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Sequence stratigraphy of a tidally dominated carbonate–siliciclastic ramp; the Tithonian–Early Berriasian of the Southern Neuquén Basin, Argentina

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Abstract: The Tithonian–Berriasian Vaca Muerta, Carrín Curá and Picún Leufú formations in the southern Neuquén Basin were deposited on a tidally dominated, mixed carbonate–siliciclastic ramp. Basinal, outer, middle, shallow and back ramp facies associations are recognized and a sequence stratigraphic analysis reveals that the ramp record consists of three shallowing-upwards sequences (Ti1, Ti2 and Ti3) set within a lower-order progradational cycle. A higher order of cyclicity is superimposed on to the middle (Ti2) sequence. The majority of the ramp facies belong to the transgressive and highstand systems tracts; however, at the base of Ti2, a lowstand systems tract is identified, characterized by a basal unconformity and an abrupt basinward shift of the shallow marine lithofacies. Transgressive systems tracts were characterized by slow sedimentation rates and rapid sea-level rises that affected carbonate productivity. Highstand systems tracts show the greatest carbonate productivity and an increased progradation rate on account of a reduction in accommodation space generation. Palaeogeography played a major role in the development of the depositional systems. Partial isolation from the Pacific Ocean reflecting the growth of the Andean magmatic arc and geographic restriction due to tectonic inversion in the central part of the basin resulted in a meso-macrotidal regime that produced a tidally dominated sedimentary record in the shallow and back ramp environments. Coeval anoxic conditions in the central part of the Neuquén Basin favoured distal ramp and basinal black shale deposition during episodes of relative sea-level rise.

Keywords: Neuquén Basin, Tithonian, Berriasian, sequence stratigraphy, depositional ramp.

Sequence stratigraphy has proved to be a powerful tool for stratigraphic and facies analysis of sedimentary successions. In this paper, the method is applied to tidally influenced, mixed siliciclastic–carbonate deposits relating to a Tithonian–Early Berriasian ramp in the southern sector of the Neuquén Basin, Argentina. A detailed description of the facies, facies relationships and stratal architecture is presented to address: (1) the facies makeup and evolution of a ramp which developed on the margin of an anoxic/suboxic basin, (2) the expression of stratigraphic sequences, systems tracts and sequence boundaries in a tidally-dominated ramp setting and (3) the influence of anoxia on the outer ramp and basinal sedimentary record.

Study area and geological framework

The Neuquén Basin is located on the eastern side of the Andes (Argentina Republic) between a latitude of 36° and 40°S (Fig. 1). The basin contains a Late Triassic to Cenozoic fill comprising continental and marine siliciclastic, carbonate and evaporitic deposits which are up to 2600 m thick and cover an area of over 120 000 km^2 (Yrigoyen 1991). The basin was limited to the east and south by cratonic areas, and to the west by the Andean volcanic arc. It has been considered by many authors as a back-arc or retro-arc basin (Digregorio *et al.* 1984; Feehan 1984; Neher 1986; Macellari 1988; Barrio 1989; Legarreta & Uliana 1991), although its precise tectonic setting remains unclear.

The studied succession comprises a set of marine units which can be recognized along the length of the Neuquén Basin. Previous work on the sequence stratigraphic framework of the basin is at regional scale and has been based on both seismic and outcrop data (Gulisano *et al.* 1984; Mitchum & Uliana 1985; Legarreta & Gulisano 1989; Legarreta & Uliana 1991; Gulisano & Gutiérrez Pleimling 1994). Legarreta & Gulisano (1989) group all the Tithonian–Valanginian deposits of the Neuquén Basin into a broad shallowing-up cycle (the Lower Mendoza Mesosequence), which they subdivided into nine depositional sequences. The marine deposits of the Tithonian–Lower Berriasian in the southern sector of the basin were recognized as comprising four sequences (Gulisano *et al.* 1984), although only three of them are recognized in the southernmost Neuquén Basin. Seismostratigraphic studies made on the same stratigraphic interval (Mitchum & Uliana 1985; Legarreta & Uliana 1991) confirm the existence of four sequences. These authors suggest a correlation between the geometry and the arrangement of the observed sequences and the global chart of third-order eustatic sea-level variations (Haq *et al.* 1987), although Jurassic and Cretaceous sequences have also been related to climatic changes and local tectonism (Hallam 1991).

The area studied here comprises the southern part of the Neuquén Basin, where five sections have been measured and correlated (Fig. 1). In this part of the basin, the Tithonian–Berriasian is represented by three marine lithostratigraphic units known as Vaca Muerta, Carrín Curá and Picún Leufú formations. The Vaca Muerta Formation, which is widely distributed over all the Neuquén Basin, consists of a thick unit (over 350 m) of dark bituminous shales and marls. The Carrín Curá Formation (120 m thick) is restricted to the southwestern margin of the basin and consists of greenish and yellowish sandstones and dark hazel shales. The Picún Leufú Formation is well developed along the entire southern margin of the basin and is characterized by a high proportion of yellow, white and

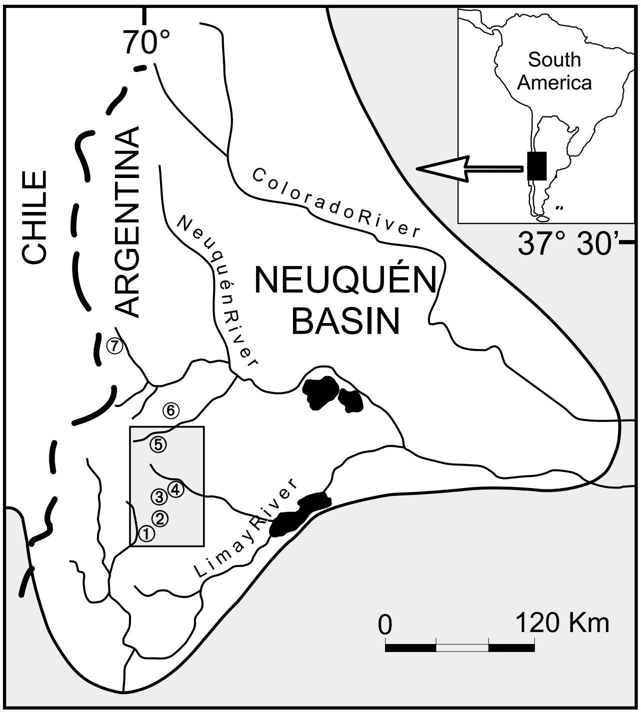

Fig. 1. Location map of the Neuquén Basin illustrating the studied area and measured sections. 1, Catán Lil River; 2, China Muerta creek; 3, Cerro del Sapo; 4, Picún Leufú anticline; 5, Los Catutos–Covunco creek; 6, Sierra de la Vaca Muerta; 7, Cajón de Almanza (Loncopué). 1–5 represent the location of measured sections discussed in the text. 6 and 7 are localities for biostratigraphic control.

pink bioclastic and micritic carbonates along with grey and greenish sandstones and mudstones (up to 350 m thick).

The contact between the Vaca Muerta and Picún Leufú formations is diachronous (Leanza 1973, 1981; Leanza & Hugo 1977; Leanza *et al.* 1977) and progradational (Gulisano *et al.* 1984; Mitchum & Uliana 1985; Legarreta & Gulisano 1989). Thus, the shallower facies (Picún Leufú Formation) become progressively younger from the southern sector to the central sector of the basin (Table 1).

The Tithonian marine sedimentary rocks overlie widespread Kimmeridgian continental deposits of the Tordillo Formation, and were deposited as a result of a sudden Pacific transgression, which Vergani *et al.* (1995) associated with a tectonic phase of compressional relaxation. Legarreta & Uliana (1991, 1996) attributed this episode to a general eustatic sea-level rise accompanied by a reduced clastic sediment supply, providing conditions suitable for anaerobic to dysaerobic sedimentation (Vaca Muerta Formation), apart from in the southeast of the basin where shallow marine clastic deposits accumulated (Carrín Curá Formation).

Along the southern margin of the Neuquén Basin, shallow marine carbonate and siliciclastic sediments of the Picún Leufú Formation began to accumulate from the mid-Tithonian, whereas in the centre of the basin the poorly oxygenated conditions represented by the dark shaly and marly facies of the Vaca Muerta Formation (Table 1) persisted until Valanginian times. In the late Tithonian, deposits of the Picún Leufú Formation occupied a much wider basinal area on account of northward progradation; these depositional environments persisted until the early Berriasian, when they were subsequently replaced by the fluvial/deltaic deposits of the 'Proximal' Mulichinco Formation (Table 1).

Sedimentary facies

The studied Tithonian–Berriasian units (Figs 2a,b, 3a,b & 4) show a complex vertical alternation of intervals dominated by carbonate and/or siliciclastic deposits, with varied textures and a range of primary sedimentary structures. There are also thick and relatively uniform sections which are characterized by shales and marls (Vaca Muerta Formation and some levels of the Picún Leufú Formation) or by fine-grained and massive biogenic carbonates (Los Catutos Member of the Vaca Muerta Formation).

The succession has been subdivided into a number of carbonate and siliciclastic facies on the basis of lithology, texture, composition, and sedimentary structures (Table 2). These are identified by a code comprising a capital letter that defines the lithology and small letters that refer to complementary attributes such as physical and biogenic structures and fossil abundance.

The most characteristic feature of the studied sections is the presence of sigmoidal beds (Facies Lsg, Ssg). These are cross-stratified sandbodies with mud drapes and reactivation surfaces. They show thick tangential, and sometimes graded, foresets. Evidence for abrupt changes in flow-regime suggests that these facies were formed by tidal currents. Sets *c.* 2 m thick and are considered to have been produced by the migration of subtidal bedforms and others between 0.3 and 0.5 m thick were generated by smaller sand-waves and dunes, typical of shallower and possibly intertidal environments. Cross-stratified facies (Lt-Lp, St-Sp) are attributed to various types of currents such as longitudinal currents linked to translational waves (Shipp 1984; Byers & Dott 1995) and tidal currents (Terwindt 1988; Leckie & Singh 1991); some bodies may result from unidirectional currents in estuarine environments. There are also tidal levels represented by thin (centimetre scale) layers with herringbone cross-bedding (Shb).

Horizons with evidence of wave reworking, such as those showing pure oscillatory and combined flow ripples (Lwr, Swr) are subordinate. These are related to a friction-dominated zone or a lower shoreface environment (Swift & Niedoroda 1985). Calcarenites and sandstones with hummocky cross-bedding (Lhcs, Shcs) are interpreted as oscillatory flow deposits produced by storm processes (Myrow & Southard 1991, 1996; Midtgaard 1996). Higher energy facies are represented by plane-bedded and low angle cross-stratified facies (Lh, Sh) which are often associated with fluid escape structures and thin (<1 cm thick) intraclast-rich horizons. These deposits represent erosional events and rapid aggradation in shallow water and are interpreted as either nearshore oscillatory current transformation (Myrow & Southard 1991) or strong tidal currents.

Massive facies (Lm, Sm) are thought to mainly represent the destruction of primary depositional structures through biogenic action. Therefore, it is difficult to establish the physical processes of deposition. However, some bodies may have been massive originally and have been produced by storm-linked gravitational flows (Aigner 1982). Some strata (Lm) show normal grading attributed both to progressive decay in flow conditions and bioturbation, whereas others with thin reverse grading are considered to have been caused by rapid flow under traction-carpet conditions.

Table 1. *Chronostratigraphic chart of the Kimmeridgian–Early Valanginian interval in the southern and central Neuquén Basin*

MYBP	EPOCH / AGE		AMMONITE ZONES	← SOUTH: CATÁN LIL RIVER, CHINA MUERTA CREEK	PICÚN LEUFÚ ANTICLINE	LOS CATUTOS, COVUNCO CREEK	NORTH OF SIERRA VACA MUERTA	NORTH →: CAJON DE ALMANZA, LONCOPUÉ
	EARLY CRETACEOUS	EARLY VALANGINIAN	Neocomites wichmanni	"PROXIMAL" MULICHINCO FORMATION		MULICHINCO FORMATION		VACA MUERTA FORMATION
$137^{\pm2.6}$	EARLY CRETACEOUS	LATE BERRIASIAN	Spiticeras damesi	"PROXIMAL" MULICHINCO FORMATION		MULICHINCO FORMATION		VACA MUERTA FORMATION
	EARLY CRETACEOUS	EARLY BERRIASIAN	Argentiniceras noduliferum	"PROXIMAL" MULICHINCO FORMATION — ? —		PICÚN LEUFÚ FORMATION	VACA MUERTA - QUINTUCO FORMATION	VACA MUERTA FORMATION
$144.2^{\pm2.6}$	LATE JURASSIC	LATE TITHONIAN	Substeueroceras koeneni, Corongoceras alternans	PICÚN LEUFÚ FORMATION		UPPER VACA MUERTA MEMBER	VACA MUERTA - QUINTUCO FORMATION	VACA MUERTA FORMATION
	LATE JURASSIC	MIDDLE TITHONIAN	Windhauseniceras internispinosum, Aulacosphinctes proximus, Pseudolisoceras zitteli	PICÚN LEUFÚ FORMATION / CARRÍN CURÁ FORMATION	PICÚN LEUFÚ FORMATION / VACA MUERTA FORMATION	LOS CATUTOS MEMBER / LOWER VACA MUERTA MEMBER	VACA MUERTA - QUINTUCO FORMATION	VACA MUERTA FORMATION
$150.7^{\pm3}$	LATE JURASSIC	EARLY TITHONIAN	Virgatosphinctes mendozanus	CARRÍN CURÁ FORMATION / VACA MUERTA FORMATION	VACA MUERTA FORMATION	LOWER VACA MUERTA MEMBER	VACA MUERTA - QUINTUCO FORMATION	VACA MUERTA FORMATION

Data from Leanza (1973, 1980, 1981, 1993), Leanza *et al.* (1977), and Leanza & Zeiss (1990). Time scale of Gradstein & Ogg (1996). For location see Fig. 1.

The heterolithic levels (H) are here considered to be of tidal origin, as suggested by the alternation between fall-out deposits and unidirectional 3D ripple deposits (Tessier *et al.* 1995). Likewise, layers with inclined heterolithic stratification are identified (Hihs) and they probably represent the lateral accretion of point bars linked to sinuous tidal (estuarine) channels (Smith 1987, 1988; Leckie & Singh 1991).

Among the fine-grained facies, three categories are distinguished: DF, GF and Mf. DF dark shales and marls are typical of the Vaca Muerta Formation and represent suspension sedimentation of siliciclastic and/or carbonate grains on an oxygen deficient sea bottom. Many of these rocks show evidence of truly anoxic conditions, such as good preservation of the original lamination (laminated facies), abundant nektonic fossils (ammonites and fish debris), and small and rounded planktonic gastropods. Facies GF comprises greenish shales, marls and mudstone–wackestones produced by suspension fallout under oxic to suboxic conditions. Even if they sometimes show faint lamination, these sediments are generally massive and show evidence of bioturbation. Some beds of the GF facies include bivalves in life position (Figs 3b & 4). The third of the fine-grained facies (Mf) is exclusively found in the Los Catutos Member of the Vaca Muerta Formation. It consists of very compact and massive dark bioclastic micrites, bearing excellent specimens of ichthyosaurs, turtles and fish (Leanza & Zeiss 1990).

Additional carbonate facies comprise isolated levels of coarse and massive floatstone (Lf) formed by well preserved bivalves, with signs of slight reworking, and an algal laminated wackestone-mudstone facies (La), accompanied by widespread sulphate nodules and desiccation cracks that reflects intra- to supra-tidal conditions.

Facies associations

The depositional facies have been grouped together into recurring facies associations which are now described. In the following section, the distal marine associations are treated first, followed by the shallower water associations (Table 3). The deposits of the deeper environments are predominantly fine-grained and four main associations are defined.

Facies Association 1 is represented by thick successions of black shales and marls (Table 3) which were deposited mainly from suspension, below storm wave base, in anoxic to suboxic basinal environments. These rocks are rich in organic matter; their average TOC content is 2.1%, reaching maximum values of 6.6% (Kugler 1987). They are associated with thin intercalations of wackestone-packstone and massive to graded sandstone beds with sharp or erosional bases. These are interpreted as the distal deposits of dilute gravitational flows, perhaps induced by storm surges (Wallace-Dudley & Leckie 1993).

Facies Association 2 consists of thick (metre scale), homogeneous bodies of massive biomicrite interbedded with thin intercalations of black shale and marl. The biomicrites represent periods of high carbonate productivity with abundant skeletal carbonate debris and a lack of extrabasinal sediment.

Table 2. *Summary of facies description of the Vaca Muerta, Carrín Curá and Picún Leufú formations*

Facies	Lithology (texture+composition)	Primary structure	Post-depositional features
Lt-Lp, St-Sp	Granule grainstone, grainstone to packstone Sandstone	Trough and planar cross-bedding Herringbone cross-bedding (Shb)	
Lsg, Ssg	Grainstone to wackestone Sandstone	Sigmoidal cross-bedding	Sometimes with water-escape structure
Lwr, Swr	Grainstone to wackestone Sandstone	Wave ripples	Often bioturbated
Lhcs, Shcs	Grainstone to packstone Sandstone	Hummocky cross-stratification	
Lh, Sh	Granule grainstone (intraformational), grainstone to packstone Sandstone and carbonate sandstone	Horizontal lamination, low-angle cross-stratification	Water-escape structure; convolute lamination
Lm, Sm	Granule grainstone, grainstone to packstone (wackestone) Sandstone and carbonate sandstone	Massive	Massive; sometimes with water-escape structure
H	Heterolithic (wackestone–mudstone or sandstone–shale)	Flaser, wavy and lenticular lamination Inclined heterolithic stratification (HIhs)	
DF	Dark (anoxic-suboxic) shale, marl	Lamination	Fissility
GF	Greenish (suboxic-oxic) shale, marl and mudstone–wackestone	(Lamination) Wackestone with fossils in life position	Massive (fissility)
Mf	Bioclastic micrite	Fossiliferous	Massive, compact
Lf	Floatstone	Massive	
La	Wackestone to mudstone	Corrugated (algal) lamination	Mudcracks

As in Facies Association 1, the intervening fine-grained deposits were formed by slow suspension settling in areas with anoxic to suboxic bottom conditions.

Facies Association 3 occurs in two sub-associations (Table 3). Facies Association 3a comprises several metre thick intervals of interbedded green, bioturbated mudstones, marls and mudstone–wackestones. These occur together with less common laminated mudstone, thin and massive layers of packstone–wackestone, and mudstone with infaunal bivalves in life position. The nature of this association suggests a quiet environment punctuated by episodes of carbonate productivity. The non-carbonate fines probably correspond to diffuse muddy flows generated by very distal/weak storm currents (Brett 1983; Aigner 1985). The deposits of Facies Association 3a represent an offshore environment with aerobic conditions and good circulation at the sediment–water interface. Facies Association 3b is made up of thin and massive levels of mudstone and mudstone–wackestone, together with tabular to lenticular beds of massive calcarenite and parautochthonous bioclastic calcirudite. The rudites show evidence of minor reworking of skeletal carbonate grains. This association indicates an environment with greater productivity of organic carbonate and slightly shallower conditions, in which suspension sedimentation alternated with weak storm-induced currents that caused some winnowing (Kreisa 1981; Jennette & Pryor 1993).

Facies Association 4 comprises a single facies (Lf), a rare but conspicuous floatstone (Table 3) interpreted as a parautochthonous biogenic deposit with very scarce post-mortem remobilization due to relatively low-energy wave conditions (Aigner 1985; Jennette & Pryor 1993).

Four shallow water to marginal marine facies associations are recognized.

Facies Association 5 is characterized by siliciclastic and carbonate sandstones showing tractional structures reflecting both tidal and wave-induced currents, along with thin intercalations of fine-grained sediment. Three sub-associations are distinguished: 5a, 5b and 5c (Table 3). Facies Association 5a consists of facies generated by variable regime oscillatory waves, in which vertical sequences (commonly incomplete) can be seen. The transition between massive, plane-bedded, HCS and ripple-laminated units is comparable to the BPHX cycle (Walker *et al.* 1983) generated by storms above the corresponding wave base (Walker 1985; Myrow & Southard 1991; Byers & Dott 1995). Facies Association 5b is by far the most common coarse-grained facies association. It is composed of laterally continuous sigmoidal and very often mounded bodies (Lsg, Ssg) which occur both isolated or in groups, with associated herringbone, inclined heterolithic stratification, massive and plane-bedded facies. These deposits are interpreted as open ramp shoals dominated by subtidal to intertidal sandwave fields amongst which interbar channels evolved. Facies Association 5c comprises planar and trough cross-stratified facies associated with massive and plane-bedded units (Table 3). The cross-bedding is attributed to wave-induced, unidirectional (longitudinal and surf) currents, as well as shallow tidal currents, developed in open near-shore environments. Deposits with horizontal to low-angle

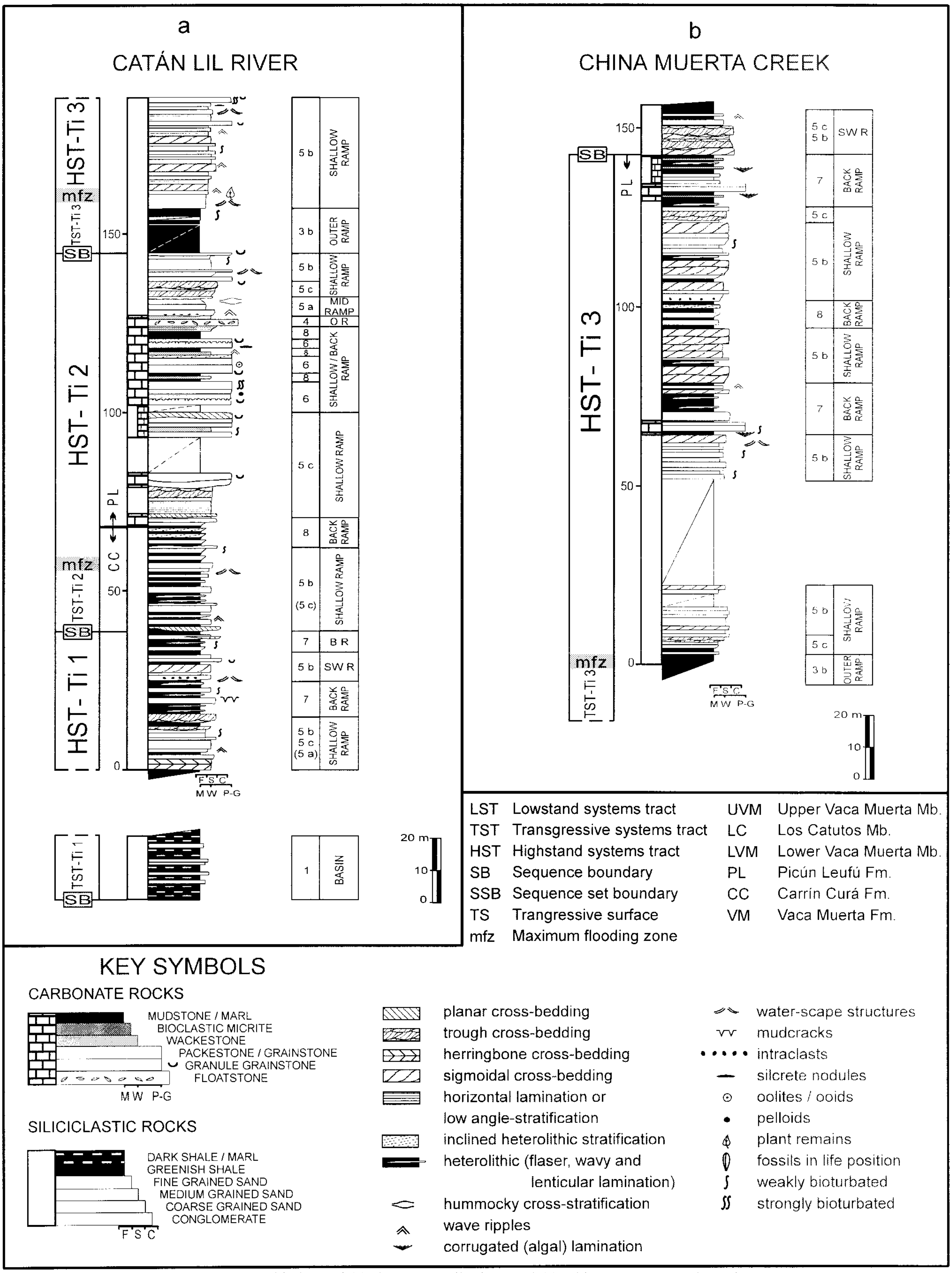

Fig. 2. Graphic logs of (**a**) the Catán Lil River and (**b**) China Muerta Creek sections.

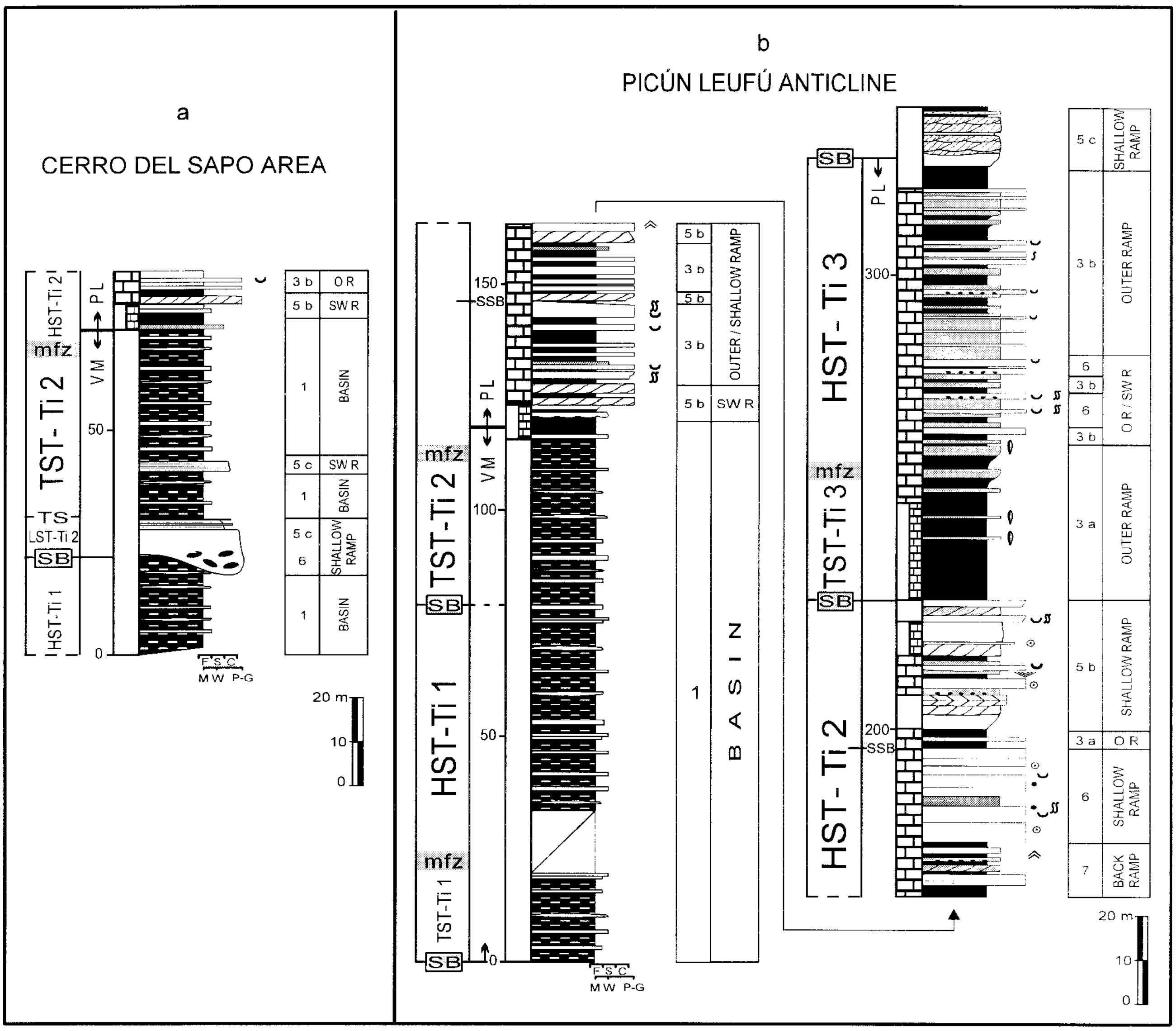

Fig. 3. Graphic logs for (**a**) Cerro del Sapo and (**b**) Picún Leufú Anticline sections. For key to symbols and abreviations, see Fig. 2.

cross-bedding were probably produced by accretion on the foreshore during shoal emergent periods. The finer-grained deposits associated with the tractional bedforms were formed by suspension fall-out (GF) and by the alternating action of tractional flows and suspension fall-out (H).

Facies Association 6 comprises oolitic and bioclastic grainstone and packstone deposits formed in moderate to high energy conditions. They show pervasive endichnial trace fossils that give them a massive appearance. Strata are thick (1.3 to 1.7 m), continuous and with a tabular to strongly lenticular geometry. Beds are commonly amalgamated, although there are sections in which the bodies are separated by thin intercalations of fine-grained sediments (GF). Some of the calcarenites show wave-ripple trains on their bedding surfaces; in other cases, horizontal and low-angle lamination suggest intermediate to supercritical flow deposition. The good sorting, presence of ooids, and fragmented and rounded fossil fragments suggest repeated reworking processes through the action of normal and/or storm waves (cf. Jennette & Pryor 1993). All these features are indicative of carbonate shoals developed in nearshore environments.

Facies Association 7 comprises a range of related facies including suspension and heterolithic fine-grained beds, some of them associated with algal accretion deposits, and coarser-grained units with wave-ripples and sigmoidal (tidal) stratification (Table 3). This association is characterized by the alternation of flow conditions. In general, the tractional episodes are attributed to waves or to weak tidal currents. These characteristics suggest a partially protected lagoonal environment developed towards the marginal marine areas (Reading & Collinson 1996). However, there are some higher energy layers (Lh) possibly related to washover processes during storms.

Facies Association 8 is characterized by the predominance of massive (bioturbated) mudstones and sandy mudstones (GF) which show evidence of subaerial exposure (mud cracks). They are associated with thin layers of fine to medium grained sandstones and calcarenites with evidence of wave reworking (Table 3). The fine grained deposits are attributed to either a restricted lagoonal or tidal flat environment. Even if tidal processes are not documented in the fine deposits due to mixing caused by bioturbation, tidal influence is suggested by the inclined heterolithic stratified bodies (Hihs) which also characterize this association.

Depositional model

The studied sections show a gradual passage from shallow marine facies in the south and southwest, to deeper marine (including anoxic) facies in the north, without evidence for a talus slope or significant slope break, suggesting deposition was on a gently inclined ramp. Ramps are zoned on the basis of bathymetry and the energy conditions which in turn dictate the lateral facies distribution (Markello & Read 1981; Calvet & Tucker 1988; Buxton & Pedley 1989; Tucker *et al.* 1993). The facies associations discussed above can be related to specific parts of the ramp which here is sub-divided into four settings; basinal, outer ramp, middle ramp and inner ramp (Fig. 5, cf. Burchette & Wright 1992).

The basinal environment is characterized by Facies Associations 1 and 2, and comprises both fine-grained shaly and organic-rich carbonate sedimentary rocks often with a cyclic depositional arrangement (cf. Gasparini *et al.* 1997). When they contain very fine-grained storm sand intercalations they can be considered transitional to the outer ramp environment. The outer ramp is composed of Facies Associations 3a, 3b and 4 (fore ramp of Tucker *et al.* 1993) and is considered to be sub-storm wave base. The middle ramp deposits formed between the fair weather and storm wave bases (Burchette & Wright 1992), and are represented by Facies Association 5a (Fig. 5).

The inner ramp encompasses various depositional environments and has a more diverse assemblage of facies associations. Thus, Facies Associations 5b, 5c and 6 reflect moderate to high energy conditions in shallow and well circulated marine areas (nearshore) that correspond to the 'shallow ramp' of Tucker *et al.* (1993). Tidally dominated deposits (Facies Association 5b), representing intertidal to subtidal sandwave fields and interbar areas are the most widespread and characteristic features of the inner ramp setting in this basin. Facies Association 7 reflects a partially restricted environment with moderate to low-energy wave and tidal action, whereas Facies Association 8 is typical of a restricted and low energy lagoonal to peritidal area, the latter being of very limited development. These last two associations are assigned to the 'back ramp' sector of the inner ramp (Tucker *et al.* 1993, fig. 5).

Sequence stratigraphy

The vertical arrangement of facies associations in each of the measured sections reflects a clear tendency to shallow upwards. However, within the overall upward-shallowing trend, three higher frequency shallowing-up cycles are recognized. Note that the studied area only represents a portion of the Tithonian–Early Berriasian ramp/basin floor profile, spanning the inner ramp to the transition between the outer ramp and basinal environments. The three internal shallowing upwards

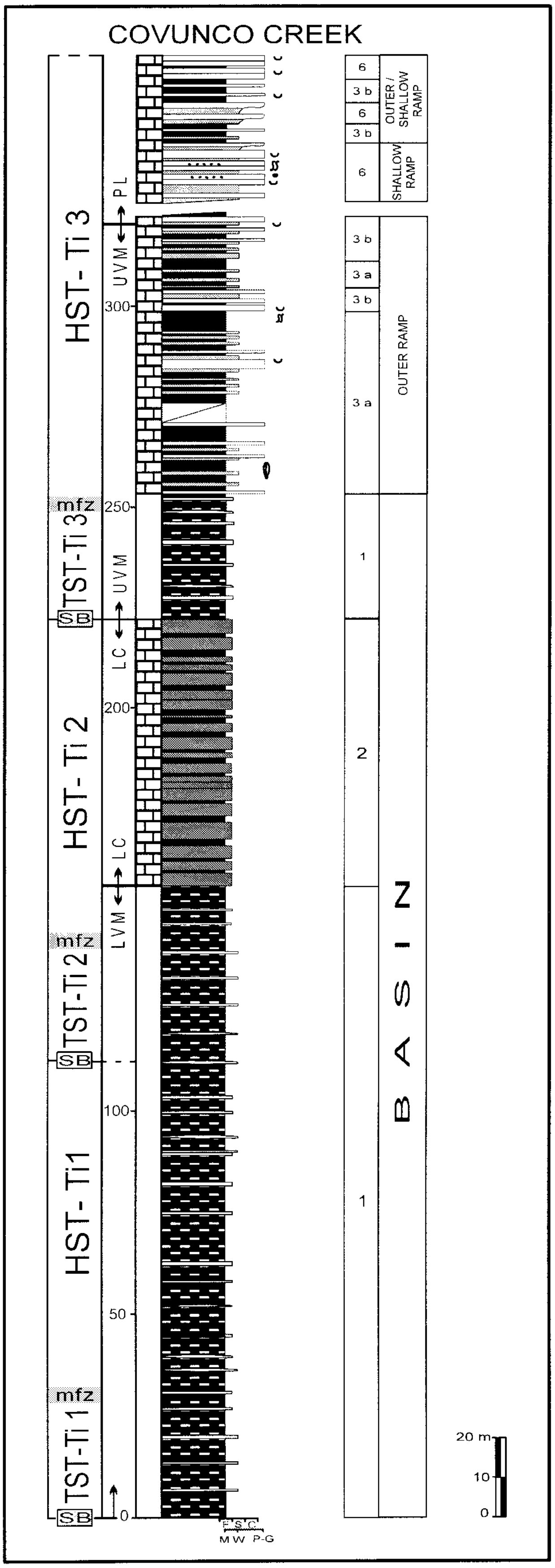

Fig. 4. Graphic log of the Covunco Creek section. For key to symbols and abreviations, see Fig. 2.

Table 3. *Summary of the facies associations and inferred depositional environments recognized in the studied sections (subordinated facies in parentheses)*

Association	Facies	Interpretation
Basin		
1	DF (Lm-Sm)	Suspension fall out, anoxic-suboxic floor
2	Mf (DF)	Bioclastics micrites (blooms), anoxic to suboxic floor
Outer ramp		
3a	GF (Lm)	Suspension fall out, oxic to suboxic. Bivalves in life position
3b	GF; Lm	Suspension fall out, oxic to suboxic
4	Lf	Biogenic framework
Mid-ramp		
5a	Lwr-Swr; Shcs; Sm; Sh (Gf, H)	Oscillatory waves
Inner (shallow) ramp		
5b	Lsg-Ssg; Shb; Hihs; Sm; Sh (Gf, H)	Medium to high energy tidal currents
5c	Lt-St; Lp-Sp; Sm; Sh (Gf, H)	Wave-induced currents
6	Lm (GF); Lm (Lwr); Lm; Lh	Carbonate shoals
Inner (back) ramp		
7	H; La; Lsg-Ssg; Lwr; Lh; GF (Lm-Sm)	Alternating fall-out and current deposition. Low-regime tidal currents and wave action
8	GF (Hihs, Lwr-Swr)	Suspension fall-out associated with weak tidal currents and wave action

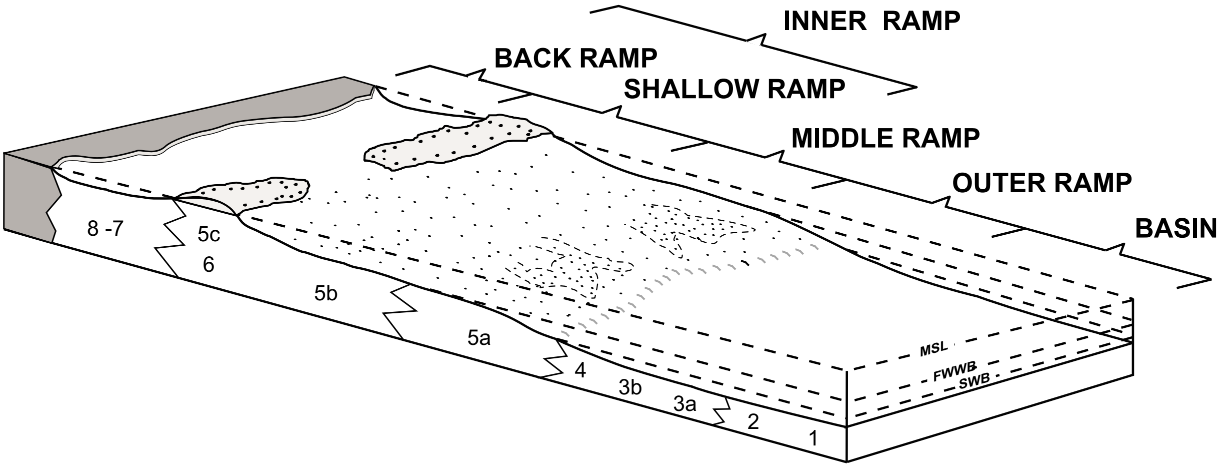

Fig. 5. Facies associations and the basin-ramp depositional model, modified from Fairchild *et al.* (1997). MSL: maximum sea-level; FWWB: fair-weather wave-base; SWB: storm wave-base.

packages are used as the basis for a sequence stratigraphic sub-division of the succession (into sequences Ti1, Ti2 and Ti3, from base to top). The low angle (?homoclinal) ramp profile means that conventional depositional sequence boundaries are poorly expressed, and an abrupt basinwards facies shift can only be demonstrated for the central (Ti2) sequence. Evidence for subaerial exposure is restricted to areas over which the inner ramp prograded, suggesting the ramp may be responding to relatively small changes in relative sea level which forced strong progradation followed by abrupt deepening, rather than extensive ramp exposure. The base of the lower and upper sequences are placed at transgressive surfaces representing marked deepening and expansion of basinal facies over continental (Ti1) and inner ramp (Ti3) deposits. Maximum flooding surfaces presumably lie within the expanded tongues of basinal facies, but the poor development of parasequence sets means that the precise position of these surfaces is often unclear. Larger scale stratal patterns in the lower section of the Picún Leufú Formation (parallel topsets, downlap and toplap culminations) locally help place the key stratigraphic surfaces.

The stratigraphic architecture is illustrated by the correlation panel shown in Fig. 6 and is shown schematically in Fig. 7. The three sequences are now described in more detail.

Sequence Ti1

This sequence is predominantly siliciclastic, with fine-grained deposits linked to a major transgression in the Early Tithonian. Regionally, the base of the sequence has an onlap relationship to deposits as old as Triassic, although in the study area it overlies the non-marine Kimmeridgian Tordillo Formation (Fig. 6). It ranges in age from the lower to the middle Tithonian (*V. mendozanus* until *A. zitteli* biozones; Leanza 1993) and is almost entirely represented by the mid-ramp to basinal anoxic facies of the Vaca Muerta Formation, although in marginal (southern) areas of the basin (the Catán Lil River section) it includes the Vaca Muerta Formation and the lower part of the Carrín Curá Formation (Fig. 6). The Ti1 sequence varies from 60 m in thickness in the proximal

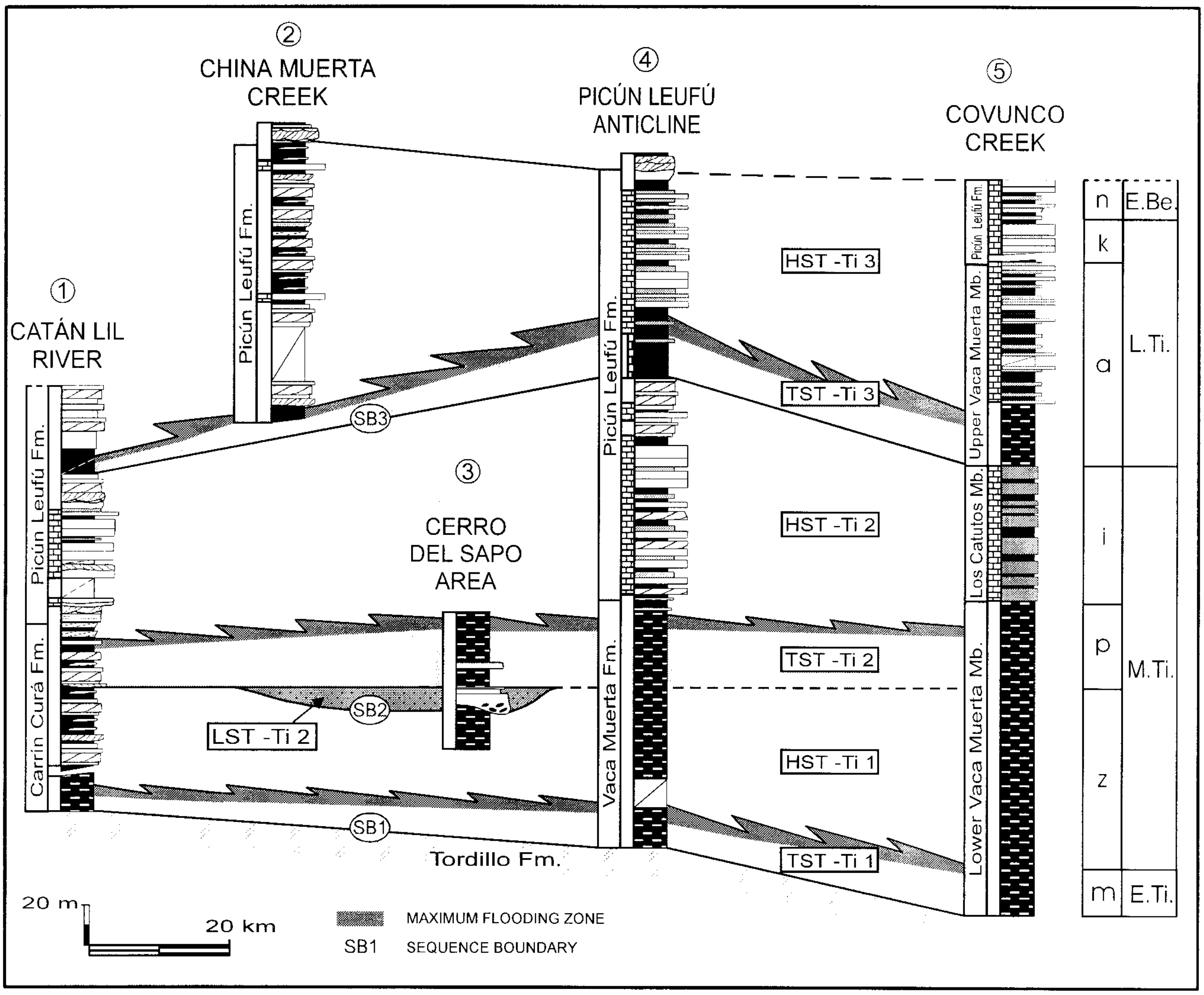

Fig. 6. Sequence stratigraphy of the Tithonian–Berriasian interval (south-central Neuquén Basin). For key to summary logs, see Fig. 2. m: *mendozanus*, z: *zitteli*, p: *proximus*, i: *internispinosum*, a: *alternans*, k: *koeneni*, n: *noduliferum*.

(southern) area, to 80 m in Picún Leufú and 115 m in Covunco. Transgressive (TST) and highstand (HST) systems tracts can be distinguished.

TST–Ti1. This is composed almost entirely of basinal euxinic sediments and outer ramp storm sands (Facies Association 1, Fig. 5) in which it is difficult to distinguish parasequence arrangements. Condensed levels with abundant organic matter are common and little lateral variation is seen. The thicknesses decrease towards the margin of the basin from 30 m to 15 m (Fig. 6).

HST–Ti1. Progradational deposits of the earliest sequence show a strong facies differentiation according to the depth reached on the ramp. In deeper sections, represented by the Covunco and Picún Leufú localities, the sedimentation pattern is very similar to the basinal and outer-ramp settings of the TST–Ti1 (Figs 3b, 4 & 6). In the most proximal section (Catán Lil), highstand deposits are represented by shallow inner ramp deposits, such as tidal and wave-dominated sandbodies (Facies Associations 5b, 5c) and marginal lagoonal mudstones (Facies Association 7). Throughout this section, evidence for subaerial exposure, reflected in the presence of hardgrounds and desiccation cracks, is common. HST–Ti1 thicknesses are greater than those of the transgressive period of the same sequence and vary between 40 m in the proximal areas to 80 m in the distal areas (Fig. 6).

Sequence Ti2

Sequence Ti2 ranges from Mid- to Late Tithonian in age (*A. proximus* and *W. internispinosum* biozones; Leanza 1993) and varies from 95–150 m in thickness. It is a mixed carbonate–siliciclastic system and includes the most extensive development of carbonate rocks in the succession. The sequence is erosively based in the Cerro del Sapo section where a coarse-grained siliciclastic deposit incises into basinal shales and sandstones of the Ti1 sequence (Fig. 6). The deposits immediately above the erosive surface are identified as a lowstand

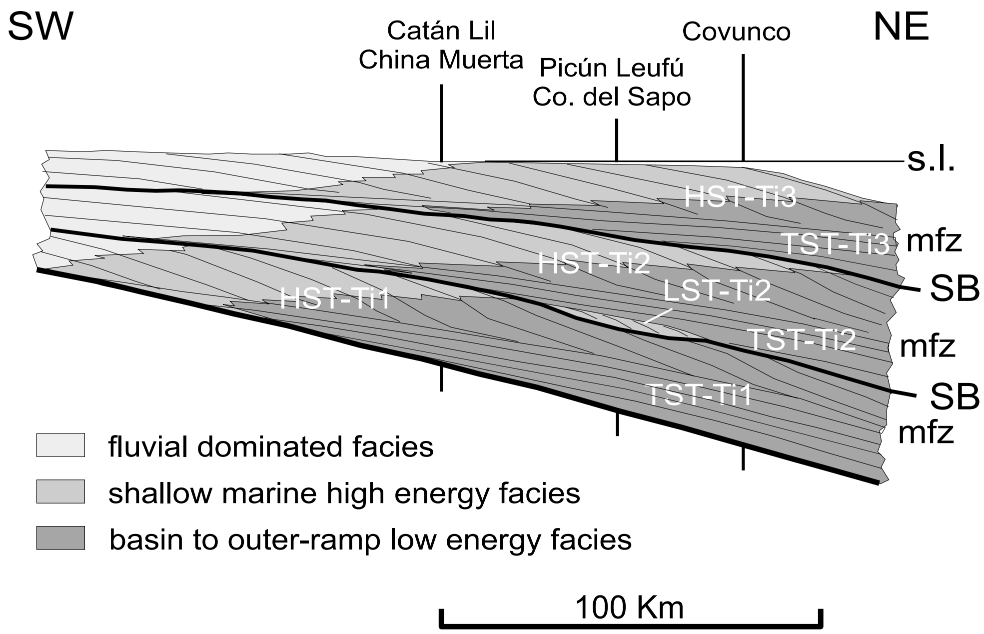

Fig. 7. Schematic diagram showing the stacking of the three sequences and the main depositional settings.

systems tract; analogous units have not been recognized in the other sequences. It is difficult to establish the boundary between Ti1 and Ti2 in the Picún Leufú and Covunco sections, since the record of both sequences reflects the same basinal to outer-ramp environment.

LST–Ti2. Lowstand systems tract deposits are present in the Cerro del Sapo area and can be followed to the north and east along the outcrop of the Vaca Muerta Formation for almost 10 km. They are composed of coarse-grained sandstones and bioclastic limestones (Facies Associations 5c and 6) with muddy intraclasts of up to 50 cm in diameter. These deposits exhibit a lensoidal geometry with overall thicknesses of about 20 m (Fig. 3a). The base is irregular and sharp, whereas the top gradually passes upwards to outer ramp fine-grained deposits (Facies Association 1). LST–Ti2 is interpreted as a set of shallow littoral deposits, isolated in the middle to distal sections of the Neuquén ramp (a detached shallow-ramp produced by a forced regression, cf. Posamentier *et al.* 1992).

TST–Ti2. Unlike Ti1, the transgressive interval of Ti2 (maximum thickness of 40 m in the Cerro del Sapo section) shows evidence of important lateral facies changes in the southerly sections. Here, the base of TST–Ti2 is marked by a facies jump from back ramp heterolithic deposits (Facies Association 7) to shallow inner ramp deposits with dominant tidal current features (Facies Association 5b). In the rest of the sections, TST–Ti2 is dominated by outer ramp and basinal facies. The upper surface of TST–Ti2 can be seen as a downlap surface in the Picún Leufú 0area, although it is not marked by any particular facies development. However, in deeper areas of the ramp (Covunco section), the position of the maximum flooding surface is not clearly expressed.

HST–Ti2. The deposits of the HST–Ti2 (80–115 m thick) are the most conspicuous of all the ramp succession. In the Picún Leufú (Fig. 3b) and Catán Lil (Fig. 2a) outcrops, the facies are very similar whereas in more distal areas (Covunco, Fig. 4) a micritic (lithographic) limestone facies was deposited.

During this stage, the majority of the ramp evolved as a heterogeneous system controlled by a general shallowing-upward trend and high carbonate productivity. There is evidence of higher order cyclicity in these deposits and this allows us to characterize the HST–Ti2 as a highstand sequence set (cf. Emery & Myers 1996) or as a composite highstand sequence (Mitchum & van Wagoner 1991). At Picún Leufú, three sequences of higher order (30 m, 50 m and 35 m thick, respectively) are identified (Fig. 3b): the first is a mixed carbonate–siliciclastic sequence, the second is carbonate and the third is of mixed provenance. The lower sequence rests on the previous transgressive deposits with a clear downlapping relationship, as a result of the development of progradational clinoforms extending from west to the east. The clinoforms are formed of outer ramp deposits (Facies Association 3b) amongst which shallower, tidal bedforms (Facies Association 5b) 1 to 6 m thick are intercalated. The central sequence is dominated in proximal areas by important carbonate levels, represented by oolitic and bioclastic grainstone shoals (Facies Association 6) with interbedded lagoonal and peritidal inner ramp deposits (Facies Association 8, Fig. 2a). This sequence shows frequent evidence of subaerial exposure (hardgrounds, ferruginous crusts), chert nodules and very abundant bioturbation. The uppermost sequence within the HST–Ti2 is, like the lower one, much more heterogeneous, with prevailing inner ramp shallow marly and sandy deposits in which large subtidal bedforms are recognized. In the marginal areas, thin estuarine channel-fills have been identified (Facies Lt-Lp and St-Sp).

In the deepest sections of the basin, deposition was continuous in an outer ramp environment. Thus, in the Covunco section, the HST–Ti2 deposits are represented by a thick (80 m) and homogeneous succession of massive biomicrites in conditions of strongly anoxic carbonate accumulation (Facies Association 2).

Sequence Ti3

The youngest of the studied sequences has a maximum thickness of 145 m measured in the Covunco section (Fig. 4). It includes the upper part of the Vaca Muerta Formation and the Picún Leufú Formation at Covunco (Fig. 4) and the middle and upper sections of the Picún Leufú Formation in the other studied localities. The Ti3 sequence ranges from the Late Tithonian to the Early Berriasian in age (*C. alternans to A. noduliferum* biozones; Leanza 1993). In the proximal areas of the ramp (Catán Lil, China Muerta, Cerro del Sapo, Picún Leufú; Figs 2 & 3), the lower limit of Ti3 is marked by a transgressive surface developed on top of the shallow deposits of the previous HST, and in the basinal and outer ramp sections (Covunco, Fig. 4) it is marked by a facies change from biomicrites (Mf facies) to dark shales (Facies Association 1). The top of the sequence is defined by the incoming of siliciclastic deposits of the Berriasian 'Proximal' Mulichinco Formation representing the base of a new sequence in the southern section of the Neuquén Basin (Gulisano *et al.* 1984). Ti3 is a mixed siliciclastic–carbonate sequence, subdivided into a fine grained transgressive section and a coarse-grained progradational highstand section. The proportion of terrigenous sediment progressively increases towards the top (Fig. 7).

TST–Ti3. This consists of greenish marly to shaly facies (Facies Association 3) over the majority of the ramp section studied. The euxinic facies (Facies Association 1) are restricted to the most distal section in this sequence. Thicknesses vary between *c.* 35 m in the basin/outer ramp setting (uppermost part of the Vaca Muerta Formation; Leanza & Zeiss 1990) to only *c.* 6 m in the most proximal locality (Catán Lil River). It is difficult to determine the upper limit of the transgressive episode since, like in the Ti2 sequence, a distinct maximum flooding surface or interval is not observed.

HST–Ti3. This comprises very heterogeneous deposits, mainly siliciclastic in proximal areas and mixed clastic/carbonate in distal areas. It's maximum thickness reaches *c.* 140 m in the China Muerta section (Fig. 2b). In the proximal Catán Lil section (Fig. 2a), HST–Ti3 begins with mid-ramp storm-dominated deposits of Facies Association 5a while in Picún Leufú the lower part of this section consists of a thick outer ramp succession (Facies Association 3b) associated with shallow water carbonate levels (Facies Association 6). Towards the top, in the marginal area of the ramp (e.g. China Muerta), subtidal sand wave deposits alternate with common bioclastic and stromatolitic carbonates deposited under more restricted shallow marine conditions (Fig. 2b). In the basinal Covunco section, outer ramp Facies Associations 3a–3b are overlain by an upper section marked by a cyclic alternation of oolitic and bioclastic shoals (Facies Association 6) showing evidence of bioturbation and dissolution features, and upward coarsening finer-grained mudstones and wackestones (Facies Association 3b). Such cyclicity is rare in other parts of the ramp, and is thought to result from higher order cycle superposition defined by parasequence sets with progradational stacking (Fig. 4).

Discussion

Early ramp development in the southern Neuquén Basin (late Early Tithonian to early Mid-Tithonian=Sequence Ti1) was characterized by widespread basinal and outer ramp depositional systems with abundant anoxic shales and marls. A sudden early Tithonian transgression generated both accommodation space and unfavourable conditions for carbonate productivity (Legarreta & Uliana 1991). In this situation, the basin was in a sediment starved or underfilled state (Legarreta *et al.* 1993), with subsidence only partially balanced by the accumulation of thick fine-grained successions and abundant production of planktonic organic material. This resulted in the widespread distribution of suboxic to anoxic bottom waters. Shallow siliciclastic sediments of mid- to inner ramp facies were deposited only along the margins of the basin.

The second sequence (Ti2=upper Middle Tithonian) started with a forced regression and basinward displacement of the inner ramp down the ramp profile. Subsequent flooding was followed by strong progradation which coincided with maximum carbonate productivity. A diminution in siliciclastic sediment supply was accompanied by expansion of the potentially favourable areas for carbonate production and the restriction of poorly oxygenated conditions to the deepest sections of the ramp profile. The youngest sequence (Late Tithonian to Early Berriasian=Sequence Ti3) comprises a mixture of siliciclastic and carbonate sediment. Its transgressive systems tract reflects changes from anoxic to suboxic conditions, whereas towards the top of the succession, and in the marginal sectors of the basin, siliciclastic facies prevail. Progradation and shallowing up were accompanied by an increased supply of siliciclastic components that led to the dilution/inhibition of skeletal production.

The three Tithonian–Berriasian sequences in the southern Neuquén Basin (Fig. 7) evolved as a 'ramp stack' (cf. Burchette & Wright 1992). In such a setting the stratigraphy is mainly built of TST and HST packages with evidence for a forced regression only at the base of the central sequence. In the lowermost transgressive sections of each sequence, slow sedimentation rates and rapid sea-level rise partially affected the productivity of the system, producing incipient carbonate drowning. The decrease in carbonate productivity inferred in the transgressive systems tracts may be influenced not only by the increase in the water depth but also by the environmental deterioration induced by anoxic waters flooding onto the basin margins. Most of the TSTs are represented by outer ramp/basin facies, and they lack clear evidence of retrogradational parasequence stacking. During deposition of the highstand systems tracts, the high carbonate productivity and a reduction in accommodation space favoured progradation, modifying the ramp geometry through the development of clinoforms. The inner ramp became partially exposed, and condensed levels are represented by hardgrounds and ferruginous pans. The significant thickness of the HST deposits, accompanied by the variable nature of the sedimentary facies, allows for the local internal differentiation of higher-order sequences, producing highstand sequence sets or highstand parasequence sets. The tendency to shallowing up is evident in all orders of cyclicity described.

A peculiarity of the studied succession is that, even though locally carbonate-prone, it does not record the formation of resistant biohermal structures. Significantly, the biogenic frame builders during the Late Jurassic (stromatoporoids, bryozoans, corals, etc) had their habitat in the middle and outer sections of the ramps (Burchette & Wright 1992). In the Neuquén Basin, the wide distribution of suboxic to anoxic substrates on the outer ramp would have inhibited the development of benthic palaeocommunities and hence suppressed build-ups.

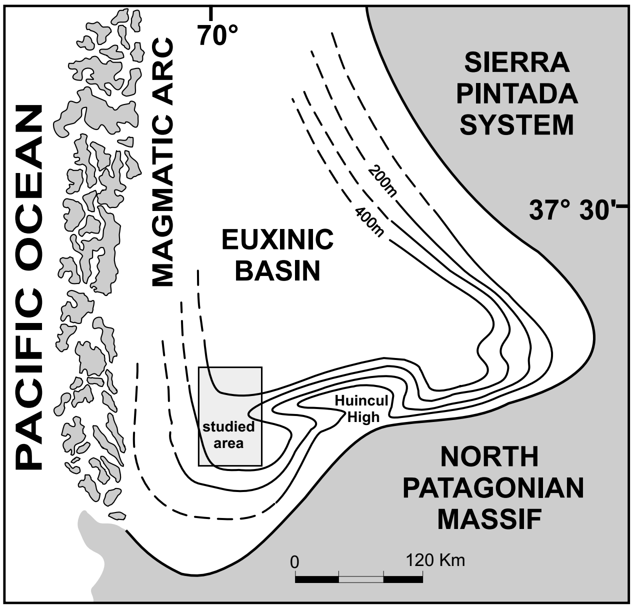

Fig. 8. Generalized isopach map (based on Orchuela & Ploszkiewicz 1984 and Cruz *et al.* 1999) and palaeogeography of the Tithonian–Berriasian Neuquén Basin ramp, and its relationship with the Andean magmatic arc to the west. Dashed lines are schematic isopachs.

The Tithonian–lower Berriasian ramp of the Neuquén Basin is characterized by abundant tidal deposits. The facies associations formed above the storm wave base on the ramp are dominated by tidal features such as sigmoidal cross-bedding, herringbone cross-bedding, reactivation surfaces, rapid changes in palaeoflow pattern, and heterolithic intervals composed of alternating traction and suspension deposits. Progradational clinoforms associated with carbonate shoals represent tidal or wave induced sand waves, formed during periods with terrigenous sand availability and/or high skeletal sand productivity, especially during formation of the high-stand systems tracts. The development of the sand wave fields is important in the distribution of open and partially restricted depositional environments in the mid and inner ramp (Calvet & Tucker 1988; Buxton & Pedley 1989; Tucker *et al.* 1993), and hence to the facies associations and stratal architecture. These features suggest a shallow ramp characterized by a mesotidal to macrotidal regime (Hayes 1979), with strong marine influence and poor to negligible barrier growth.

The tidally dominated shallow ramp is one of the less known systems in the ramp models proposed by Burchette & Wright (1992), and are most likely to be found in environments with partial restriction, such as sounds or gulfs. A wide bay or gulf-like geometry is envisaged for the southern section of the Neuquén Basin (Bracaccini 1970; Ramos 1978; Legarreta & Uliana 1991, 1996), limited to the west by the emergent Andean magmatic arc (Digregorio & Uliana 1980; Digregorio *et al.* 1984; Hallam *et al.* 1986). During the Late Jurassic, a further physiographic restriction of the southernmost part of the basin (Fig. 8) resulted from the growth of a topographic barrier running east-west (Cruz *et al.* 1999). This regional structure, known as the Huincul High (Dorsal de Huincul, Ploszkiewicz *et al.* 1984), is the result of an important tectonic inversion in response to a reorganization of the regional stress field (Vergani *et al.* 1995). This barrier significantly controlled the palaeogeographic distribution of the sedimentary record and could have acted as a funnel-like device that led to the amplification of tides and the development of a tidally dominated system as envisaged for the southern part of the Neuquén Basin.

Facies patterns, the orientation of progradational clinoforms and sequence geometries indicate that the southern portion of the basin had a semicircular shape with emergent areas to the west, south and east, and ramps converging in the basin centre (Fig. 8). In this palaeogeographic realization, a wide depositional ramp significantly separated the center of the basin from the magmatic arc. We suggest that the western limit of the basin comprised a volcanic island chain crossed by marine corridors, as is indicated by the interstratification of marine shales and carbonates with volcaniclastic and volcanic rocks in eastern Chile and westernmost Argentina (Hallam *et al.* 1986; Burns 1994).

Though anoxia was a persistent feature throughout the analysed interval in most of the Neuquén Basin (Gasparini *et al.* 1997, fig. 8), it was only during periods of relative sea level rise when euxinic conditions reached the southernmost Neuquén Basin and allowed accumulation of offshore black shales in transgressive settings. Black shale deposition was favoured by water exchange from an ocean (the Pacific) in which the oxygen minimum layer was expanded (Heckel 1977), and by dry climatic conditions and relatively low surrounding relief. The expanded oxygen minimum layer can be related, in turn, to abundant nutrient availability, to upwelling processes (very conspicuous in the eastern margin of the Pacific) and to the global greenhouse conditions that characterized the end of the Jurassic and the beginning of the Cretaceous (Frakes & Francis 1990).

Conclusions

The Tithonian–lower Berriasian succession in the southern Neuquén Basin was deposited on a gently sloping marine ramp which accounts for the gradual passage from shallow marine areas located along the southern and southwestern margins of the basin, to the deepest areas located to the north.

The ramp stratigraphy reflects a rapid transgression followed by puncutated upward shallowing; three progradational sequences are recognized, but evidence for a basinward shift in facies and forced regression is only present for the central sequence. Evidence for subaerial exposure is restricted to areas over which the inner ramp prograded, suggesting the ramp may be responding to relatively small changes in relative sea level which forced periods of strong progradation followed by abrupt deepening, rather than extensive exposure. Maximum flooding surfaces are difficult to place within sections of the basinal facies on account of poor development of para-sequence sets. Carbonates are common in the highstand deposits of the second sequence, with mixed siliciclatic–carbonate facies in the other sequences.

The deep basinal waters of the Neuquén Basin were anoxic, and this meant that reduced carbonate productivity suppressed mid-to outer ramp framework builders. Anoxic conditions reached the southern sub-basin only during episodes of relative sea-level rise and favoured condensed outer ramp and basinal black shale deposition.

Outer ramp environments were dominated by storm processes, whereas tidal deposits are characteristic of the inner ramp. Abundant tidal deposits in the shallow marine settings suggest the development of widespread tidal sand wave fields.

More restricted and low-energy lagoonal to peritidal deposits appear in the the most landward (back ramp) part of the ramp profile.

The restricted gulf-like palaeogeography of the southern portion of the Neuquén Basin played a major role in the development of the depositional systems. Partial isolation from the Pacific Ocean reflecting the growth of the Andean magmatic arc and geographic barrier running east–west along the Huincul High favoured the development of a meso-macrotidal regime that produced the tidally dominated sedimentary record in the shallow and back ramp environments.

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