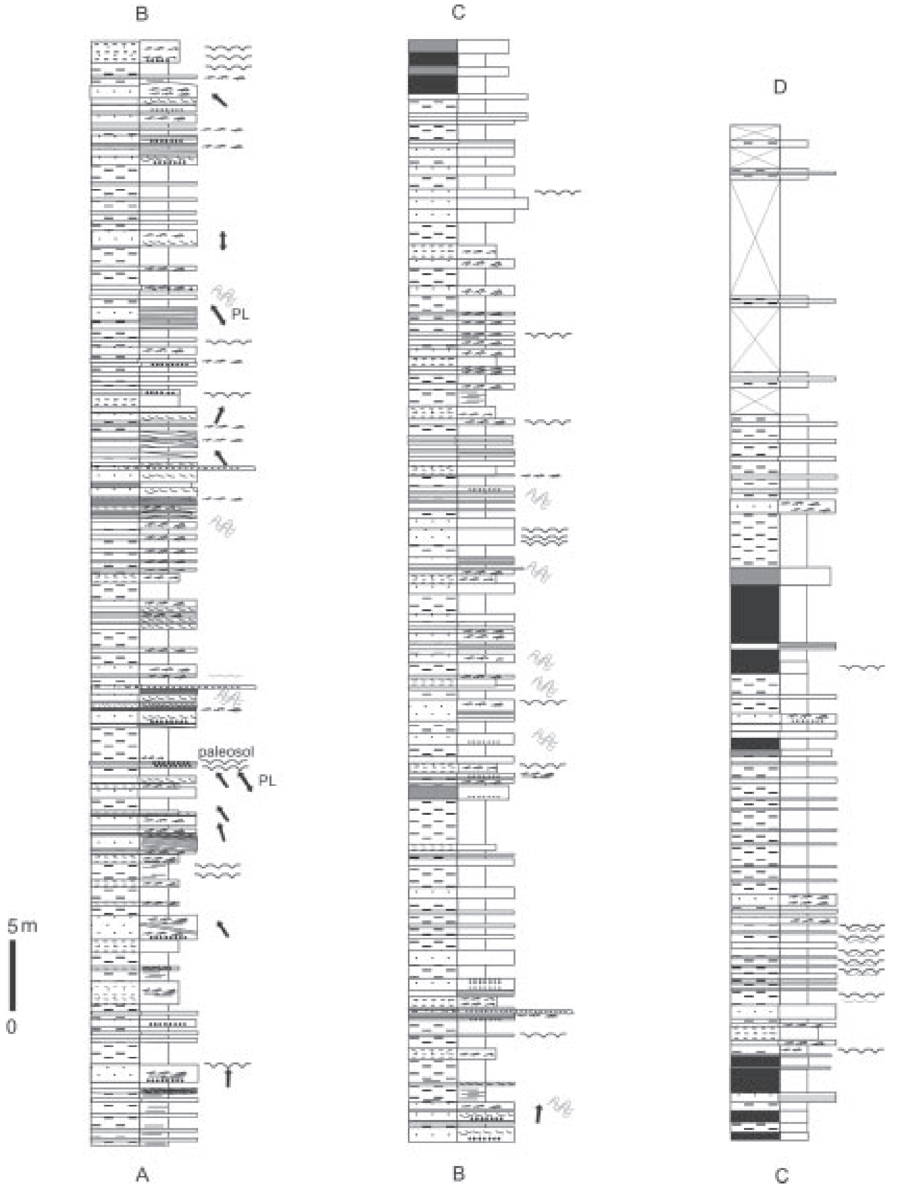

Fig. 8. Sedimentary log of the distal facies association at Loncopué (see Fig. 4 for location).

-600 m and are found in 2–9 m-thick packages. Upper and lower contacts are sharp. Lower contacts are largely erosional, although most are essentially flat, whereas upper contacts tend to be slightly convex up (lobe geometry, Fig. 13A).

Individual beds are 0.3 to 0.5 m-thick. Amalgamation of sandstone layers is common. However, some sandstone beds are separated by thinner mudstone intercalations and fine-grained sandstone-mudstone couplets. The most common sandstone facies consists of thin-bedded (2–4 mm) parallel stratified to low-angle planar cross-stratified sets with primary current lineation (Sh, Sl). Ripple cross-laminated, cross-bedded and even structureless sandstone (Sr, St, Sm) may also be present. In rare cases standing wave lamination was preserved. Many of the sandstones contain rounded and flat mudstone intraclasts. These intraformational clasts, at bed bases or within the sandstone beds, are usually aligned above basal surfaces and internal foresets. In 5–10% of beds, the lamination displays a degree of soft-sediment deformation (convolute lamination) due to excess pore water pressure in the sands (Tunbridge, 1984). Deformational sole marks (e.g., load casts) are less common.

The external geometry of major sandstone sheets, the importance of abundance of lithofacies Sh and Sl, and the abundance of intraformational lags are all features of typical ephemeral fluvial regimes (Picard and High, 1973; Tunbridge, 1984; Eberth and Miall, 1991). Sandstone sheets have many of the characteristics of hyperconcentrated sheetflood deposits that represent periods of rapid fluvial

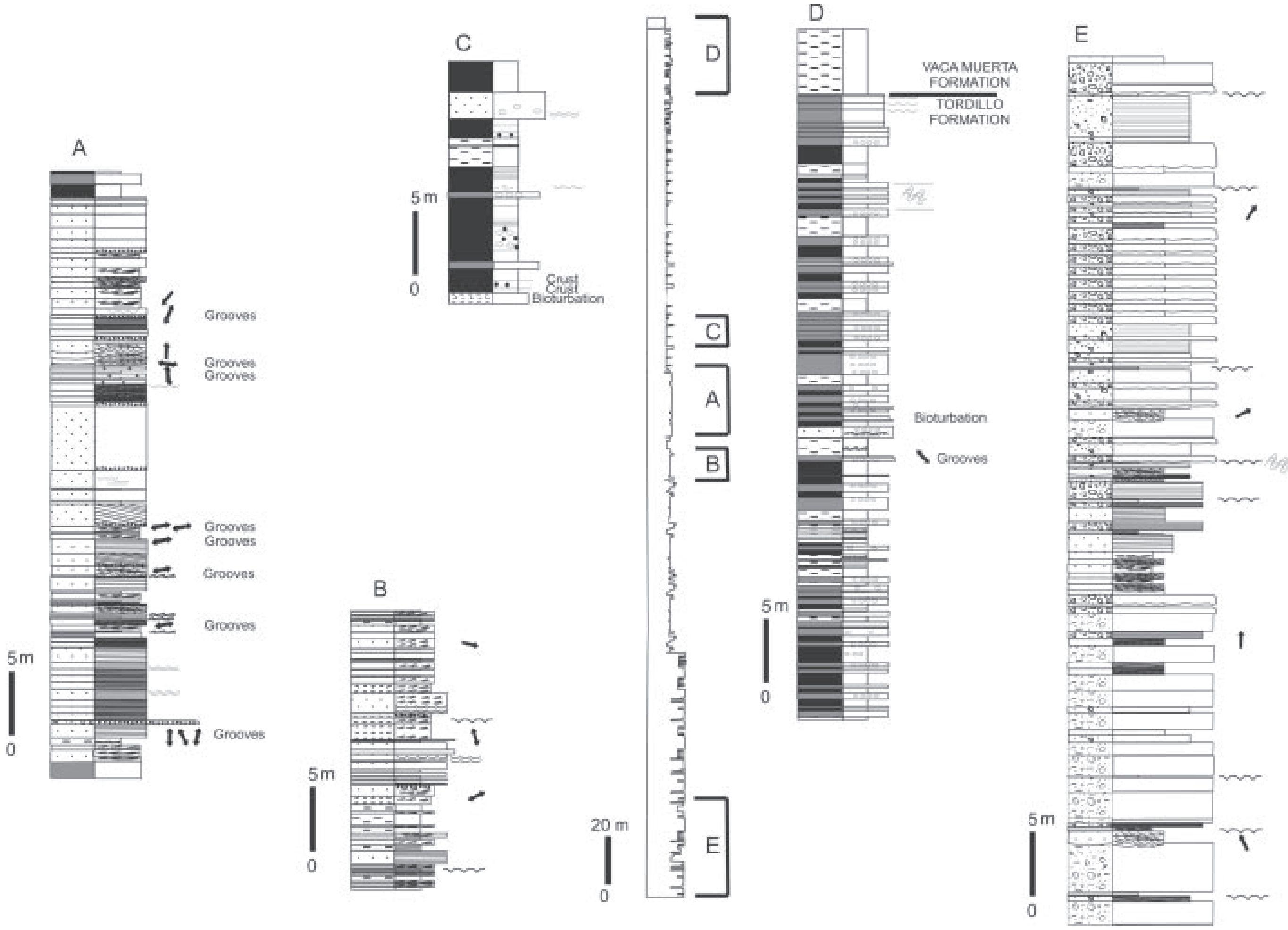

Fig. 9. Sedimentary logs of the Tordillo Formation in the Neuquén River section (see Fig. 4 for location). Note that the lower part of the section is composed of a proximal facies association, whereas the rest of the stratigraphic column is characterized by fine grained deposits, major sandstone sheets and amalgamated volcaniclastic deposits.

aggradation. These facies accumulated downslope as a result of significant loss of competency when sediment-charged sheetflood rapidly expanded (Blair, 2001).

The widespread development of tractional bedforms in fine-grained sandstone-dominated successions implies sudden and marked changes in flow conditions. Ubiquitous horizontal stratification can be attributed to sedimentation occurring in a moving layer of highly concentrated bedload material beneath a turbulent flow. Thus, flat laminations indicate that these facies aggraded under plane-bed conditions because of repeated generation and destruction of standing wave trains (Rahn, 1967; Blair, 1999b, 2000). Low-angle cross-bedded sandstone reflects migration of low-amplitude, long wavelength bedforms. These bedforms, which are known from experimental studies of fluvial processes (Saunderson and Lockett, 1983; Roe, 1987), appear to develop at the transition between dune migration and upper-stage plane-bed flow conditions.

The occurrence of sandstones with standing wave lamination suggests emplacement as event deposits and could theoretically represent migrating antidunes developed beneath supercritical currents. Structureless sandstones are most readily interpreted as having formed under conditions of high rates of suspension settling from currents of moderate to high sediment concentration (Lomas, 1999; Grecula et al., 2003). Deposition may occur by collapse fallout associated with rapid deceleration of the flow. Local convolution and load casting indicate rapid deposition and a certain degree of dewatering. Mud clasts imply a local origin and the presence of an erosion-dominated area located only a short distance upstream, as the natural fragility of mudstone clasts prevents long transport. Their preferential location towards the base of sandstone layers as well as along cross-stratified laminae implies that rip-up clasts were deposited from turbulent flows (Grecula et al., 2003).

Major sandstone ribbons are more frequent in the lower part of the Loncopué section, but also occur in other parts of the formation (Fig. 8). The vertical scale of this element varies considerably from 0.8 to 1.8 m, and has an approximate width of 50–60 m. It can readily be indented by the presence of a single, basal, concave-up erosion surface. Ribbon bodies are typically isolated from one to another laterally, between intervals of laterally extensive fine-grained deposits or sandstone sheets. Some multistoried sandstone bodies comprise ribbons overlain by sheets (Eberth and Miall, 1991). These erosionally based channels are infilled by medium- and fine-grained sandstones with mud intraclasts up to 4.5 cm in diameter. They may be composed of a single sandstone bed (up to 1.4 m-thick) or amalgamated 0.2–0.6 m-thick sandbodies separated by steeper internal erosional surfaces. Bedding surfaces in single channels are typically parallel to underlying erosional surfaces, whereas complex infills are composed of multistorey parallel-stratified, trough cross-bedded and cross-laminated sets (facies Sh, Sl, St and Sr).

Sandstone ribbons are interpreted as the deposits of broad, shallow and isolated channels. Trough cross-bedded sandstone lenses probably were deposited by dilute stream flows. These flows apparently occurred during periods when the rate of aggradation was lower, perhaps during waning stages of hyperconcentrated flow

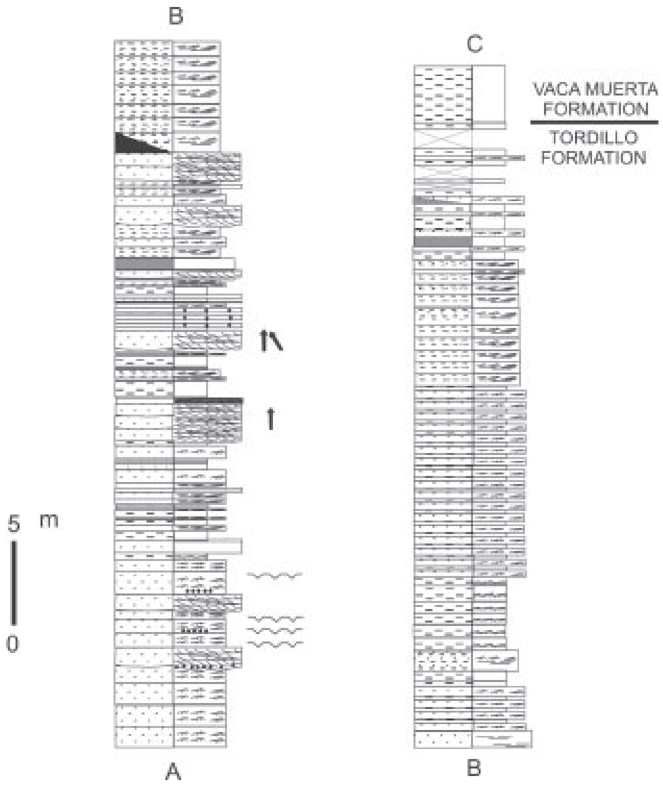

Fig. 10. Sedimentary log of the distal facies association at Puerta de Curacó (see Fig. 4 for location).

when less sediment was added to drainages (Cole and Ridgway, 1993). The scarcity of lateral accretion deposits and the paucity of other types of macro-forms are interpreted to imply that the channels were shallow and lacked large, well-developed bank-attached or mid-channel macro-form bars (Eberth and Miall, 1991).

Amalgamated volcaniclastic deposits consist essentially of poorly sorted fine- to medium-grained vitric tuff to silty tuff and volcaniclastic sandstones. These deposits are found in the middle and especially at the top of the Neuquén River section (Fig. 9) where they make up a 45 m-thick volcaniclastic succession. They appear also in the upper third of the Loncopué section (Fig. 8). Tuffaceous individual beds are laterally continuous and can be traced for about 500 m along strike. They are internally structureless and range in thickness from 0.2 m to over 1 m. Their basal and upper contacts are sharp and irregular. Pumice grains (0.5 to 10 mm in diameter) are commonly dispersed within the fine-grained vitric tuff matrix. Several levels showing grouped columnar joints and root traces suggest incipient development of soil horizons. Tuff deposits are interstratified with volcaniclastic sandstones, heterolithic mud-rich couplets and mudstones. In particular, individual beds of volcaniclastic sandstones are tabular and 0.3 to 1m-thick. Internally most beds display faint horizontal stratification defined by pumice stringers and alternating coarser- and finer-grained laminae.

The lateral continuity of internally structureless beds, moderate to poor sorting of grains and abundant vitric groundmass indicate that tuff and silty tuffs are the result of primary pyroclastic fallout (Teruggi et al., 1978; Fisher and Schmincke, 1984; Mazzoni, 1986). Volcaniclastic sandstones represent the rework of primary pyroclastic deposits by shallow stream flows.

Transport Directions

Palaeocurrents from almost all parts of the Tordillo outcrops show unimodal distributions (Fig. 14). In the southern localities (Covunco, Chenque Colorado) they consistently indicate a N to NE trend (Fig. 14) and suggest a long term fixed source in the Huincul area. At Mallín Quemado the sediment transport directions were more irregular with vector magnitudes towards the N-NE and E (Fig. 14). Far north, at Loncopué, in the lower part of the Neuquén River section and at Puerta de Curacó almost all data are unimodal with consistent northward flow directions. However, the deposits of the dominant distal facies association in the Neuquén River section are regularly oriented within the northern and the eastern quadrants, indicating also a positive land located to the west of the basin.

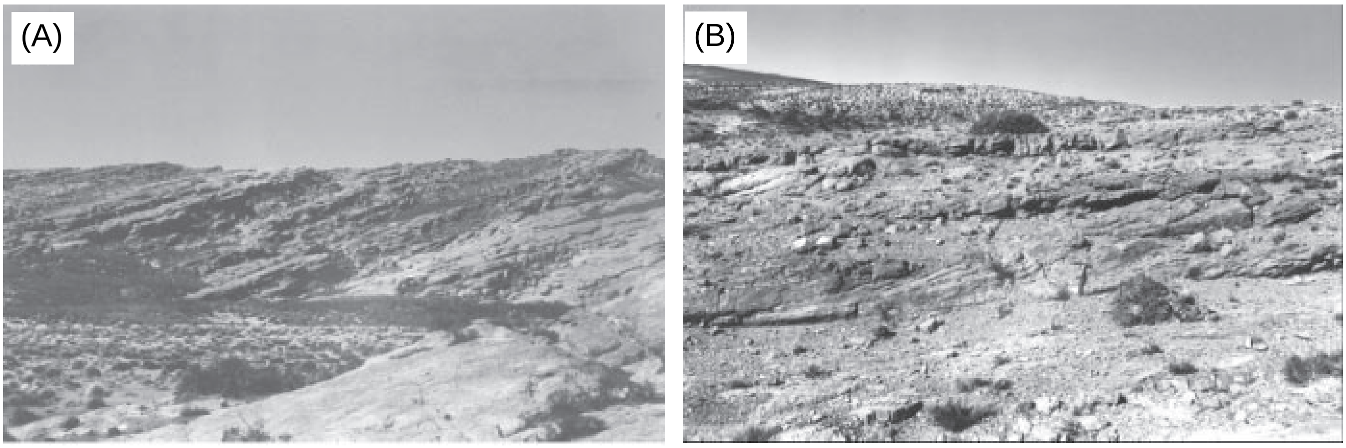

Fig. 11. (A) Outcrop of the proximal facies association at Chenque Colorado. (B) Downstream accreting deposits of the proximal facies association at the same locality. Note the vertical and lateral stacking of lenticular, trough cross-bedded pebbly sandstones and coarse-grained sandstones.

Depositional Model

The Tordillo Formation is interpreted as the deposits of an arid fluvial-dominated system (terminal fan, according to Friend, 1978) that was marked by a systematic downstream variation in the architectural style. In the southern sector of the study area, northerly flowing channels transported abundant sandy and gravely bedload. Channels were unstable and shifted their positions frequently as a result of bank erosion and avulsion. Common cross-stratification suggests sediment accumulation as downstream accreting bars. Vertical and lateral alternation of tightly packed gravels, sandy gravels and sands is indicative of highly unsteady and non-uniform flows. Development of multistory sandbodies towards the top of the proximal facies association reveals a general decrease in stream power and/or sediment supply (Blum and Tornqvist, 2000). The attributes of these proximal deposits and the almost absolute absence of fluvial incision indicate that the influx of sediment largely exceeded basin subsidence (Eberth and Miall, 1991; Schwarz, 2004).

Laterally extensive conglomerate-dominated lithosomes located in the basal part of the Neuquén River section were deposited by cohesive debris flows and unconfined high-energy bed-load currents. The facies association and processes involved suggest a transition from type I (debris flow-dominated) to type II alluvial (sheetflood-dominated) alluvial fans (Blair and McPherson, 1994). The factors responsible for the promotion of these two different fan-types are source rock (clay content), size of the catchment area and fan slope (Blair, 1999a). In our case, bedrock lithology did not change. Therefore we assume that type I fan was the result of straight and short drainage basins, and fan slopes between 5° and 15°. The transition from type I fan to type II fan is indicative of the enlargement of catchment areas and fan slopes between 2° and 8° (Blair and McPherson, 1994).

The distal facies association, recorded to the north and northeast of the study area (Loncopué, Neuquén River and Puerta de Curacó), is interpreted as the deposits of a wadi-sand flat–playa fluvial system. This system developed as a response to reductions in flood-plain gradient, flow expansion, low competence and discharge loss due to infiltration (Sadler and Kelly, 1993). Flows were probably seasonal and typically ephemeral. These areas were characterised by episodic low-energy shallow sheetflooding, settlement from residual flood discharge, and protracted periods of subaerial exposure and non deposition. High energy flooding events are represented by unchannelised bedload sandstone lobes. The deposits were formed by unsteady, non-uniform Newtonian flows with a rather high sediment concentration. These flows were probably supplied by avulsive short-lived ephemeral channels in which water depths were inadequate for the formation of macroforms (Eberth and Miall, 1991). The light red sediment colour, the ubiquitous evidence of subaerial exposure, and the absence of fossils and palaeosoils indicate that the climate was arid and the water tables were low. However, the association of wave ripples with numerous desiccation cracks is suggestive of ephemeral shallow ponds supplied by flood waters. In the more distal section of the Tordillo Formation (Puerta de Curacó) and towards the top of the unit at Loncopué and in the Neuquén River section, predominance of primary and reworked pyroclastic facies is accompanied by frequent development of soil horizons and a general change towards green and green dark sediment colours. These deposits preclude the widespread Vaca Muerta transgression and provide evidence of longer periods of high water table emplacement associated with a marked increase in explosive activity from volcanoes located along the magmatic arc.

Stratigraphic Architecture

Major trends

The Tordillo Formation represents part of the sedimentary infill of an elongate backarc basin that is subparallel to the Andean magmatic arc trend. Its sedimentary record was probably related to and controlled by events of the Araucanian (Upper Jurassic) tectonic inversion and the cordilleran arc. The Huincul arch was the main Araucanian structure and formed the southern shoulder of the studied trough. It became the source area of recycled lower Mesozoic rocks. Besides, the magmatic arc constituted a positive land to the west and had a strong effect on the Tordillo deposits. It formed a mountain chain between the proto-Pacific ocean and the Neuquén Basin, and probably acted as a climatic barrier favouring the development of semiarid to arid conditions in the basin. Coeval volcanic activity and erosional processes in the arc exerted considerable influence on the provision of sediment volume and sediment character.

The most diagnostic feature of the Tordillo Formation is the development of an overall fining-upward sedimentary succession (Figs. 5 to 10), probably as a response to extensional widening and rapid subsidence. These deposits rest on top of restricted shallow marine deposits and are covered by basinal black shales. They are therefore interpreted as a lowstand wedge. The base of the Tordillo Formation represents the sequence bounding unconformity. The abrupt emplacement of continental conglomerate beds above this unconformity consitututes a master low order sequence boundary. This important base level fall is interpreted as the result of the additional effect between a generalised eustatic drop and a relative period of tectonic quiescence that followed the onset of Upper Jurassic tectonic inversion.

The overall decrease in sediment grain size up section reveals a change towards higher aggradation rates related to an increase in the space of accommodation (Marriott, 1999). The fining-upward stacking pattern of the Tordillo Formation is particularly evident in the western arc margin (Neuquén River section), where three stages of evolution may be recognised (Fig. 15). Stage 1 represents coarse-grained deposition on alluvial fan systems fed by a small and steep drainage basin developed on the uplifted magmatic arc. Stage 2, characterised by a thick succession of distal ephemeral fluvial and playa deposits, is the result of rapid backstepping of depositional systems. This retrogradational stack seems to be associated with a lowering of the depositional slope. Stage 3, represented by fine-grained amalgamated volcaniclastic deposits, is the result of a rapid subsidence and rise in base level probably related to dip-slip displacement along bounding fault systems combined with a general. The progressive variation in sediment colour towards darker staffs and the common appearance of palaeosoil levels found in muddy layers would indicate increased precipitation and high water table emplacement. These deposits correspond to the end of the long-term lowstand wedge and pre-announce the beginning of the Early Tithonian major transgression (Spalletti et al., 2000).

As shown by thickness analysis (Fig. 3B), two depocenters may be identified to the north of the Huincul arch. A positive structure, known as the Chihuidos High (Fig. 16), separated the fluvial-dominated

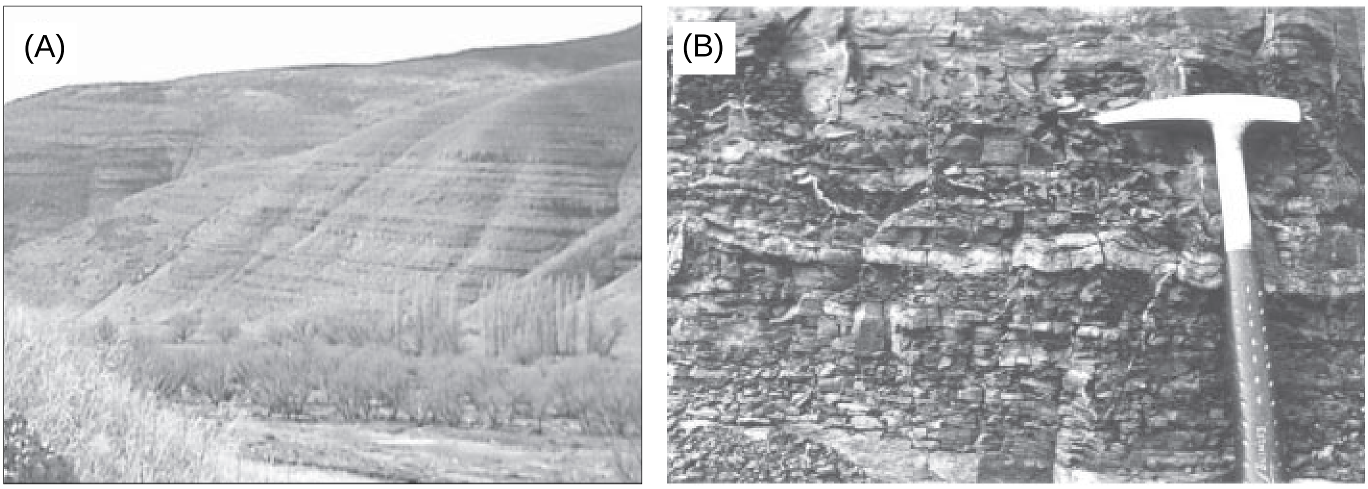

Fig. 12. Distal facies association. (A) General view of the Tordillo Formation at Loncopué showing the typical alternation between laterally extensive fine-grained deposits and major sandstone sheets. (B) Close view of laterally extensive fine-grained deposits composed of thinly laminated mudstones with common desiccation cracks.

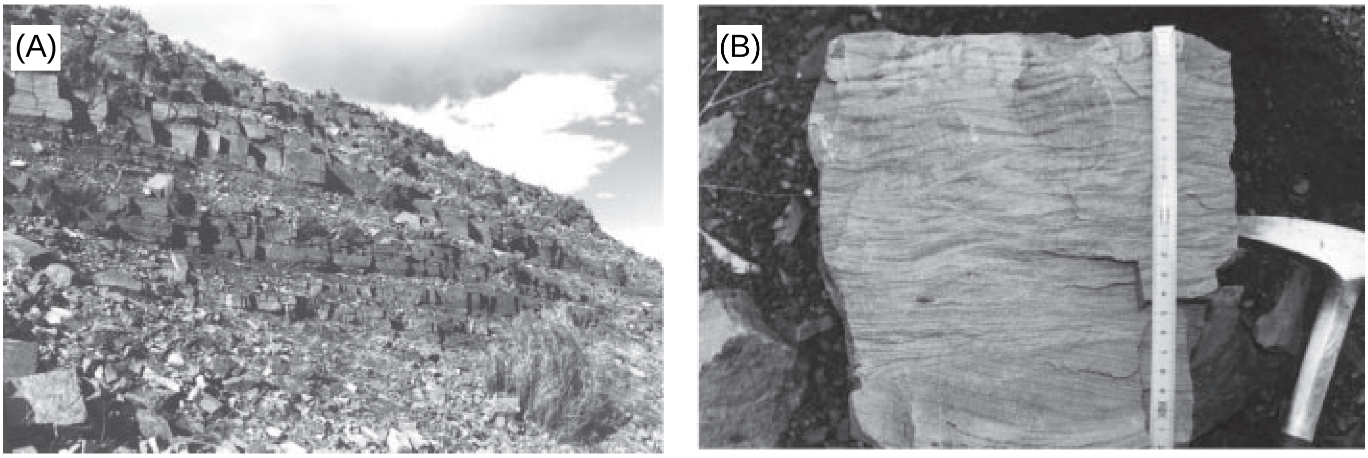

Fig. 13. Distal facies association. (A) View of amalgamated sandstone sheets showing convex-up lobate morphology; (B) typical internal organisation of tractional structures in a sandstone sheet. From base to top: small scale cross-bedding, horizontal lamination and ripple cross-lamination.

western depocenter from the aeolian-fluvial-dominated eastern depocenter (Fig. 16). There are several modern examples of arid regions showing a similar panorama.

The earliest deposits within the western trough fill (stage 1) indicate that the area was initially dominated by high energy flows moving from the Huincul arch (south to north) and from the magmatic arc (west to east). A belt of alluvial fans and bajadas were eventually formed along the foothills of these positive lands (Fig. 16). These proximal deposits passed downslope to widespread wadi fluvial deposits and mud-dominated playa deposits (Fig. 16). A prominent change in the fluvial style occurred in the western depocenter during stage 2. The expansion of distal fluvial systems and playas suggests an abrupt increase in accommodation, especially towards the western margin of the basin (Fig. 16). Finally, stage 3 shows a reactivation of explosive volcanism from the magmatic arc associated with a rise in base level that allowed widespread deposition of fine-grained volcaniclastic deposits.

Sequence patterns

Stratal architecture of fluvial deposits should reflect regional and temporal variations in accommodation, sediment supply and sequence stratigraphic development of the basin fill (Diessel et al., 2000; Davies and Gibling, 2003). However, sequence stratigraphy has usually been applied to understand vertical changes in facies successions as a response to fluctuations in sea level, tectonic regime, climate and sediment supply (Shanley and McCabe, 1991, 1993; Wright and Marriott, 1993; Gibling and Bird, 1994; Currie, 1997; Martinsen et al., 1999). In contrast, the Tordillo Formation shows a difference in sedimentary facies, stacking patterns and architecture between the proximal deposits of the southern part and the distal deposits of the northern part of the study area. In this case the regional variation in accommodation has played a significant role in controlling the overall stacking pattern of ephemeral fluvial deposits.

The basin fill architecture in the southern upstream sector, characterised by reduced thickness and coarse grain size, suggests a steep gradient, excess of bedload supply and a low subsidence rate that resulted in diminished accommodation space. The fluvial successions show a cyclic sedimentation pattern evidenced by alternations between gravely-dominated and sand-dominated fluvial deposits. Interpreting which variables controlled this stacking pattern is complicated because different factors, such as changes in source-rock composition, tectonism and climate, can produce similar results (Schumm, 1991, 1993). Variation in source-rock composition does not seem a reasonable explanation for cycle development, since sediment dispersal systems maintained similar patterns draining toward the north from the inverted Huincul arch. We suggest that the changing style of fluvial deposition would be the result of a combination between vertical pulses of uplift in the source area and long-term variations in sediment and/or water discharge. In this sense, and as proposed by Rhee et al. (1998), the shift of successive coarse-grained lithosomes is nearly perpendicular to the palaeoslope and is suggestive of structural influences on the development of architectural units within the proximal facies association.

Thicker and finer-grained deposits dominate in the areas located to the west and northwest. This marked change in sedimentation is not only the result of a palaeogeographic variation in fluvial style from proximal to distal settings, but also indicates increasing accommodation due to high rates of subsidence relative to coarse siliciclastic sedimentation rates. Within the overall fining-upward trend that can be attributed to a long-term sea level rise, these deposits show cyclic alternations between mud-dominated and sand-dominated packages (Fig. 17). Following the nomenclature proposed by Martinsen et al. (1999) the sand-dominated subcycles may be interpreted as low-accommodation systems tracts, whereas the mud-dominated subcycles may be interpreted as high-accommodation systems tracts (Fig. 17). Stratal variations are probably associated with changing river sizes and networks, sediment supply rates and shifts in the position of major feeder channels (Khan et al., 1997). Although these cycles may have been the result of variations in tectonic uplift and subsidence rate, climate might have played a significant role in controlling stacking patterns (Blum, 1993; Kocurek and Havholm, 1993; Sweet, 1999). Hence, a sudden increase of sand influx due to strong climatic fluctuations is another plausible explanation for the appearance of stacked major sandstone lobes in the distal facies association.

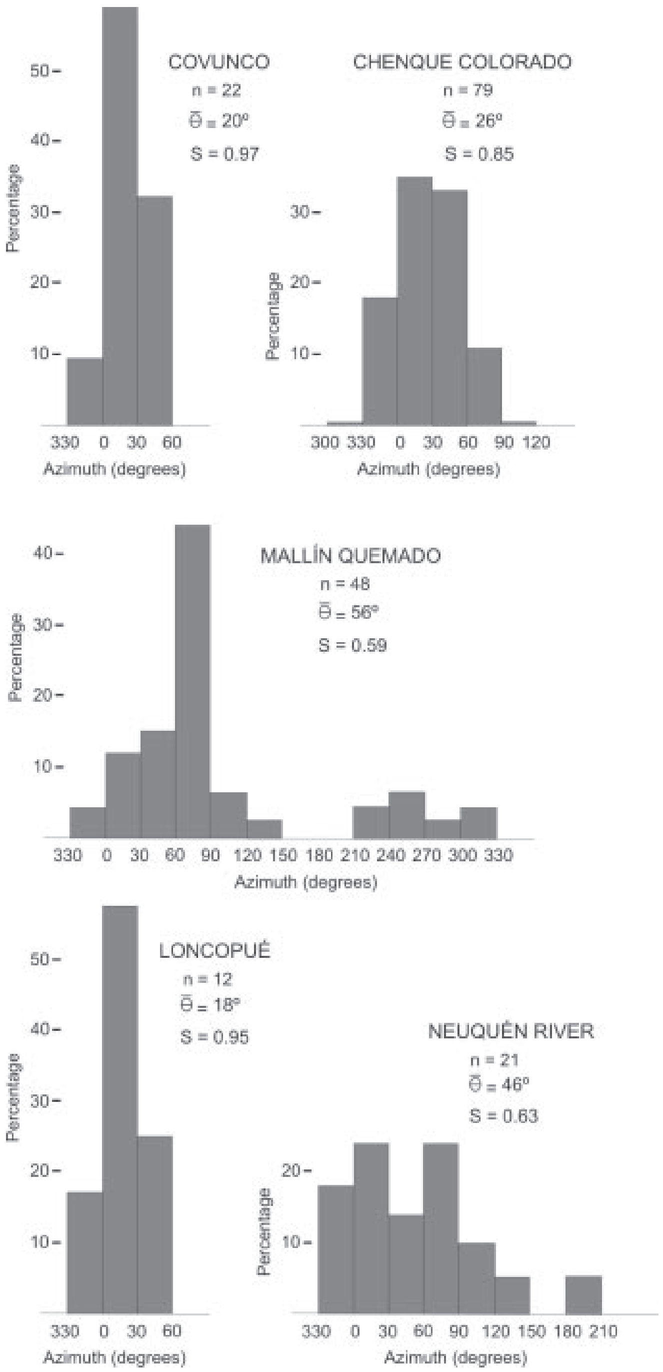

Fig. 14. Histograms of flow directions from Covunco, Chenque Colorado, Loncopué and the Neuquén River sections. Note the concentration of much of the data into a much narrower palaeocurrent range in the Covunco, Chenque Colorado (proximal facies association) and Loncopué (distal facies association) sections. S is the vector strength and lower values indicate higher dispersion.

Correlations using sequence stratigraphy in continental deposits are controversial because key components of sequences created by changes in accommodation, such as marine transgressive surfaces, are not developed and/or identifiable. We have interpreted that cyclic gravelly- and sand-dominated bedload fluvial systems passed downslope into cyclic sand- and mud-dominated wadi and playa systems. However, the nature of field exposures, the lack of chronostratigraphic markers and the regional changes in subsidence and sediment supply, make it difficult to determine the precise correlation among cycles. Further studies from other parts of the basin will be essential in order to sort out these questions.

Conclusions

The following conclusions may be drawn from the analysis of the Tordillo Formation exposures in the western part of the Neuquén Basin:

(1) The Tordillo Formation represents part of the sedimentary infill of an elongate backarc basin that is subparallel to the Andean magmatic arc trend. Its deposits were related to and controlled by the Araucanian (Upper Jurassic) tectonic inversion and the activity of the magmatic arc.

(2) The most diagnostic feature of the Tordillo Formation is the development of an overall fining-upward sedimentary succession, probably as a response to extensional widening and rapid subsidence.

(3) Palaeocurrent azimuths show unimodal distributions. In almost all localities they consistently indicate a N to NE trend and suggest a source area in the Huincul arch. In the Neuquén River section currents flowed towards the east, indicating a positive land (the Andean magmatic arc) located to the west of the basin.

(4) An arid fluvial-dominated system is proposed for the Tordillo deposits. Two main lithofacies associations

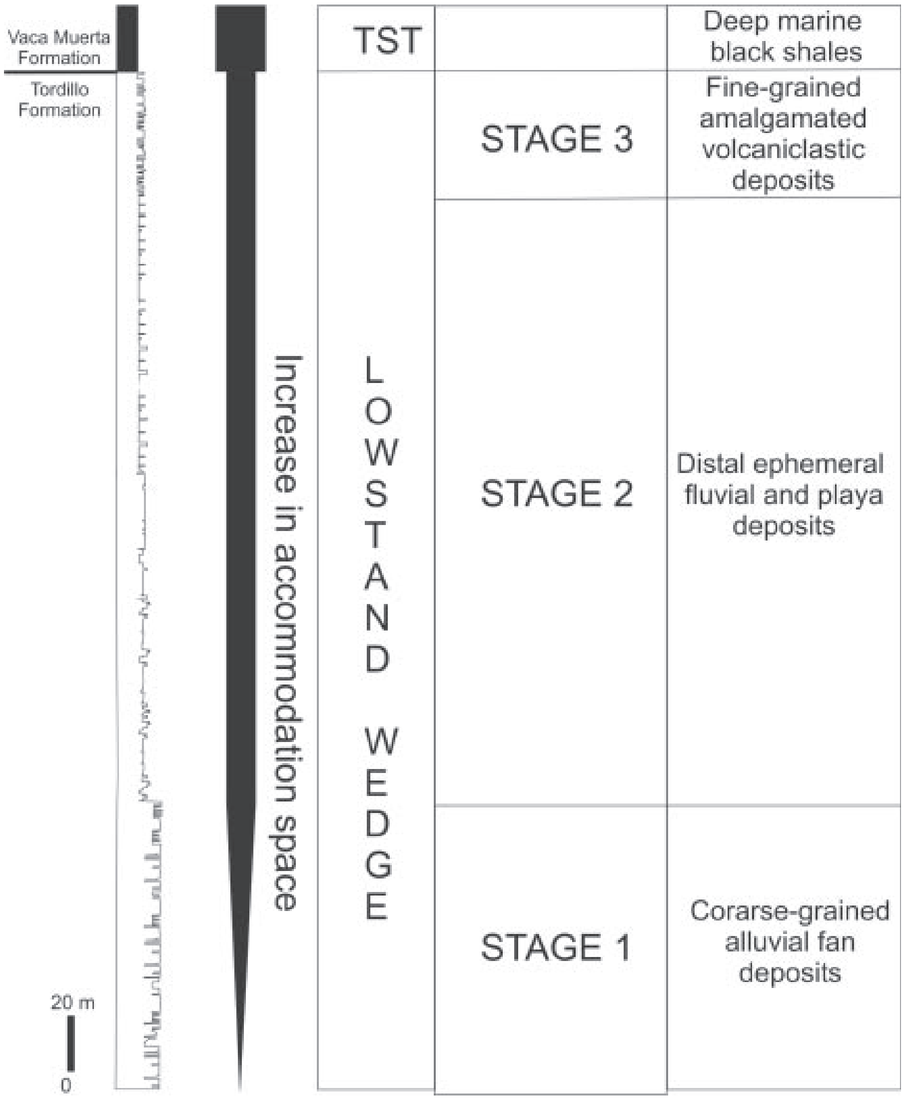

Fig. 15. Schematic column of the Neuquén River section showing the three stages of evolution described in this paper for the Tordillo Formation.

(proximal and distal) are recognised in the study area. The proximal association is defined in the sections located to the south of the study area and in the basal part of the Neuquén River section. The distal association occurs throughout the Tordillo Formation at Loncopué and Puerta de Curacó, and in most of the Neuquén River section above the proximal deposits.

(5) The stratigraphic architecture in the southern area is characterised by reduced thickness and coarse grain size. These features suggest a steep gradient, excess of bedload supply and a low subsidence rate that resulted in diminished accommodation space. The sandy and gravely deposits of this proximal fluvial system were accumulated as downstream accreting bars in very unstable channels. Vertical and lateral alternation of gravels, sandy gravels and sands is indicative of highly unsteady and non-uniform flows. This cyclic pattern of sedimentation seems to be the result of a combination between vertical pulses of uplift in the source area and long-term variations in sediment and/or water discharge.

(6) In the basal part of the Neuquén River section, laterally extensive conglomerate-dominated lithosomes were deposited by cohesive debris flows and unconfined high-energy bed-load currents. The stacking pattern of these deposits suggests a transition from debris flow-dominated to sheetflood-dominated alluvial fans.

(7) The distal facies association dominates in the areas located to the west and northwest. This is interpreted as the deposit of a wadi-sand flat–playa fluvial system developed as a response to reductions in flood-plain gradient, flow expansion, low competence and discharge loss due to infiltration. Red sediment colour, common evidence of subaerial exposure, and the absence of fossils and palaeosoils indicate that the climate was arid and the water tables were low. Unchannelised sandstone lobes were formed by high-energy, unsteady and

non-uniform sheetfloods with a rather high sediment concentration.

(8) Cyclic alternations between mud-dominated and sand-dominated packages are interpreted as the result of tectonic and climatic fluctuations.

(9) The marked change in sedimentation from proximal to distal settings is not only the result of a palaeogeographic variation in fluvial style, but also suggests increasing accommodation in the distal areas due to high rates of subsidence relative to coarse siliciclastic sedimentation rates.

(10) The more distal sections the Tordillo Formation show predominance of primary and reworked pyroclastic facies accompanied by frequent development of soil horizons and a general change towards green and green dark sediment colours. These features indicate longer periods of high water table emplacement and increase in explosive activity from volcanoes located along the magmatic arc.

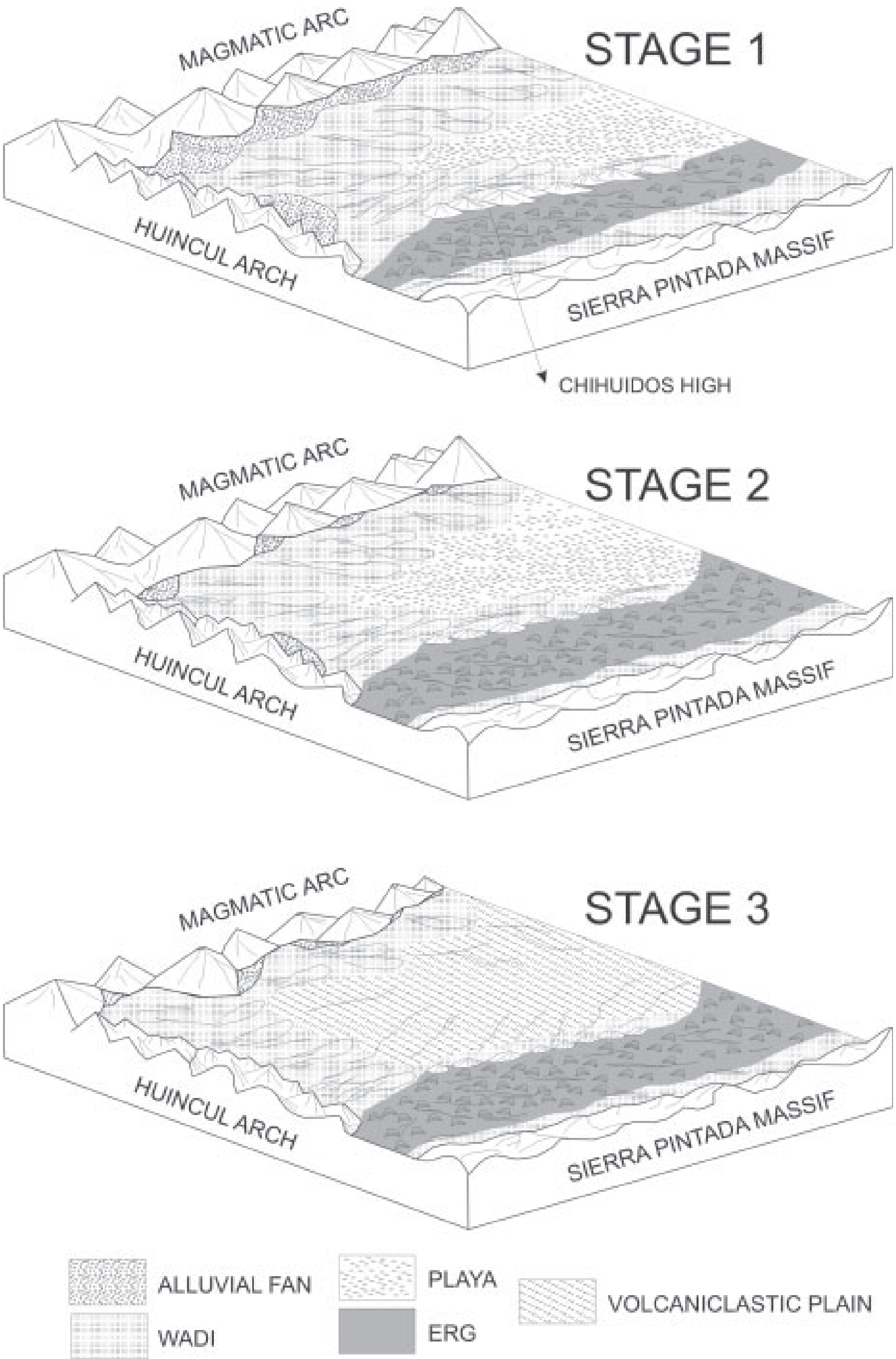

Fig. 16. Schematic palaeogeographic evolution of the Tordillo lowstand wedge to the north of the Huincul arch. Note the development of two depocenters separated by the north-south trending Chihuidos structure.

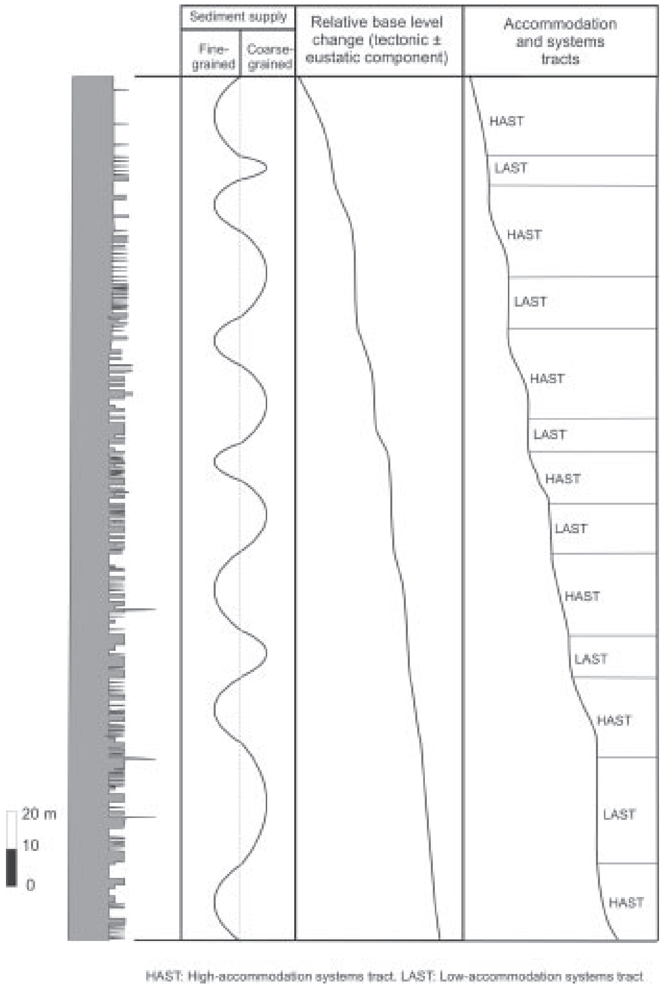

Fig. 17. Cyclic alternations between mud-dominated (high accommodation) and sand-dominated (low-accommodation) packages in the Loncopué section.

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