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VARIABILITY OF CONTINENTAL DEPOSITIONAL SYSTEMS DURING LOWSTAND SEDIMENTATION: AN EXAMPLE FROM THE KIMMERIDGIAN OF THE NEUQUEN BASIN, ARGENTINA

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Abstract: Several second order lowstand wedges are recognized in the Jurassic-Early Cretaceous sedimentary record of the backarc Neuquén Basin (central-west Argentina). They are distinguished by sharp based continental and marginal marine siliciclastic deposits encased in offshore shales. The Kimmeridgian lowstand wedge was developed slightly after the emergence of the Andean magmatic arc and the tectonic inversion of previous intrabasinal extensional structures. As a result, the Neuquén Basin was compartmentalized into three main depocentres characterised by widespread continental sedimentation under arid to semiarid climatic conditions. A fluvial-dominated system characterised by systematic downstream changes in architectural style is recognized in the Northwestern Depocentre. A gravely and sandy bedload fluvial system was developed in the southern upstream sector, while ticker beds of finer-grained sediments formed in a distal ephemeral fluvial system prevail in the downstream part of the system. The overall fining upward stacking pattern of the sedimentary record in the Northwestern Depocentre accompanied by frequent development of soil horizons and darker deposits suggests a change towards higher accommodation and high water table emplacement. In the Southwestern and Eastern Depocentres, the sedimentary successions show a conspicuous internal transition from fluvial ephemeral fluvial systems to aeolian systems. However, the lowstand deposits of the Eastern Depocentre are characterised by a larger areal distribution and a thicker record of both the fluvial and the aeolian deposits. Marked changes in thickness and in the depositional style of the fluvial and aeolian facies associations within the Southwestern and Eastern depocentres indicate that the sedimentary infill was controlled by systematic variations in accommodation. Low accommodation conditions favoured a high degree of lateral migration of fluvial channels with substantial erosion of fine-grained deposits and the development of sinuous-crested aeolian dunes typically associated with wet interdune deposits. Under higher accommodation conditions the fluvial deposits show a retrogradational stacking with preservation of thick packages of fine-grained sediments, while a large sand sea characterised by amalgamation of dune deposits was developed in the aeolian-dominated uppermost successions. The detailed analysis of the Kimmeridgian lowstand wedge of the Neuquén Basin illustrates how facies and stratigraphic organisation responded to regional and temporal changes in basin configuration, accommodation, sediment supply and water table position. The Kimmeridgian lowstand deposits are geographically distributed as the subsequent transgressive deposits and reveal no major basinward shift during the early stages of sequence stacking. However, they show a much more complicated facies distribution. Consequently, the lowstand wedge deposits better reflect the complex interplay of episodic local tectonism, siliciclastic source area variation and climatic change.

Resumen: En la sucesión jurásico-cretácica de la Cuenca Neuquina se reconocen varias cuñas de mar bajo que se distinguen por el desarrollo de depósitos continentales y marinos someros en los

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sectores más distales de la cuenca, dispuestos mediante una discontinuidad basal por encima de depósitos marinos relativamente profundos. La cuña de mar bajo kimmeridgiana se acumuló inmediatamente después del ascenso del arco magmático andino y la inversión tectónica de estructuras extensionales intracuencales. Como resultado, la Cuenca Neuquina quedó compartimentalizada en tres depocentros principales, caracterizados por el dominio de sedimentos continentales acumulados bajo condiciones climáticas áridas hasta semiáridas. En el Depocentro Noroeste prevalecieron los depósitos fluviales, caracterizados por un cambio sistemático de la arquitectura fluvial desde las zonas proximales a las distales del sistema. El diseño de superposición granodecreciente en este depocentro, junto con el frecuente desarrollo de suelos hacia la parte superior del registro, sugiere el incremento progresivo de la acomodación y el emplazamiento mucho más superficial del nivel freático. Las sucesiones sedimentarias en los depocentros Sudoeste y Este están caracterizadas por la transición desde sistemas fluviales efímeros a eólicos. Sin embargo, los depósitos de la cuña de mar bajo en el depocentro oriental poseen una más amplia distribución areal y mayores espesores de los depósitos fluviales y eólicos. Importantes variaciones en el espesor y en la arquitectura de los depósitos fluviales y eólicos en los depocentros sudoriental y oriental indican que la sedimentación estuvo controlada por cambios importantes en la acomodación. Situaciones de baja acomodación favorecieron la migración lateral de los canales fluviales desarrollados en condiciones algo más húmedas, junto con el desarrollo de campos de dunas de crestas sinuosas asociados con áreas de interduna húmeda. Bajo condiciones de alta acomodación los depósitos fluviales tendieron a sistemas retrogradacionales con preservación de importantes sucesiones de sedimentos finos, junto con la formación, en especial hacia la parte superior del registro, de un importante mar de arena caracterizado por la amalgamación de dunas complejas. En contraste con la uniformidad que muestran los depósitos transgresivos y de mar alto en la Cuenca Neuquina, la cuña de mar bajo kimmeridgiana constituye un excelente ejemplo para comprender la respuesta estratigráfica a las variaciones regionales y temporales en acomodación, aportes detríticos y fisiografía como una respuesta a la interacción de los controles tectónicos y climáticos.

Keywords: Fluvial-aeolian interactions; Kimmeridgian; lowstand wedges; Neuquén Basin; Argentina.
Palabras clave: Argentina; interacciones fluvio-eólicas; Kimmeridgiano; cuña de mar bajo; Cuenca Neuquina, Argentina.

INTRODUCTION

The effect of forced regressions in ramp settings is expressed by a sudden basinward shift in the depositional systems (Vail *et al.*, 1977; van Wagoner *et al.*, 1988, 1990; Posamentier *et al.*, 1992). The deposits formed immediately after this drastic change in stratigraphic architecture are known as lowstand wedges (van Wagoner *et al.*, 1988). Although lowstand wedges may form in a variety of depositional systems, in basins devoid of a marked shelf-break margin they are represented by continental (fluvial and aeolian), transitional (*e.g.* deltaic) and shallow marine deposits. Siliciclastic sands with an excellent reservoir potential are commonly accumulated in these settings, and constitute some of the best stratigraphic trap targets where they encased within impermeable mudrocks. However, the internal architecture of lowstand wedges, their regional variations, and their response to changes in sediment supply, subsidence rate and base level are far to be understood.

Non-marine lowstand wedges dominated by fluvial and aeolian deposits are very common in the Upper Jurassic-Lower Cretaceous record of the Neuquén Basin. These deposits are commonly developed over sharp and erosive lower contacts upon offshore mudstones and capped also by offshore mudstones across major transgressive surfaces. As a contribution to the knowledge of the lowstand wedges development, the Upper Jurassic-Lower Cretaceous fluvial and aeolian deposits of the Neuquén Basin (central west Argentina) are studied in this paper. Our aims are: 1) to characterise the Kimmeridgian lowstand wedge in terms of facies, geometry, regional development and distribution; 2) to define depositional systems and their regional and vertical variability; 3) to investigate the internal stratigraphic evolution and heterogeneity of the Kimmeridgian lowstand wedge; and 4) to assess the influence of sea level changes / tectonics / climate on its development.

GEOLOGICAL SETTING

The Neuquén basin is located in west central Argentina and eastern Chile between 36° and 40° S (Fig. 1). Throughout much of its history, the Neuquén Basin has been limited on its northeastern and southern margins by wide cratonic areas of the Sierra Pintada Massif and North Patagonian Massif, respectively (Fig. 1). The western boundary of the basin is the Andean magmatic arc on the active western margin of the Gondwanan-South American Plate. 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). The basin fill is more than 4,000 m thick, and it is composed of near continuous Late Triassic to Early Cenozoic continental and marine siliciclastic deposits, carbonates and evaporites (Gulisano and Gutiérrez Pleimling, 1994; Vergani *et al.*, 1995).

Two main regions are commonly recognised in the basin: the Neuquén Andes to the west and the Neuquén Embayment to the east and southeast. Due to the development of an Upper Cretaceous - Cenozoic fold and thrust belt, outcrops of exceptional quality appear all along the Neuquén Andes. Instead, the Mesozoic sedimentary record in the Neuquén Embayment is in the subsurface, and this is the region where most of the oil fields of the basin are located.

Three stages of evolution have been proposed for the Neuquén Basin (Howell e*t al.*, 2005): 1) From the Late Triassic to Early Jurassic, a series of extensional narrow and isolated troughs, filled with volcaniclastic and continental deposits, were formed as a result of continental intraplate extension (Manceda and Figueroa, 1995; Vergani *et al.*, 1995; Franzese and Spalletti, 2001), 2) From the Early Jurassic to the Early Cretaceous, a steeply dipping, active subduction zone was developed along the western active Gondwana margin, and as a result of the growth of the Andean magmatic arc the basin became a back-arc system (Vergani *et al.*, 1995; Howell *et al.*, 2005). A thick succession of marine and continental deposits was deposited during this long period of protracted thermal subsidence and regional back-arc extension, 3) From the Late Cretaceous to the Cenozoic, a compressional tectonic regime associated with a decrease in the angle of slab subduction produced the uplift of a foreland thrust belt. Flexural subsidence towards the east of the tectonic front allowed the accumulation of more than 2,000 m of continental syn-orogenic deposits in the Neuquén Basin (Legarreta and Uliana, 1991; Ramos, 1999).

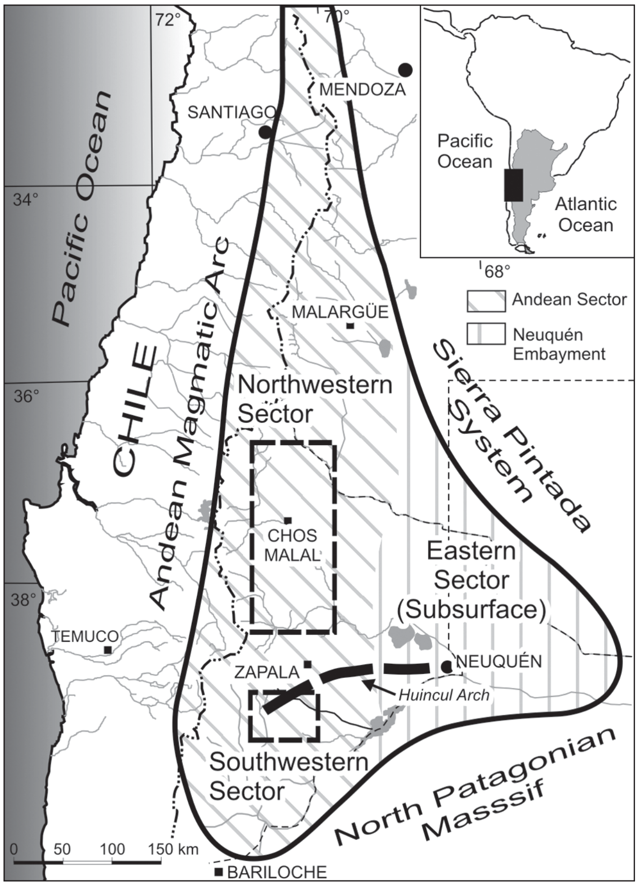

Figure 1. General map of the Neuquén Basin showing the location of the study sites.

Figura 1. Mapa general de la Cuenca Neuquina con la ubicación de las áreas de estudio.

During the Jurassic - Early Cretaceous postrift stage, an extensional regime in both the arc and back-arc settings occurred as a result of steep subduction and negative roll-back velocity (Ramos, 1999). Back-arc subsidence led to an expansion of the marine realm and flooding of the basin, which was connected to the proto-Pacific through gaps in the arc (Spalletti *et al.*, 2000; Macdonald *et al.*, 2003). Although the depositional systems were marine-dominated, a complex series of transgressive-regressive cycles of different magnitude were developed during the postrift stage (Gulisano *et al.*, 1984; Legarreta and Gulisano, 1989; Legarreta and Uliana, 1991, 1996a, b), controlled by the combined effects of changes in subsidence rates, localised uplift and eustatic sea-level oscillations (Fig. 2). Vergani *et al.* (1995), Veiga *et al.* (2001) and Pángaro *et al.* (2002) have suggested that this regime of regional thermal subsidence was interrupted by several episodes of structural inversion (Fig. 2). Regional unconformities and subsequent lowstand wedges of the postrift stage seem to be controlled and/or intensified by these episodes of tectonic inversion.

THE KIMMERIDGIAN LOWSTAND WEDGE

One of the most characteristic lowstand wedges of the Neuquén Basin was deposited during the Kimmeridgian. These deposits have received different stratigraphic names (Fig. 2): Tordillo Formation in the north and northwest, Quebrada del Sapo Formation in the south, and Bardas Blancas and Catriel Formations to the east, in the subsurface of the Neuquén Embayment. According to 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) and Cruz *et al.* (2000), the Kimmeridgian units were developed after the intramalmic tectonic inversion, and unconformably rest upon the Oxfordian marine siliciclastic deposits, carbonates and evaporites of the Lotena, La Manga and Auquilco formations. In turn, they are sharply overlain by Tithonian deep marine anoxic shales and marls of the Vaca Muerta Formation across a major, low-order transgressive surface (Fig. 2).

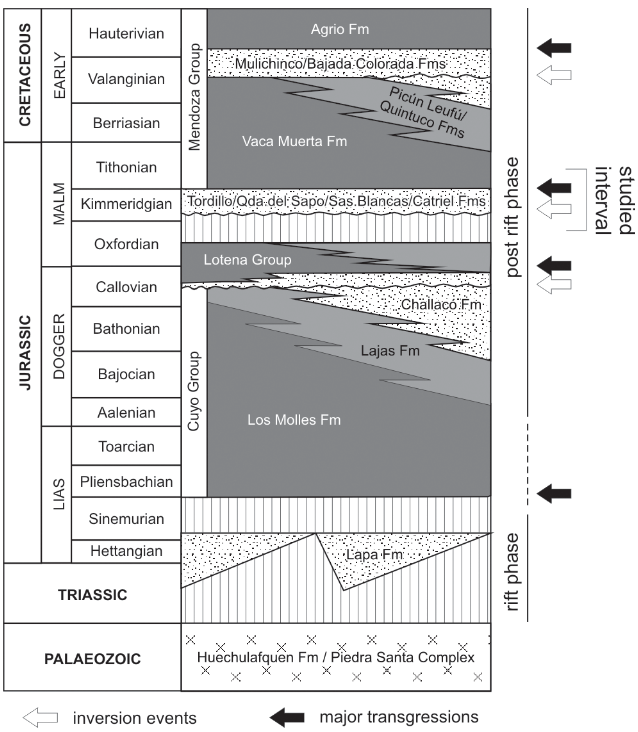

Figure 2. Jurassic and Lower Cretaceous lithostratigraphy of the Neuquén Basin, and stratigraphic location of the studied interval (Kimmeridgian lowstand wedge).

Figura 2. Litoestratigrafía del Jurásico y Cretácico de la Cuenca Neuquina y ubicación estratigráfica del intervalo estudiado (cuña de mar bajo kimmeridgiana).

The Kimmeridgian continental deposits of the Neuquén Basin have been assigned to proximal (alluvial fans) and distal fluvial systems related to playa-lake depressions and aeolian dune fields by Marchese (1971), Legarreta and Gulisano (1989), Legarreta *et al.* (1993) and Legarreta and Uliana (1996a, b, 1999). The thickness distribution of the Kimmeridgian lowstand wedge shows a clear relationship with the areas reactivated during the late Oxfordian and earliest Kimmeridgian inversion (Fig. 3). Three main depocentres are clearly defined. The Northwestern and Southwestern Depocentres, located along the Neuquén Andes, are clearly separated by the E-W oriented structural high known as the Huincul Arch (Dorsal de Huincul, Ploszkiewicz *et al.*, 1984), an area strongly affected by intrabasinal tectonics throughout the evolution of the basin. Another N-S trending structural high, the Chihuidos High (Dorso de Los Chihuidos, Ramos, 1977), can be delineated between the Andean Northwestern Depocentre and the Eastern Depocentre located in the Neuquén Embayment due to a gradual decrease in thickness of the Tordillo Formation (Fig. 3). The relationship between the Southwestern and Eastern Depocentres is not clear due to uplift and erosion occurred later in the evolution of the basin; therefore, it is not possible to establish a direct correlation between these depocentres.

Northwestern Depocentre

This depocentre is an elongate depression that runs sub-parallel to the Andean magmatic arc trend. The Kimmeridgian deposits, known here as the Tordillo Formation, have been recently described in detail by Spalletti and Colombo Piñol (2005). They record important thickness variations from south to north and from west to east (Figs. 3 and 4), being the thickest

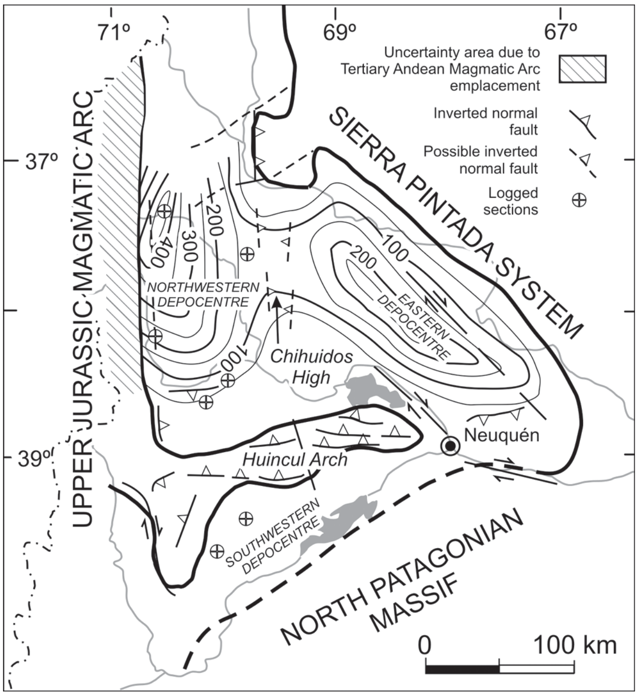

Figure 3. Isopach map and depocentres of the Kimmeridgian lowstand wedge, and location of intrabasinal uplifted areas (Huincul Arch, Chihuidos High), the Andean magmatic arc to the west, and the NE and S-SE cratonic margins. Structural framework modified after Vergani et al. (1995), courtesy of A.J. Tankard.

Figura 3. Mapa isopáquico y depocentros de la cuña de mar bajo kimmeridgiana con la ubicación de las areas intracuencales invertidas (Dorsal de Huincul, Alto de Los Chihuidos), el arco magmático andino hacia el oeste y los márgenes cratónicos al NE y S-SE. El marco estructural ha sido modificado de Vergani et al. (1995), cortesía de A. J. Tankard.

sections located towards the northwest, close to the magmatic arc chain, with more than 470 m. The thickness is drastically reduced to the south (85 m immediately to the north of the Huincul arch) and east (90 m near the Dorso de los Chihuidos high).

The Tordillo Formation in the Northwestern Depocentre is almost entirely fluvial. The proximal lithofacies association is composed of multi-storey, multi-lateral lenticular conglomerates and pebbly sandstones, and minor trough cross-bedded and laminated sandstones (Fig. 5b). This association is typically exposed in the southernmost sector of this depocentre (Fig. 4), to the north of the Huincul arch. Spalletti and Colombo Piñol (2005) have suggested that these deposits accumulated in a channelised fully turbulent bedload fluvial system.

Coarse-grained deposits are also present at the lower levels of the Tordillo Formation in the northwestern sector of the depocentre (Neuquén River section, Fig. 4). They consist of laterally continuous and thick units of matrix-supported, massive volcanic conglomerates and pebbly sandstones. They are followed by sheet-like and multi-storey packages of clast-supported conglomerates and pebbly sandstones, either massive or horizontally bedded, separated by massive and/or trough cross-bedded coarse-grained sandstones and mud-cracked siltstones. According to Spalletti and Colombo Piñol (2005), the matrix-supported conglomerates suggest deposition en masse from subaerial viscous and cohesive debris flows. The sheet-like clast supported conglomerates and pebbly sandstones are interpreted as the result of unconfined high-energy bed-load currents; sandstone lenses and siltstone interbeds likely represent deposition from shallow waning flows.

Most of the sedimentary record of the northwestern, central and northeastern areas of the depocentre is characterised by a distal lithofacies association that consists of intercalations of structureless and mud-cracked mudstones, thin intraformational conglomerates and fine- to medium-grained sandstones (Fig. 4). Laterally extensive fine-grained redbed deposits constitute the most common record of this lithofacies association (Fig. 5a). They are interpreted as the deposits of shallow ephemeral ponds following periods of episodic low-energy flooding in a mudflat and/or playa environment (Spalletti and Colombo Piñol, 2005). Deposits of unconfined sheet splays composed of minor sandstone and heterolithic intervals are intercalated throughout the fine-grained succession (Fig. 5c). The most prominent coarse-grained bodies of the distal lithofacies association consist of 2 - 9 m thick sandstone lobes produced by rapidly expanding and distal hyperconcentrated sheetfloods (Blair, 2001). Commonly associated with sandstone lobes, meter-scaled sandstone ribbons appear. They may be composed of a single bed or amalgamated parallel-stratified, trough cross-bedded and cross-laminated sandbodies, which are interpreted as the deposits of shallow and isolated distal channels. Isolated large-scale (up to 2 m) wedge-shaped sandstones arranged in cross-stratified sets with planar to tangential foresets also intercalate between mud-dominated successions. They have been interpreted by Spalletti and Colombo Piñol (2005) as solitary aeolian dunes.

Towards the top of the distal sector of this depocenter, primary pyroclastic fall out deposits (green and green dark poorly sorted fine-to medium-grained vitric tuffs to silty tuffs) are commonly interstratified with sandstones, heterolithic mud-rich couplets and mud-

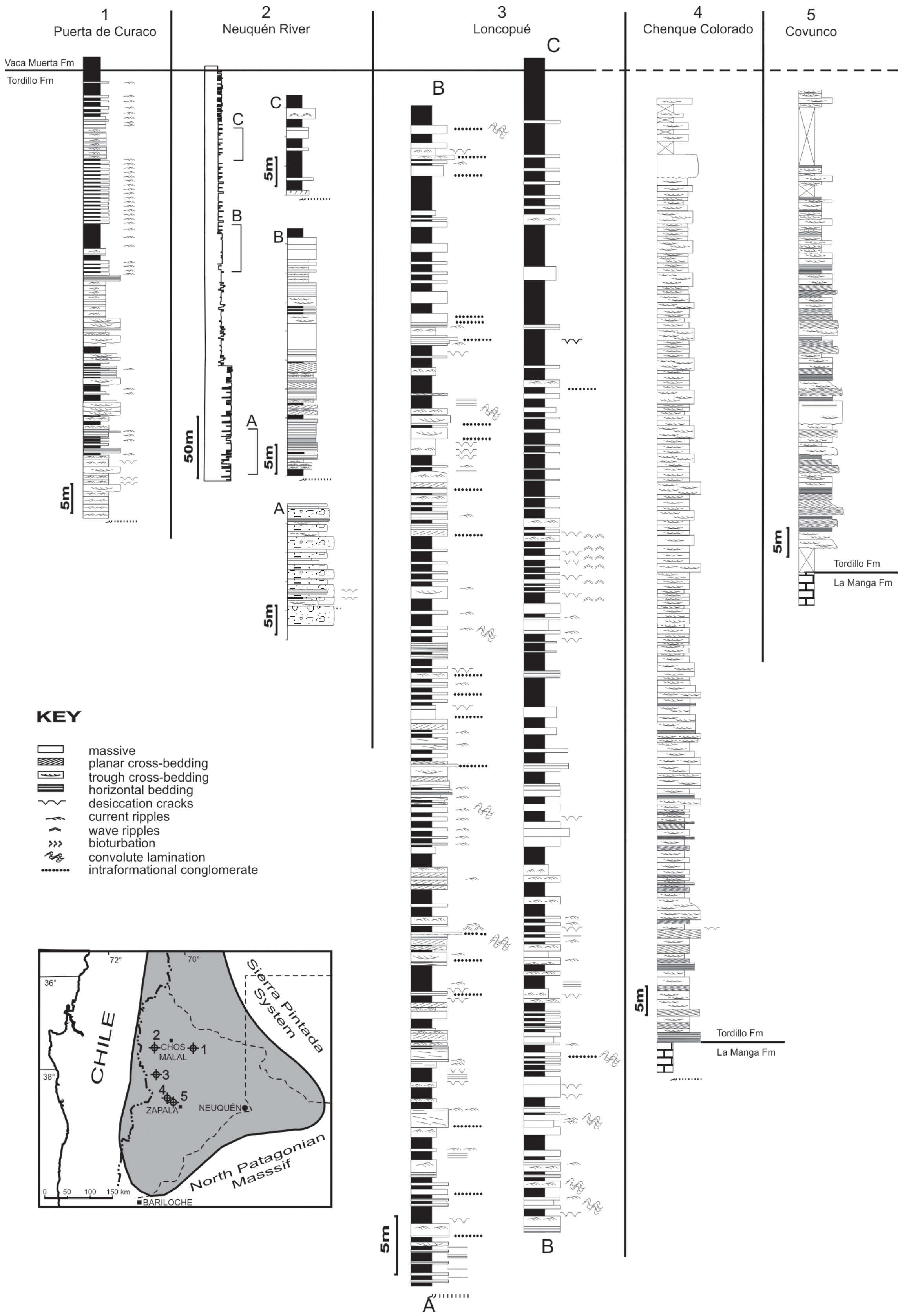

Figure 4. Sedimentary logs of the Northwestern Depocentre. Measured sections: 1: Puerta de Curacó, 2: Neuquén River, 3: Loncopué, 4: Chenque Colorado, 5: Covunco.

Figura 4. Columnas sedimentarias del Depocentro Noroeste. Secciones: 1: Puerta de Curacó, 2: Río Neuquén, 3: Loncopué, 4: Chenque Colorado, 5: Covunco.

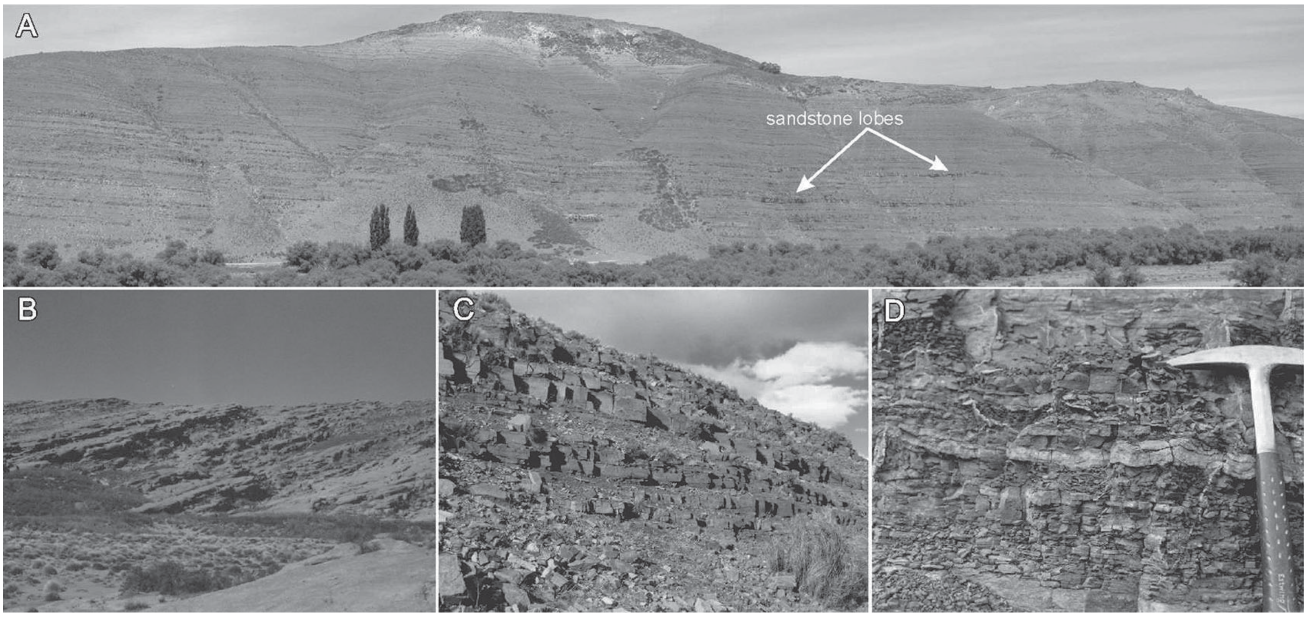

Figure 5. The Kimmeridgian lowstand wedge in the Northwestern Depocentre. a) General view of the ephemeral fluvial systems at Loncopué. b) Coarse-grained proximal fluvial systems at Chenque Colorado section. c) Sandstone lobes of the ephemeral fluvial systems (Loncopué section). d) Detail of fine-grained distal fluvial plains, Neuquén River section.
Figura 5. La cuña de mar bajo kimmeridgiana en el Depocentro Noroeste. a) Vista general de los sistemas fluviales efímeros en Loncopué. b) Depósitos fluviales proximales de grano grueso en Chenque Colorado. c) Lóbulos arenosos de sistemas fluviales efímeros en Loncopué. d) Detalle de los depósitos fluviales distales de grano fino en la sección del Río Neuquén.

stones (Fig. 5d). They consist of decimeter to meter thick and laterally continuous structureless beds. Some levels display a faint horizontal stratification defined by pumice stringers within the fine-grained vitric tuff matrix. Grouped columnar joints, probably produced by contraction of expansive clay minerals, root traces and slickensides are identified in these fine-grained deposits and indicated the development of immature soils (andisols) upon fine-grained pyroclastic materials.

The Tordillo Formation has been interpreted as the deposits of an arid fluvial-dominated system (Spalletti and Colombo Piñol, 2005) that was marked by a systematic downstream variation in the architectural style. The proximal facies association was formed in flow-dominated to sheetflood-dominated alluvial fans, whereas the distal facies association has been interpreted as a wadi-sand flat-playa fluvial system (Spalletti and Colombo Piñol, 2005). High energy flooding events are represented by unchannelised bedload sandstone lobes supplied by short-lived ephemeral channels. In the most distal section of the Tordillo Formation and towards the top of the unit at the northwestern sections, primary pyroclastic deposits -accompanied by frequent development of soil horizons and a general change towards darker sediment colours- suggest a marked increase in explosive activity and longer periods of high water table emplacement.

The palaeocurrent orientation from almost all parts of the Tordillo Formation is unimodal with consistent axial northward flow directions (Spalletti and Colombo Piñol, 2005). However, several deposits of the distal facies association in the northwestern sector of the depocentre are oriented to the north and east. These data indicate a long term fixed source in the Huincul arch combined with an important clastic contribution from the Andean magmatic arc, especially in the areas located by the western margin of the depocenter (Spalletti *et al.*, 2004).

In the Northwestern Depocentre, marked changes in sedimentary facies, stacking patterns and architecture are recorded between the southern proximal deposits and those located to the north (Fig. 4). The southern upstream sector is characterised by reduced thickness and coarse grain size as the result of a steep gradient of the area, excess of bedload supply, low subsidence rate and diminished accommodation space. On the other hand, thicker and dominant finer-grained deposits are registered in the areas located to the west and northwest, where coarse-grained alluvial facies associations are only developed at the lowermost part of the Tordillo record. This is not only the consequence of a palaeogeographic variation in fluvial style from proximal to distal settings, but it also indicates increasing accommodation due to high rates of subsidence relative to coarse siliciclastic sedimentation rates. To the northeast, the most distal areas of the Northwestern Depocentre are characterised by reduced thickness and fine-grained deposits. These attributes reveal a change towards an overall decrease in coarse-grained sediment supply (these localities are far from the source), accompanied by a low rate of subsidence and therefore in accommodation space.

Southwestern Depocentre

The Kimmeridgian deposits of the southernmost Neuquén Basin are included in the Quebrada del Sapo Formation. Veiga and Spalletti (2007) showed that this unit is composed of an up to 40 m-thick succession of coarse- to fine-grained fluvial deposits at the base, capped by aeolian deposits (Fig. 6).

The fluvial deposits are characterised by a wide variety of grain sizes, ranging from coarse-grained conglomerates to very fine-grained sandstones and mudstones. The coarser-grained deposits are tabular and lenticular beds of medium- to coarse-grained polymictic conglomerates (Fig. 7A). Vertical changes from conglomerates to pebbly sandstones and sandstones along one single set are common. Planar and less-common trough cross-bedding is present in most places, and sets range from 0.3 to 0.5 m thick. Gutter casts and grooves can be present at the lower boundary of the beds. These deposits are interpreted as in-channel and marginal bars within bedload dominated fluvial channels (Veiga and Spalletti, 2007).

Centimetre-thick couplets of horizontally bedded to low-angle cross-bedded fine- to medium-grained conglomerates and sandstones are intercalated with fluvial channel deposits (Fig. 7b). Primary current lineation is common in the sandstone interbeds. These deposits were formed under plane-bed conditions by short-lived supercritical sheetfloods.

The finer-grained fluvial deposits consist of intercalations of massive and commonly mottled red siltstones and sandy-mudstones. Isolated cm-thick massive sandstone layers with an erosive, horizontal lower contact are also present. However, some of them may show a faint horizontal lamination, while others develop normal grading. The fine-grained deposits were formed under high rates of suspension settling in a

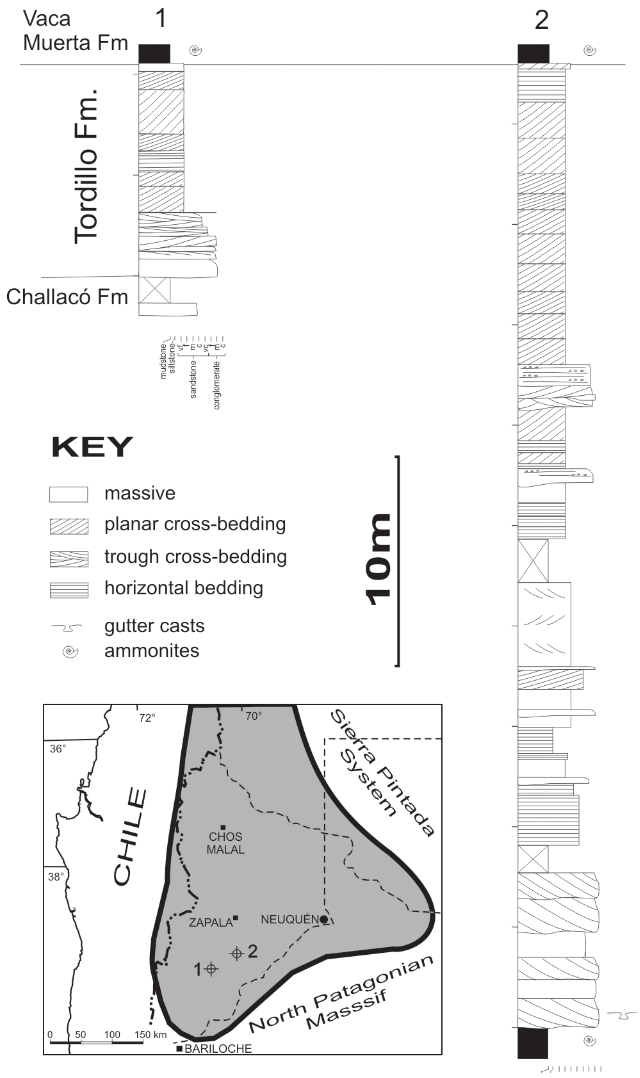

Figure 6. Sedimentary logs of the Southwestern Depocentre. Measured sections: 1: Cortaderas, 2: Picún Leufú.

Figura 6. Columnas sedimentarias del Depocentro Sudoeste. Secciones: 1: Cortaderas, 2: Picún Leufú.apa general de la Cuenca Neuquina con la ubicación de las áreas de estudio.

relatively low-energy distal and ephemeral fluvial environment (Veiga and Spalletti, 2007). Bed massiveness and mottled structure may indicate both postdepositional bioturbation and pedogenesis. Sandstone intercalations are the deposits of distal unconfined sheetfloods.

A 7 to 20 m thick succession dominated by large-scale (up to 2 m) amalgamated sets of tabular to wedge-shaped sandstone bodies with sharp and flat lower boundaries characterises the upper part of the Quebrada del Sapo Formation (Fig. 6). These sets are composed of fine- to medium-grained, bimodally sorted sandstones. They are internally cross-stratified with planar to tangential foresets, showing abundant reactivation surfaces (Fig. 7c). The bottom part of the foresets displays medium- to coarse-grained, massive to inversely graded laminae. Lenticular sandstone beds with trough cross-bedding are less common. The presence of thinly laminated wind ripple lamination (Hunter, 1977) associated with massive and inverse graded grain fall and grain flow laminae allows for the interpretation of these deposits as slipfaced aeolian dunes (Hunter, 1977; Veiga *et al.*, 2002; Veiga and Spalletti, 2007). Reactivation surfaces are thought to represent slight changes in wind direction or in the rate at which these dunes migrated (Kocurek, 1988; Mountney and Jagger, 2004). Soft sediment deformation features, such as water escape structures and folded foresets, are recorded in the aeolian dune deposits located towards the top of the Quebrada del Sapo Formation.

Two different types of deposits are intercalated within aeolian dunes. One type is composed of tabular, 20-40 cm thick beds of fine- to medium-grained bimodally sorted sandstones with horizontal lamination interpreted as aeolian sand sheets (Veiga and Spalletti, 2007). The other type is represented by thin (15 to 30 cm thick) alternations of fine- to medium-

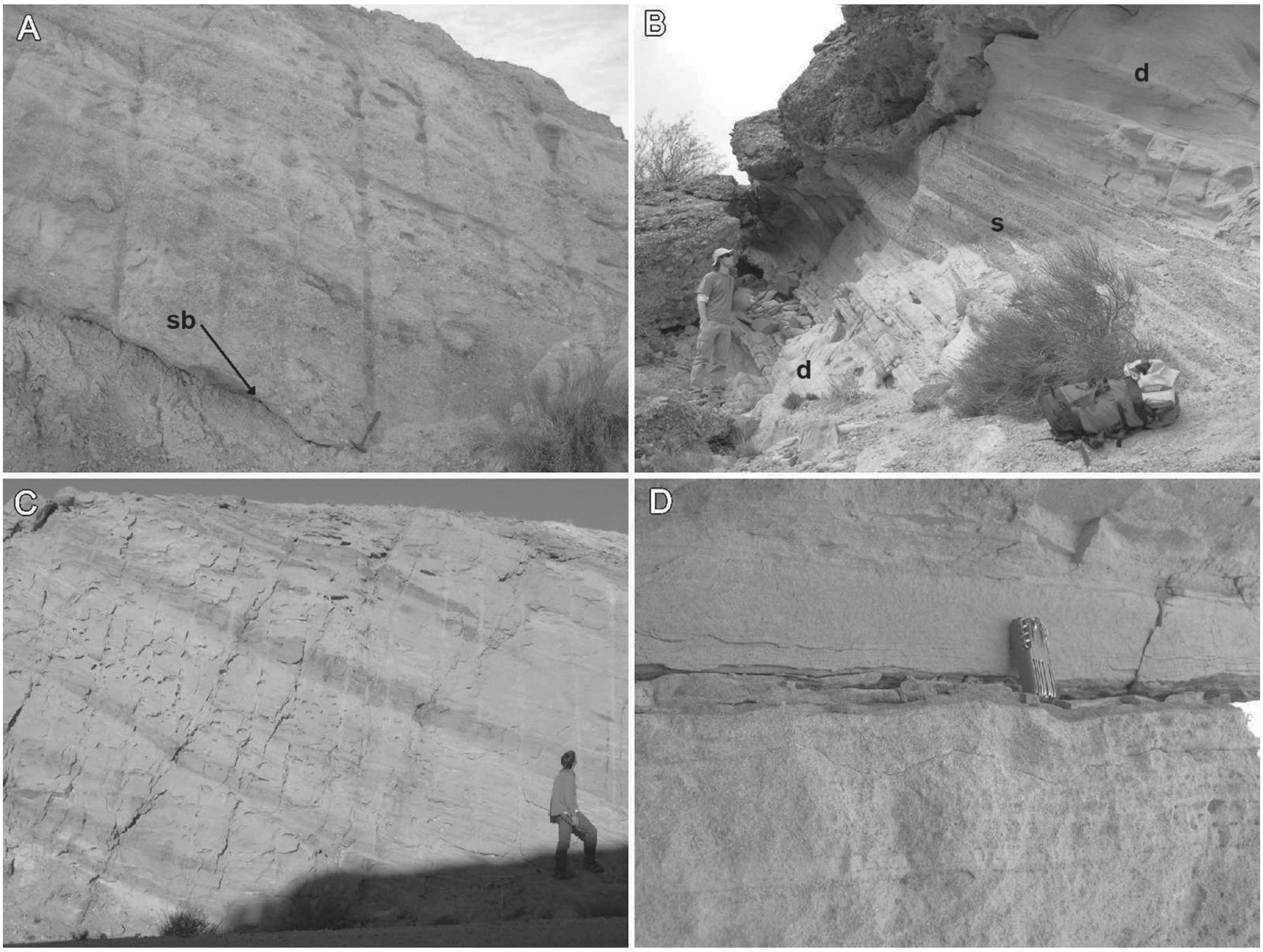

Figure 7. The Kimmeridgian lowstand wedge in the Southwestern Depocentre. a) Coarse-grained fluvial channels on top of low-order sequence boundary (sb), Picún Leufú section. b) Close view of sheetflood deposits (s) intercalated betweed aeolian dune deposits (d), Picún Leufú section. c) Amalgamated aeolian dune deposits at Picún Leufú. d) Thin wet interdune deposits at the upper part of the Cortaderas section.

Figura 4. La cuña de mar bajo kimmeridgiana en el Depocentro Sudoeste. a) Canales fluviales con depósitos de grano grueso en el tope de un límite de secuencia de bajo orden (sb), sección de Picún Leufú. b) Vista de detalle de depósitos de crecidas no encauzadas (s) intercalados entre areniscas eólicas (d), sección de Picún Leufú. c) Depósitos amalgamados de dunas eólicas en Picún Leufú. d) Depósitos delgados de interduna húmeda en la parte alta de la sección de Cortaderas.

grained sandstones and red mudstones (Fig. 7d). Mudstones are massive or may show faint lamination. Some sandstone beds display features of both aeolian deposition and water reworking, such as bimodal sorting and horizontal lamination, and symmetric and asymmetric aggrading ripples. Veiga and Spalletti (2007) interpreted these deposits as aeolian interdunes (sensu Kocurek, 1981). The presence of features indicative of windlain and waterlain accumulation suggests water table oscillations within the interdune environment.

Palaeocurrent data for fluvial deposits indicate a main flow direction towards the North, suggesting contribution from the southern margin of the basin. However, a potential contribution from positive areas located to the North (Dorsal de Huincul) can not be disregarded. In the case of the aeolian deposits located to the upper part of the Quebrada del Sapo Formation, a consistent transport direction towards the NE is defined.

Depositional systems and facies stacking are essentially similar in the studied localities. However, important thickness differences have also been recorded in the Southwestern Depocentre (Fig. 6). In this case, both the fluvial and aeolian sections of the Quebrada del Sapo Formation increase significantly towards the north. Veiga and Spalletti (2007) interpreted that this change may be attributed to marked differences in accommodation space between the areas located to the south and to the north of the depocentre. The greater accommodation in the northern area is also illustrated by variations in the depositional systems. To the north, the fluvial stacking is retrogradational and thick packages of fine-grained deposits were preserved, whereas to the south, the low accommodation conditions favoured a high degree of lateral migration of fluvial channels with substantial erosion of fine-grained deposits. In addition, in the southern sector, the aeolian succession is characterised by sinuous-crested dunes typically associated with wet interdune deposits, and the lower boundary of this aeolian succession is a continuous and flat deflation surface. To the north, instead a dryer aeolian system, almost entirely dominated by amalgamated dune deposits, is developed. The thickness increase of the aeolian record to the north, accompanied by the greater participation of dune deposits (larger sand availability) and a general NE direction of aeolian palaeocurrents, suggests that the northern sector of the depocentre might represent a more central portion of an erg environment (Veiga and Spalletti, 2007).

Eastern Depocentre

The Kimmeridgian deposits located in the subsurface of the Neuquén Embayment are known as the Sierras Blancas and Catriel formations (Digregorio, 1972). However, Muñoz *et al.* (1984) and Cazau and Melli (2002) considered that the most appropriate nomenclature is Tordillo Formation, since the stratigraphic subdivision created by Digregorio (1972) is mainly based on petrophysical properties. The maximum thickness of the Kimmeridgian deposits is 250 m, but it is drastically reduced towards the northeastern, eastern and southern margins of the depocentre (Arregui, 1993; Cazau and Melli, 2002; Maretto *et al.*, 2002).

The sedimentary record is characterised by rapid lateral and vertical facies variations. Coarse-grained fluvial deposits prevail in the lowermost sections (Fig. 8) and towards the southern (Huincul Arch) and northeastern margins of the depocentre (Arregui, 1993; Maretto *et al.*, 2002). Benito and Manassero (1992), Arregui (1993) and López *et al.* (2005) indicated that the fluvial deposits are composed of tabular and lenticular beds of volcaniclastic very coarse- to fine-grained sandstones, gravelly sandstones and polymictic conglomerates. Internally, they are massive or may show horizontal and low-angle cross-bedding. Cross-bedded sets and normal graded beds are less common. Thin cm-intercalations of parallel laminated mudstones and claystones occur. Palaeocurrent trends for the fluvial deposits are mainly perpendicular to the northeastern margin of the depocentre. This is the case of the fluvial deposits in the southern sector of the depocentre that show a consistent palaeoflow direction from the Huincul Arch towards the north (López *et al.*, 2005). This facies association was attributed to poorly confined and high-regime sandy and gravelly braided fluvial systems (Benito and Manassero, 1992; Arregui, 1993; Cazau and Melli, 2002; López *et al.*, 2005).

In the eastern depocentre the most common and important (from the hydrocarbon viewpoint) facies association is the one characterised by a thick (up to 160 m) monotonous, unfossiliferous succession mainly composed of well-sorted fine- to medium-grained sandstones attributed to an aeolian field (Muñoz *et al.*, 1984; Peroni *et al.*, 1984; Limeres, 1988; Arregui, 1993). Although this dune field is mainly developed in the central area of the depocentre, it also onlaps marginal positive lands inherited from the Intramalmic tectonic movements (Maretto and Zavala, 2005). Three different facies constitute the aeolian succession (Fig.8): 1) dunes,

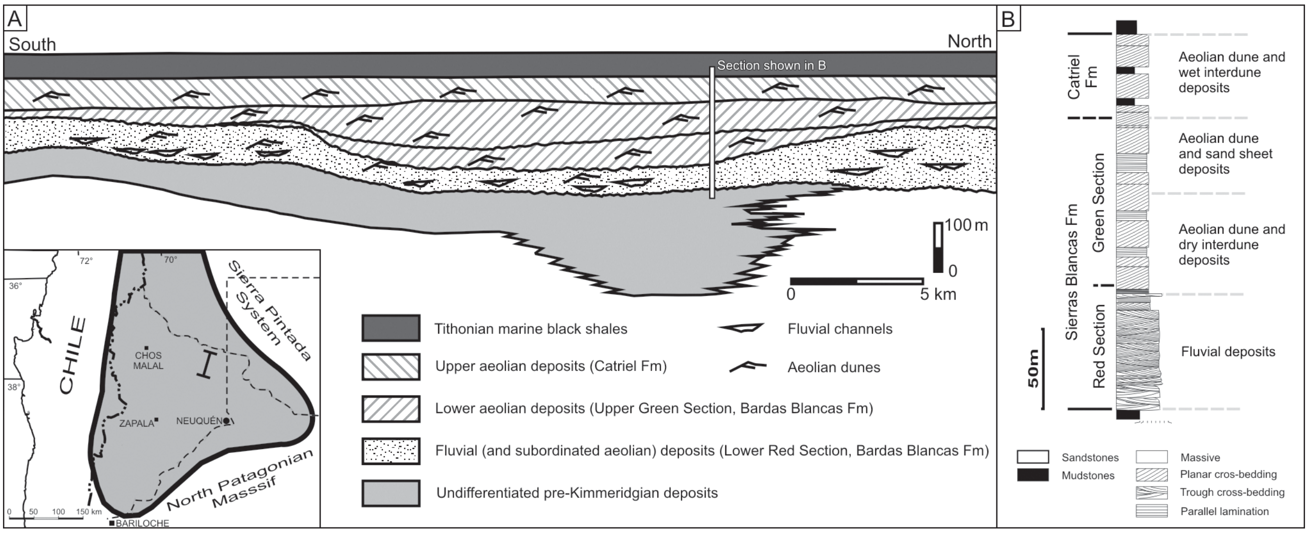

Figure 8. a) Stratigraphic cross-section showing the Kimmeridgian stratigraphy and main depositional systems in the Eastern Depocentre (modified from Maretto et al. 2002). b) Lithostratigraphic log of the Eastern Depocentre, main facies associations and interpreted depositional systems.

Figura 8. a) Sección estratigráfica que muestra la estratigrafía kimmeridgiana y los principales sistemas de depositación en el Depocentro Este (modificado de Maretto et al. 2002). b) Sección litoestratigráfica del Depocentro Este con las principales asociaciones de facies y los sistemas de depositación.

2) dry interdunes and 3) wet interdunes (Muñoz *et al.*, 1984; Maretto *et al.*, 2002; López e*t al.*, 2005).

Up to 12 m, and commonly between 0.5 and 5 m thick, tabular and wedge-shaped cross-stratified sets composed of high angle (15°-30°) planar and asymptothic laminae of alternating fine-grained and medium- to coarse-grained sandstones characterise aeolian dune deposits. These deposits show a consistent palaeocurrent orientation towards the NE (Peroni *et al.*, 1984; Benito and Manassero, 1992; Cazau and Melli, 2002; López *et al.*, 2005). Towards the top of the aeolian succession, aeolian dune sandstones show abundant features of water scape structures (*e.g.* convolute lamination).

Interdune deposits consist of 2 to 5 m-thick successions of horizontal laminated to low-angle cross-laminated sandstones (Muñoz *et al.*, 1984; Arregui, 1993; Maretto *et al.*, 2002; López *et al.*, 2005). Dry interdune deposits are composed of coarse- to fine-grained bimodally sorted sandstones with horizontal lamination and aeolian ripples. Wet interdunes are characterised by fine-grained sandstones showing water lain current ripples and ripple cross- lamination associated with brecciated structures (Muñoz *et al.*, 1984).

To the northwestern sector of the depocentre and especially towards the top of the sedimentary record, Arregui (1993) described a succession of very fine-grained to medium-grained sandstones with horizontal lamination and low-angle cross-stratification associated with common massive and laminated siltstones and claystones, and only a few intercalations of plane-bedded conglomerate beds. They are interpreted as the deposits of a distal non chanellised ephemeral fluvial system and a playa lake system.

Maretto *et al.* (2002) and Cevallos (2005) described a consistent vertical evolution of the depositional systems in the Eastern Depocentre that broadly resembles the one depicted for the Southwestern Depocentre (Figs. 6 and 8). Coarse-grained fluvial deposits dominate the lower portion of the Kimmeridgian succession while aeolian deposits prevail towards its top. In the Eastern Depocentre, the important thickness of the aeolian deposits allowed to establish a vertical trend within this depositional system. Maretto *et al.* (2002) and Cevallos (2005) demonstrated that the aeolian succession evolved from dry to wet depositional conditions.

REGIONAL VARIATIONS IN THE KIMMERIDGIAN LOWSTAND WEDGE

The previous analysis demonstrated that the three depocentres identified in the Kimmeridgian lowstand wedge show clear differences in accommodation and in the depositional systems (Fig. 9). The Kimmeridgian deposits show their maximum thickness in the Northwestern Depocentre where all the accumulation took place in a fluvial setting. Most of the clastic material was derived from a volcanic arc developed to the west (Vergara *et al.*, 1995; Charrier *et al.*, 1996) and from the uplifted Huincul Arch to the south. This contrasts substantially with the fill of the other two depocentres, which show a more reduced thickness and a fluvial section at the base that evolves into an aeolian depositional system to the top (Fig. 9). Even when the Eastern and Southwestern depocentres share a similar pattern in vertical facies succession they show contrasting thickness and palaeocurrent distribution. In this sense, the record of the Eastern depocentre is up to six times thicker than in the Southwestern one, with a marked fluvial sediment supply from the northeastern basin margin ramp and the reactivated structure of the Huincul Arch form the south for the former. The main source area for the Southwestern Depocentre was the southern margin of the basin (North-Patagonian Massif). Interestingly, the upper aeolian systems in both depocentres show a similar main transport direction towards the NE (Peroni *et al.*, 1984; Veiga and Spalletti, 2007), with the exception of the area situated close to the Huincul Arch, where the topography could have been responsible for a local change of wind directions towards the N-NW (Cevallos, 2005).

Therefore, clear similarities and differences are recorded in the Kimmeridgian lowstand wedge throughout the Neuquén Basin (Fig. 9). For example, there is a

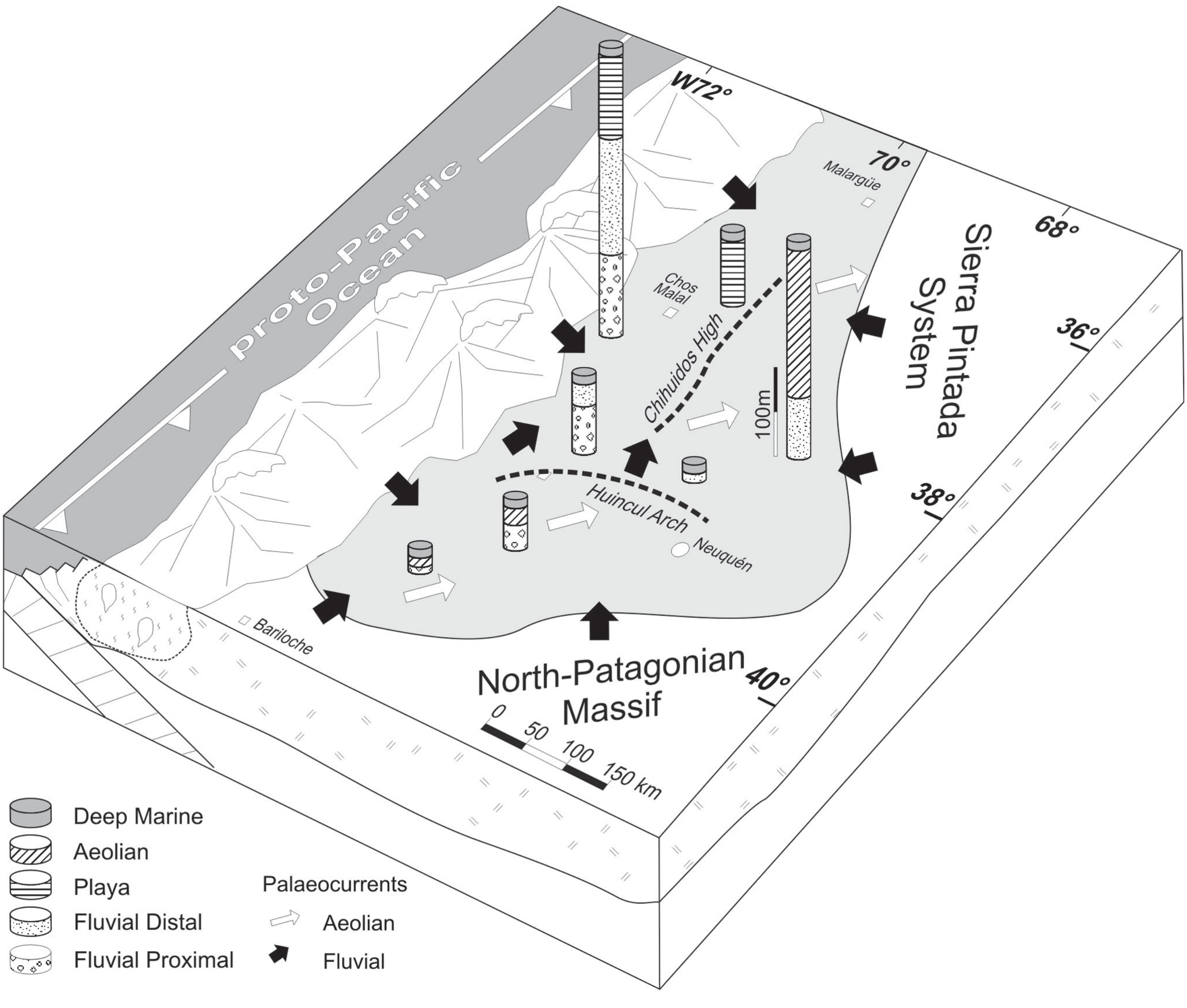

Figure 9. Panorama of the basin during the Kimmeridgian lowstand wedge and schematic evolution of depositional systems.
Figura 9. Panorama de la cuenca durante el Kimmeridgiano y evolución esquemática de los sistemas de depositación.

clear difference in thickness between the sections accumulated north and south of the inverted Huincul Arch. To the north of this inverted structure (Northwestern and Eastern Depocentres) the record of this lowstand shows a much greater thickness than that in the south (Southwestern Depocentre). This difference suggests that in the northern part of the basin, greater accommodation conditions developed after the Oxfordian-Kimmeridgian tectonic event, although the reduced thickness in the south could also be related to a reduction in sediment supply and the development of a non-marine underfilled depocenter (Fig. 10). There are also differences in thickness between the Northwestern and Eastern depocentres, as well as important thickness changes within the Northwestern depocentre itself (Figs. 9 and 10). In this sense, the Kimmeridgian succession shows its maximum thickness towards the west, close to the magmatic arc chain, while it drastically diminishes in an eastward direction, towards the structure that separates this depocentre from the Eastern one (Chihuidos High). These differences could indicate that accumulation in the Northwestern Depocentre was strongly influenced by the western magmatic arc, not only as a main source of clastic supply, but also in the accommodation creation related to differential subsidence controlled by the load of the volcanic arc chain.

At the same time, the Chihuidos High constitutes a significant boundary between the Northwestern and Eastern depocentres especially in the facies associations accumulated in either side of the structure (Fig. 9). To the west of Chihuidos (Northwestern Depocentre), the sedimentation took place in an ephemeral fluvial environment, but to the east, the initial fluvial accumulation evolved to an aeolian system. Therefore, the inverted Chihuidos High acted as an eastern depositional boundary for the fluvial systems of the Northwestern Depocentre. Despite its importance in the delimitation of different boundaries within the basin, the Chihuidos High did not have enough topographic expression to constitute an active, intrabasinal source area - as it was the case for the Huincul Arch - as the palaeocurrent distribution was not affected by this structure.

The aeolian deposits present at the top of the Kimmeridgian lowstand wedge in the Eastern and Soutwestern Depocentres deserve a special consideration. The potential correlation between these deposits and the similar palaeocurrent trend towards the NE (Fig. 9) suggests a common origin and the same driving mechanisms controlling the aeolian accumulation in this sector of the basin towards the end of the Kimmeridgian. The great differences in the thickness of the aeolian succession between the Eastern and Southwestern depocentres might reflect contrasting accommodation conditions but, more probably, different palaeogeographic positions within a major erg system, especially with low sedimentation rates and sand availability in the upwind margin of the erg in the SW.

Therefore, the regional differences in thickness and in the facies pattern observed in these depocentres are directly related to the compartmentalization of the ba-

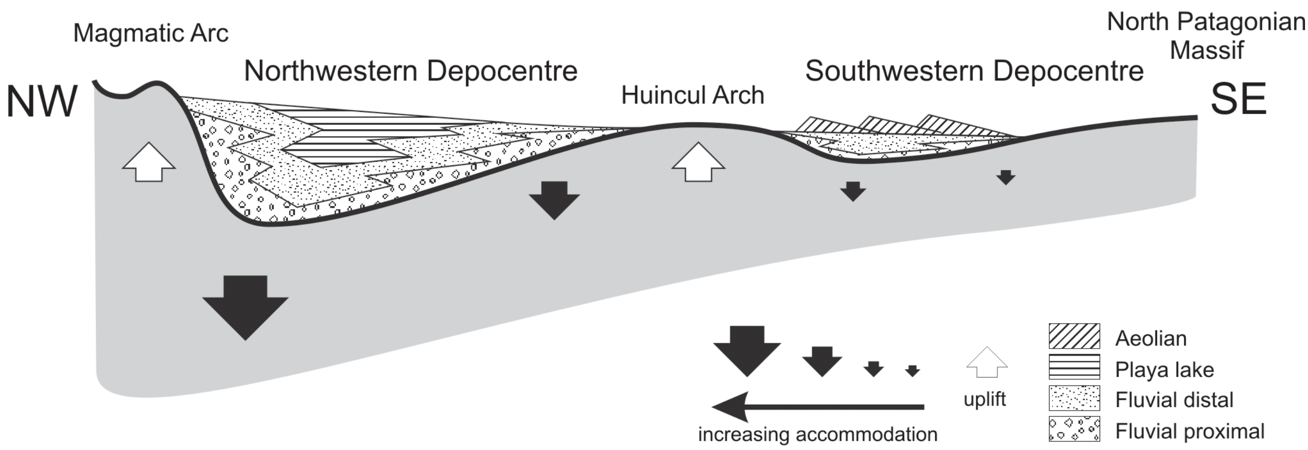

Figure 10. Interpreted NW-SE section of the Kimmeridgian lowstand wedge. Vertical and regional variations in main depositional systems in the Northwestern and Southwestern Depocentres, and lateral changes in basin accommodation.

Figura 10. Sección NO-SE de la cuña de mar bajo kimmeridgiana. Variaciones regionales y verticales en los sistemas de acumulación sedimentaria de los depocentros Noroeste y Sudoeste y cambios laterales en la acomodación.

sin due to the inversion of previous structures and the development of intrabasinal highs (Figs. 9 and 10). Then, three relatively independent depocentres were formed, in which different driving mechanisms might have had dissimilar influence in the stratigraphic record of each depocentre. In this sense, the Northwestern Depocentre constitutes an asymmetric clastic wedge controlled mainly by the accommodation creation to the west, close to the volcanic arc, and coarse-grained sediment supply derived, not only form the uplifted arc, but also from the inverted structure of the Huincul Arch to the south. Another inverted structure to the east (the Chihuidos High) acted as a boundary for the accumulation in this depocentre, although it might not have had enough topographic expression to constitute an active source area and to control the ephemeral fluvial network.

The fluvial systems of the Eastern Depocentre also evolved in a high accommodation setting, with a main active source area in the inverted Huincul Arch to the south, but also with sediments being supplied from the passive NE margin of the Neuquén Basin (Sierra Pintada Massif).

Finally, the Southwestern Depocentre might have evolved under low accommodation conditions or reduced clastic input supplied from the southern and southwestern margins of the basin. The absence of coarse-grained clastic material from the west is noticeable, especially during the accumulation of the basal fluvial section. This could indicate that the magmatic arc did not have a considerable expression to the south of the Huincul Arch. This could be also the reason for reduced sedimentary thickness of the Kimmeridgian succession in the southern part of the basin, as no flexural subsidence was created due to the absence of a well developed magmatic arc towards the western flank of the basin.

There are several modern examples of arid regions showing a similar panorama. Figure 11 is a satellite image of the Rincón Salt Lake (Puna region, northwestern Argentina, 24°S - 67°W) in which a huge transversal bajada-longitudinal ephemeral fluvial system is clearly separated from a large aeolian dune field by a N-S trending structural lineament.

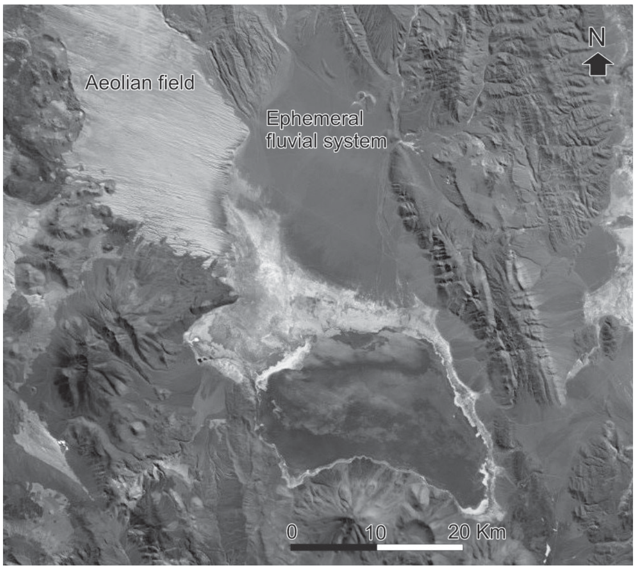

Figure 11. A present-day analogue of the Kimmeridgian lowstand wedge, showing the compartmentalisation of depositional systems. The Rincón playa-lake, Puna region, northwest Argentina.

Figura 11. Análogo actual de la cuña de mar bajo kimmeridgiana en el que se ilustra la compartimentalización de los sistemas de depositación. El Salar del Rincón, región de la Puna del noroeste argentino.

THE SEQUENCE PATTERN: DEVELOPMENT OF AN EARLY AND LATE KIMMERIDGIAN LOWSTAND WEDGE

Despite the regional differences observed in the Kimmeridgian deposits throughout the Neuquén Basin it is possible to establish a consistent vertical evolution for the sedimentary record of this lowstand wedge. This suggests that although the existence of local controls might have accumulated different stratigraphic successions in each depocentre, their evolution could have been controlled by the same regional-scale driving mechanisms.

A diagnostic feature that characterises this lowstand wedge is the development of a low-order sequence boundary at its base. This boundary is conspicuous throughout the entire Neuquén Basin and it is marked by the sudden appearance of the non-marine deposits of the lowstand wedge on top of shallow-marine and even deep-marine facies in the centremost part of the basin. It is plausible that the development of this important discontinuity at the base of the Kimmeridgian deposits might not have been exclusively produced as a result of an eustatic fall. Tectonic uplift along the western active margin of Gondwana might have enhanced this fall in sea level. In this sense, during the Late Oxfordian-Early Kimmeridgian an important change in the subduction regime is recorded in the active margin of the Neuquén Basin that resulted in the vertical growth of the magmatic arc to the west and the temporary cease of the regional extensional regime recorded in the backarc since the Early Jurassic (Sanguinetti and Ramos, 1993). This tectonic episode also resulted in the inversion of some of the early rift structures within the basin due to the development of a locally compressive stress field (Vergani *et al.*, 1995). The fact that continental deposits are present even in the centremost parts of the basin suggests that the growth of the magmatic arc might have produced the temporary disconnection of the basin from the proto-Pacific Ocean.

The early stage of evolution of the lowstand wedge as a result of Late Jurassic inversion and the growth of the volcanic arc was characterised by widespread fluvial sedimentation (Fig 12a). The main source areas were the Andean magmatic arc to the west, the inverted Huincul arch and the passive cratonic margins of the basin towards the NE and S. These high-relief areas were flanked by well developed proximal fluvial systems, and supplied most of the siliciclastic material for the fluvial infill. Besides, the N-S trending structure of the Chihuidos High allowed the compartmentalisation between the Northwestern and Eastern Depocentres; however, it apparently lacked the sufficient topographic expression to constitute another area for sediment supply.

During the late lowstand important changes were produced in the sedimentary record of the depocentres (Fig. 12b). The Northwestern Depocentre is now characterised by an overall fining-upward stacking pattern implying the retrogradational transition from alluvial fan systems to a thick succession of ephemeral fluvial and playa redbeds. The expansion of distal fluvial-playa systems suggests an abrupt increase in accommodation, especially towards the western margin of the depocentre. The development of fine-grained amalgamated volcaniclastic deposits on top of the Kimmeridgian succession seems to be the result of a rapid subsidence and rise in base level probably combined with a general increase in explosive volcanism.

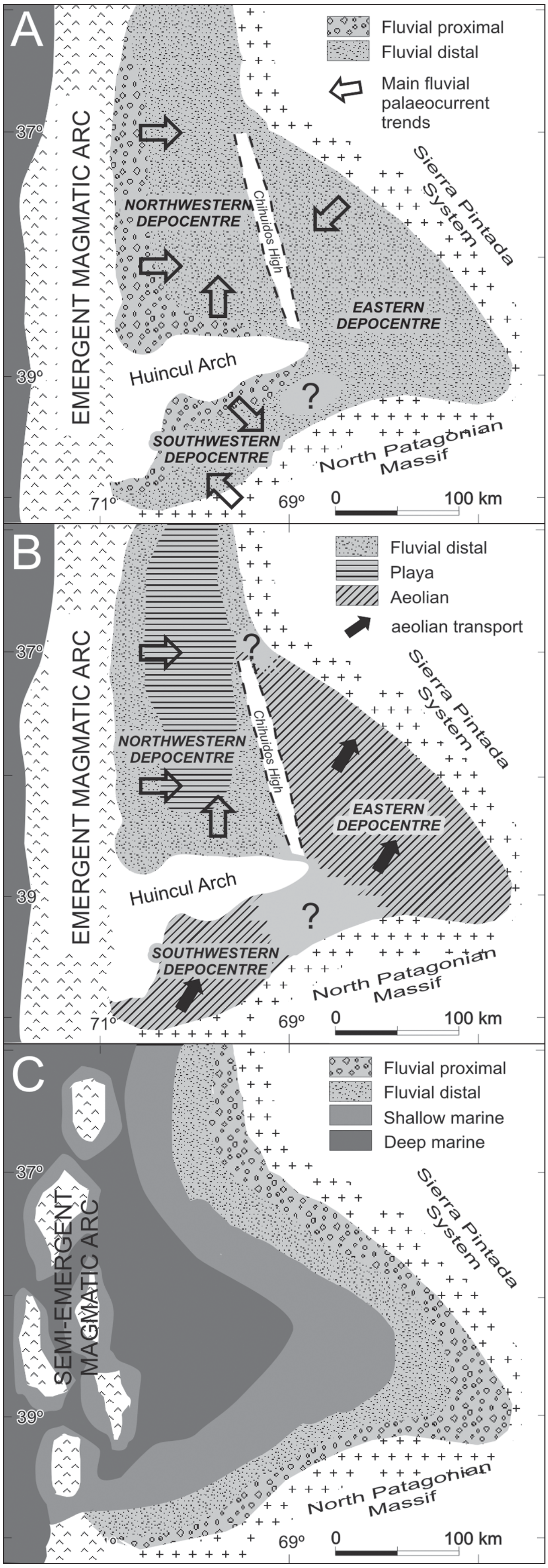

Figure 12. Schematic palaeogeographic evolution of the Kimmeridgian lowstand wedge. a) Early Lowstand Stage. b) Late Lowstand Stage. c) Subsequent Transgressive Stage.

Figura 12. Evolución paleogeográfica esquemática de la cuña de mar bajo kimmeridgiana de la Cuenca Neuquina. a) Estadio de mar bajo temprano. b) Estadio de mar bajo tardío. c) Estadio transgresivo subsecuente.

Darker sediment colours and the common appearance of palaeosols indicate increased precipitation and high water table emplacement.

In the Southwestern and Eastern Depocentres the early fluvial sedimentation ceased and allowed the development of widespread aeolian systems (Fig. 12b). Although a plausible explanation for this transition is a gradual change towards arid climatic conditions (Howell and Mountney, 1997; Mountney *et al.*, 1999), there is no evidence of a global change towards dryer conditions during Late Jurassic. The growth of the magmatic arc towards the west and the development of a topographic barrier between the basin and the palaeo-Pacific Ocean might be invoked to suggest the overall drying upward trend during the Kimmeridgian lowstand wedge. However, there is no evidence of a transition towards more arid conditions in the fluvial deposits of the Northwestern Depocentre despite the clear evidence of an elevated magmatic arc to the west. Therefore, the development of a widespread aeolian depositional system in the Eastern and Southwestern depocenters cannot be merely explained by climatic changes. Veiga and Spalletti (2007) assumed that the development of the late lowstand Kimmeridgian erg was controlled by an overall fall in the position of the water table (related to the tectonic-enhanced relative sea level drop) combined with an important rate of sand supply and availability. Aeolian deposits are commonly identified in several Mesozoic lowstand wedges of the Neuquén Basin (Veiga *et al.*, 2002; Veiga *et al.*, 2005). These aeolian deposits are typically associated with low accommodation settings, and although they tend to accumulate after a widespread fluvial episode, they do not appear in lateral relationship to fluvial systems.

The upper boundary of the Kimmeridgian lowstand deposits is also sharp. It is characterized by the sudden accumulation of deep-marine black shales of the Vaca Muerta Formation across the whole basin. These black shales are developed on top of the fluvial succesion in the Northwestern Depocentre and on top of the aeolian deposits in the Eastern and Southwestern ones. This indicates the development of a low-order transgressive episode. The presence of soft sediment deformation structures in the uppermost aeolian dune deposits suggests that the transgression occurred while the aeolian system was still active and it implies the lack of a considerable hiatus between the lowstand wedge and the subsequent transgressive deposit (Eschner and Kokureck, 1986; López *et al.*, 2005). This is also a common scenario in the Mesozoic evolution of the Neuquén Basin, as transgression-related soft sediment deformation -together with dune topography preservation- has been reported for the upper portions of other low-order lowstand deposits (Strömbäck *et al.*, 2005).

Even when this low-order transgressive surface indicates a generalized and almost synchronous event all over the basin, a transgressive effect can also be identified in the upper portion of the Kimmeridgian lowstand wedge. In this sense, the retrogradational stacking pattern of the fluvial systems recorded in the Northwestern Depocentre could be the result of a progressive increase in accommodation (compared to clastic sediment supply) that can be related either to an increase in subsidence and/or to a progressive rise in the fluvial systems base level during the beginning of the transgression (Spalletti and Colombo Piñol, 2005). Moreover, this suggests that the connection between the Neuquén Basin and the proto-Pacific Ocean might have been resumed late during the accumulation of the lowstand deposits. The presence of dark, fine-grained facies at the top of the Kimmeridgian record in the Northwestern Depocentre suggests a relatively shallow water table that could be related to the beginning of the transgressive event. On the other hand, the evolution from dry to wet aeolian systems in the Eastern Depocentre also suggests an overall rise in the position of the water table that can be related to a general transgressive pattern as well (Kocurek *et al.*, 2001).

Transgressive deposits developed on top of the Kimmeridgian lowstand wedge shows a rather uniform distribution of deep marine black shales and marls, without a major control of the inverted structures (Fig. 12c). This demonstrates that facies and stratigraphic organisation within lowstand deposits was much more complicated than facies distribution during the subsequent transgression. Consequently, models based on the distribution of marine deposits may not predict the strong variability observed during lowstand periods, especially in basins where the lowstand wedges are controlled by tectonic reactivations.

CONCLUSIONS

Three depocentres (Northwestern, Southwestern and Eastern) are identified in the Kimmeridgian lowstand wedge of the Neuquén Basin. Their development is directly related to the growth of the Andean magmatic arc, the late Oxfordian and earliest Kimmeridgian tectonic inversion of previous structures, and the development of intrabasinal highs, known as the Huincul Arch and the Chihuidos High.

These depocentres show clear differences in accommodation and in the regional distribution and evolution of the depositional systems. The thickest deposits are identified in the Northwestern Depocentre where all the accumulation took place in an alluvial-ephemeral fluvial-playa lake system. Palaeocurrent trends indicate preferential contributions from the Huincul Arch in the south and the Andean magmatic arc in the west. Therefore, in the asymmetric clastic wedge of the Northwestern Depocentre, fluvial sedimentation was controlled by clastic contributions from the south and west, as well as by differential subsidence and high accommodation to the west, related to the load of the volcanic arc chain.

The Eastern and Southwestern Depocentres show a more reduced thickness; however, the record of the former is up to six times thicker than the Southwestern one. Although thickness variations seem to be related to accommodation, the development of thin successions in the Southwestern Depocentre could also be related to a reduction in sediment supply. The Eastern and Southwestern Depocentres are composed of a fluvial section at the base that evolves into an aeolian depositional system towards the top. In the Eastern Depocentre, the fluvial sediments were supplied from the northeastern passive margin of the basin and the reactivated structure of the Huincul Arch from the south. The main source area for the Southwestern Depocentre was the southern margin of the basin (North-Patagonian Massif). The aeolian systems in both depocentres show a similar main transport direction towards the NE. The great differences in the thickness of these aeolian successions are attributed to different palaeogeographic positions within a major erg system, especially with low sedimentation rates and sand availability in the upwind margin of the erg in the SW.

The Kimmeridgian lowstand wedge is limited by a low-order sequence boundary at its base. It is marked by the sudden appearance of the fluvial deposits of the lowstand wedge on top of shallow- and deep-marine Oxfordian deposits. This unconformity might not have been exclusively produced by eustatic movements. Tectonic uplift of the magmatic arc chain to the west of the Neuquén Basin -related in turn to an important change in the subduction regime in the active margin of Gondwana- might have enhanced the relative fall in sea level and produced a temporary disconnection of the basin from the proto-Pacific Ocean. This Late Jurassic tectonic episode also resulted in the inversion of some of the early rift structures and the subsequent compartmentalisation of the basin.

During the early lowstand, fluvial sedimentation dominated in every depocentre, while, during the late lowstand, important changes were produced in the sedimentary record. In the Northwestern Depocentre, an abrupt increase in accommodation resulted in the expansion of distal fluvial-playa systems and in the development of an overall fining-upward retrogradational stacking pattern of the sedimentary record. Coevally, in the Southwestern and Eastern Depocentres, the early fluvial sedimentation ceased and a late lowstand sand sea was developed.

The upper boundary of the Kimmeridgian lowstand wedge is also sharp and it is marked by the sudden accumulation of deep-marine black shales on top of the continental deposits. However, this transgressive episode is also identified in the uppermost Kimmeridgian lowstand wedge. The presence of soft sediment deformation features in the uppermost aeolian dune deposits suggests that this low-order transgression occurred while the aeolian system was still active. Moreover, the retrogradational stacking pattern of the fluvial systems, together with the dark, fine-grained facies at the top of the Kimmeridgian record in the Northwestern Depocentre, suggest a progressive rise in fluvial base level and a shallow water table emplacement that could be associated with the beginning of the transgressive event.

The uniform distribution of marine black shales across the whole Neuquén Basin indicates that the inverted structures did not exert an effective control on transgressive palaeogeography. Therefore, sequence stratigraphic models merely based on the distribution of marine deposits and marine key surfaces may not show the significant palaeogeographic and depositional changes revealed by lowstand wedges, especially in basins with synsedimentary tectonism.

Acknowledgments

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