STRATIGRAPHY, DEPOSITIONAL ENVIRONMENTS AND ICHNOLOGY OF THE LOWER PALEOZOIC IN THE AZUL PAMPA AREA - JUJUY PROVINCE

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ABSTRACT

Cambrian-Ordovician deposits are widely represented in the Azul Pampa area, Cordillera Oriental, Jujuy Province. The stratigraphic column begins with the Mesón Group (Lower to Middle Cambrian) which records shallow-marine sedimentation in a tide-dominated environment. The Mesón Group includes the Lizoite, Campanario and Chalhualmayoc formations. The Lizoite and Chalhualmayoc formations contain subtidal sandbar deposits similar to those farther south in the Quebrada de Humahuaca region and surrounding areas. The Campanario Formation includes intertidal flat and channels deposits, representing the regressive maximum of the Mesón Group. Overlying the Mesón Group is an Upper Cambrian to Arenigian succession previously referred to as the Casayok Sandstones and Azul Pampa Formation. Integrated sedimentologic, paleontologic and sequence-stratigraphic studies indicate that these units are lithologically similar and temporarily equivalent to the Santa Rosita Formation (Upper Cambrian to Tremadocian) and the Acoite Formation (Arenigian), respectively, which are widely accepted in adjacent areas. Thus, the Casayok Sandstones and Azul Pampa Formation nomenclature can be abandoned. The lower interval of the Santa Rosita Formation is represented by tide-dominated estuarine deposits of the Pico de Halcón Member, while the upper interval is included in the Alfarcito Member and consists of wave-dominated shallow-marine deposits, ranging from the upper shoreface to the lower offshore and displaying a series of transgressive-regressive cycles. The Acoite Formation records a basinwide maximum transgressive episode and is dominated by shelf deposits with subordinate offshore deposits. There is an absence or scarcity of bioturbation in high-energy settings, an increase in ichnodiversity along salinity gradients, an abundance of firm substrates in Cambrian marginal-marine environments and an increase in degree and depth of bioturbation through the Early Ordovician interval.

Keywords: *Cordillera Oriental, Argentina, Stratigraphy, Ichnology, Lower Paleozoic..*

RESUMEN: *Estratigrafía, ambientes deposicionales e icnología del Paleozoico inferior en el área de Azul Pampa, provincia de Jujuy.*
En la región de Azul Pampa, Cordillera Oriental de Jujuy los depósitos cambro - ordovícicos se encuentran ampliamente representados. La columna estratigráfica se inicia con el Grupo Mesón (Cambrico Inferior - Medio), el cual registra sedimentación en un ambiente marino somero dominado por mareas. Este incluye las Formaciones Lizoite, Campanario y Chalhualmayoc. Las Formaciones Lizoite y Chalhualmayoc contienen depósitos de barras submareales similares a aquellas descriptas anteriormente hacia el sur en la región de la quebrada de Humahuaca y en las áreas circundantes. La Formación Campanario incluye depósitos de canales y planicies intermareales, representando un máximo regresivo para el Grupo Mesón. Sobreyacente al Grupo Mesón se sucede un intervalo cámbrico superior - arenigiano referido previamente como Areniscas Casayok y Formación Azul Pampa. Los estudios integrados, tanto sedimentológicos, paleontológicos como estratigráficos secuenciales, indican que ambas unidades son litológicamente similares y temporalmente equivalentes a la Formación Santa Rosita (Cámbrico Superior - Tremadociano) y a la Formación Acoite (Arenigiano), respectivamente, las cuales son ampliamente aceptadas en las áreas adyacentes, por lo que se recomienda el abandono de la nomenclatura Areniscas Casayok y Formación Azul Pampa. El intervalo inferior de la Formación Santa Rosita está representado por depósitos de estuarios dominado por mareas del Miembro Pico de Halcón. El intervalo superior se incluye dentro del Miembro Alfarcito y consiste en depósitos marino someros dominados por el oleaje, variando desde *shoreface* superior hasta *offshore* inferior, representando una serie de ciclos transgresivos-regresivos. La Formación Acoite registra un episodio de máximo transgresivo a escala de cuenca y se encuentra dominada por depósitos de plataforma con depósitos subordinados de offshore. Los análisis icnológicos revelan la ausencia o la escasez de bioturbación en los ambientes de alta energía, un incremento en la icnodiversidad a lo largo de gradientes de salinidad, la abundancia de substratos firmes en los ambientes marinos marginales cámbricos y un incremento en el grado y profundidad de bioturbación a traves del Ordovícico Temprano.

Palabras clave: *Cordillera Oriental, Argentina, Estratigrafía, Icnología, Paleozoico Inferior.*

INTRODUCTION

Lower Paleozoic deposits are widely represented in the Azul Pampa area, Cordillera Oriental, Jujuy Province (Fig. 1) (Fernández 1983). The Cordillera Oriental Geologic Province represents a fold-thrust belt oriented NNW (Turner and Mon 1979, Ramos 2000). Lower Paleozoic outcrops in the
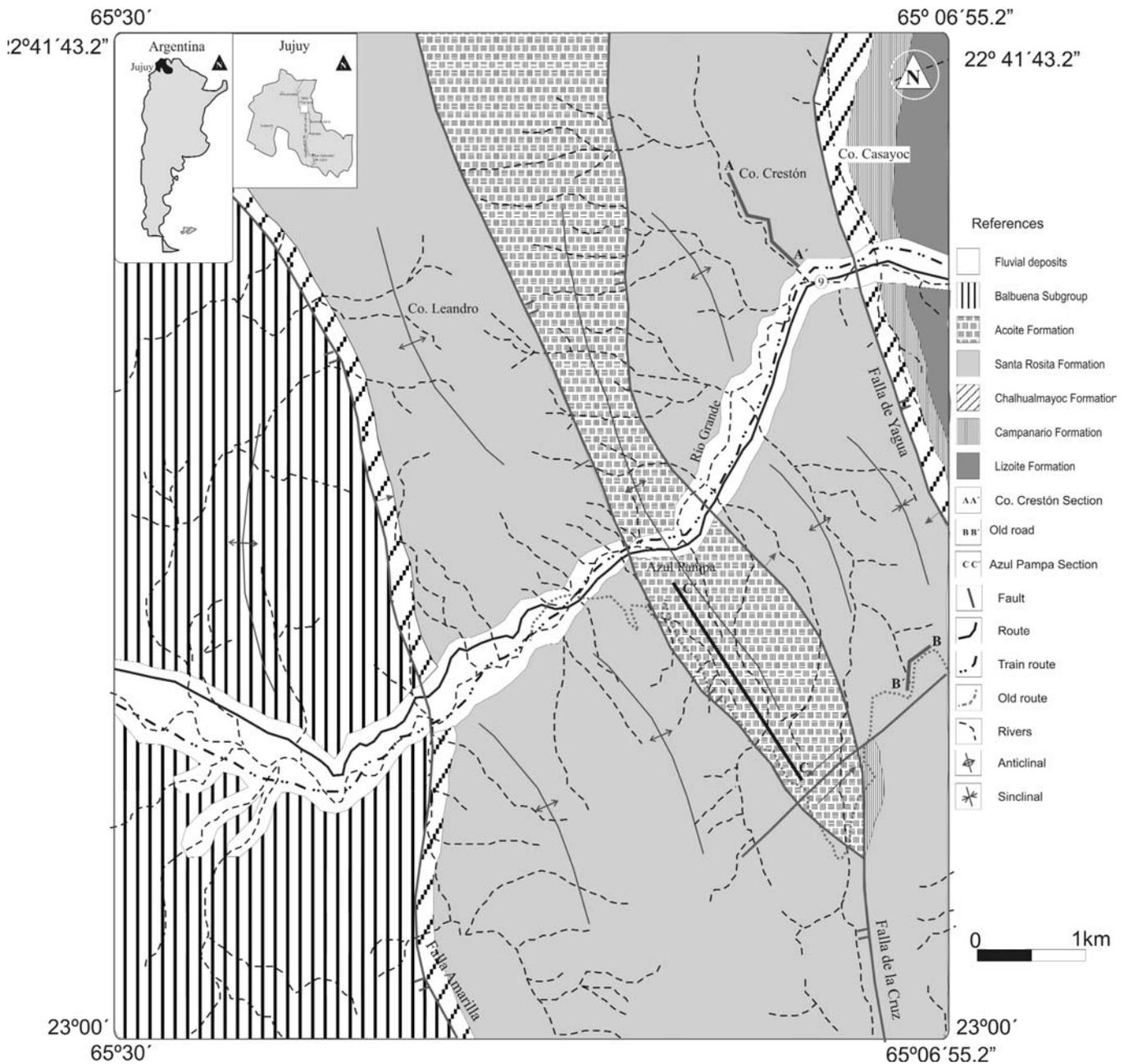
Figure 1: Geologic map of the Azul Pampa area (based on Such 2005).

Azul Pampa area represent a link between those located farther north in Sierra de Santa Victoria where most of the lithostratigraphic units were defined (Turner 1960) and those exposed towards the south in the Quebrada de Humahuaca and Alfarcito area that have been analyzed recently in detail (Buatois and Mángano 2003, Buatois *et al.* 2006). In particular, the Alfarcito area has furnished a paleoenvironmental framework for Cambrian-Tremadocian strata and allo-

wed subdivision of the Santa Rosita Formation into a number of members (Buatois *et al.* 2006). The absence of detailed studies in the Azul Pampa area prompted us to undertake this work in an attempt to characterize the main Cambrian-Ordovician sedimentary units and their depositional environments. Additionally, we provide a re-evaluation of the stratigraphic nomenclature of the Upper Cambrian-Lower Ordovician interval there and we briefly discuss

paleoecological and evolutionary aspects of the ichnofaunas.

GEOLOGICAL FRAME-WORK AND STRATIGRA-PHIC NOMENCLATURE

The geologic structure of the Azul Pampa area is characterized by a fold-thrust style with major faults oriented roughly NW, defining three main thrust slices, and N-tren-

ding folds. Deformation affected both lower Paleozoic and Cretaceous-Tertiary strata. Minor faults are located perpendicular to the orientation of the main thrusts.

The oldest rocks exposed in the Azul Pampa area belong to the Mesón Group (Lower to Middle Cambrian) consisting, from base to top, of the Lizoite, Campanario and Chalhualmayoc formations (Turner 1960). The Mesón Group is exposed in the northeastern zone where it comprises part of a large thrust slice in the flank of a syncline and in the central and western zone it forms another thrust slice (Fig. 1). The base and top of the Group are not observed. The Lizoite and Chalhualmayoc formations consist of thick packages of light-pink, medium- to fine-grained quartzite. The Campanario Formation mostly consists of interbedded light-pink, fine- to very fine-grained quartzite and red mudstone.

Overlying the Mesón Group, an Upper Cambrian to Arenigian succession previously referred to as the Casayok Sandstones and the Azul Pampa Formation is exposed (Harrington and Leanza 1957). Our observations indicate that these units are equivalent to the Santa Rosita (Upper Cambrian to Tremadocian) and Acoite (Arenigian) formations, respectively, of the Santa Victoria Group. These units have been widely used in the adjacent regions, including their type area farther north in Sierra de Santa Victoria and the Quebrada de Humahuaca and Alfarcito areas to the south (e.g., Turner 1960, Turner and Méndez 1975, Turner and Mon 1979, Buatois and Mángano 2003, Buatois et al. 2006). Accordingly, it seems reasonable to extend these units into the Azul Pampa region and to abandon the Casayok Sandstones and Azul Pampa Formation in order to simplify stratigraphic nomenclature. The Santa Victoria Group comprises the most abundant rocks in terms of outcrop area in the Azul Pampa region (65% of map area) (Fig. 1). The contact between both formations is not exposed. The Santa Rosita Formation consists of yellowish green and gray, fine- to very fine-grained sandstone and mudstone. The Acoite Formation is recessive and is dominated by thick intervals of dark-grey mudstone with minor amounts of very fine-grained sandstone.

The youngest rocks in the area are represented by the Balbuena Subgroup (Cretaceous-Tertiary) which overlies the Santa Victoria Group in faulted contact. The Balbuena Subgroup comprises the Lecho and Yacoraite formations (Gómez Omil 1983) and is exposed in the western zone of the Azul Pampa area in a synclinal structure oriented roughly N-S (Fig. 1).

SEDIMENTARY FACIES, DEPOSITIONAL ENVIRONMENTS AND STRATIGRAPHY

In this section the main sedimentary facies and depositional environments for each stratigraphic unit are described and interpreted. The fossil content and age of each unit is briefly evaluated also. Both physical (lithology, bed boundaries and physical sedimentary structures) and biogenic attributes were considered in the facies analysis. The latter includes a trace fossil study, including recognition and characterization of ichnofacies. Degree of bioturbation is assessed following Taylor and Goldring (1993). In this scheme, a bioturbation index (BI), ranging from 0 (no bioturbation) to 6 (complete bioturbation) is defined. Environmental zonation of estuarine deposits follows the scheme by Dalrymple et al. (1992), while that of MacEachern et al. (1999) is adopted for open marine settings. In this latter scheme, the offshore is defined as the area ranging from the fairweather wave base to the storm wave base, while the shelf extends from the storm wave base to the slope break. The most proximal zone of the offshore is referred to as the offshore transition.

MESÓN GROUP

The Mesón Group has historically been considered as Middle to Late Cambrian. However, a more critical evaluation of the available evidence indicates that no definitive indicator of a Late Cambrian age is present and, rather, it may range from the late Early to the Middle Cambrian (Mángano and Buatois 2004a, Buatois and Mángano 2005). Aceñolaza (2003) mentioned the presence of the Late Cambrian trilobite *Parabolina* (*Neoparabolina*) *frequens argentina* at Azul Pampa. However, Buatois and Mángano (2005, p. 67) showed that the host strata - part of what was originally regarded as the Chalhualmayoc Formation in this area (Fernández et al. 1982, Fernández 1983) - actually corresponds to the Santa Rosita Formation. This was accepted subsequently by Aceñolaza (2005, p. 74).

`Lizoite Formation:` The Lizoite Formation is restricted to the northeast corner of the Azul Pampa area, where it is approximately 15 m thick (no base exposed). It is made up of a single facies that consists of light-grey to light-pink, medium- to thick-bedded, large-scale planar cross-bedded, well-sorted, medium- to fine-grained quartzite, forming laterally extensive bedsets. Beds have erosive bases and reactivation surfaces are common. Bed tops are sharp or undulatory, revealing asymmetrical ripples. Individual beds are 20-40 cm thick. Bioturbation is absent.

This facies was recognized in previous sedimentologic studies of the Mesón Group and is interpreted as the result of high-energy tidal currents producing migrating two-dimensional dunes within a subtidal sandbar complex (Sánchez and Salfity 1990, 1999, Mángano and Buatois 2004b).

`Campanario Formation:` This unit, approximately 45 m thick, is patchily distributed in the Azul Pampa area. Of the five main sedimentary facies identified in this unit by Mángano and Buatois (2004b), only the "thinly interbedded sandstone and mudstone" facies is present. This facies consists of light-pink, tabular, fine- to very fine-grained sandstone and red mudstone with ripple cross-lamination and locally parallel lamination. Bed tops are undulating, showing symmetric, asymmetric and interference ripples. Wavy and flaser bedding are common. Individual beds are 5-25 cm thick. *Skolithos linearis* is the dominant trace fossil and the bioturbation index is typically moderate to high (BI = 2-4).

This facies records the alternation of tidal flood and ebb currents with slack-water periods in a middle intertidal, mixed-flat environment locally with channels (Mángano and Buatois 2004b). The Campanario For-

mation essentially records sedimentation in extensive intertidal areas and, to a lesser extent, shallow subtidal regions (Sánchez and Salfity 1990, 1999, Mángano and Buatois 2003a, 2004b). As noted in previous studies (e.g. Moya 1998, Mángano and Buatois 2004b), the Campanario Formation represents the most proximal unit of the Mesón Group, recording a regressive maximum during basin evolution.

Chalhualmayoc Formation: In the Azul Pampa area this unit is up to 70 m thick and dominated by a single facies that is almost identical to the one present in the Lizoite Formation. This facies consists of light-grey to light-pink, laterally extensive, planar to trough cross-bedded, well-sorted, medium - to fine-grained quartzite. Erosive bases and reactivation surfaces are common. Bed tops locally display asymmetrical and symmetrical ripples that are commonly out of phase with respect to the internal structure of the bed. Possible gutter and tool casts occur at the base of some sandstone beds. Individual beds are 20-35 cm thick. Bioturbation is rare, with local presence of *Skolithos linearis* (BI = 0-1). In places thick quartzite beds are separated by thinly-bedded, very fine-grained sandstone and parallel laminated mudstone layers. This facies was identified in previous studies (Sánchez and Salfity 1990, 1999, Mángano and Buatois 2004b) and is interpreted as the result of intense tidal currents that generated migrating two- and three-dimensional dunes within a subtidal sandbar complex.

SANTA VICTORIA GROUP

Santa Rosita Formation: Studies in other areas of Cordillera Oriental have subdivided the Santa Rosita Formation into different members (Moya 1988, Buatois and Mángano 2003, Buatois *et al*. 2006). In the Azul Pampa area the Pico de Halcón and Alfarcito members have been recognized. The bulk of the Santa Rosita Formation is included within the Cajas supersequence of Astini (2003). No fossils have been recorded in the Pico de Halcón Member, but regional correlations suggest a

Late Cambrian age (Buatois *et al*. 2006). Trilobites (*Angelina* sp., *Kainella* sp.), brachiopods (*Nanorthis calderensis*) and scarce graptolites (*Rhabdinopora flabelliformis* cf. *R. f. flabelliformis*) occur in the Alfarcito Member, suggesting a Lower Tremadocian age (Ortega and Albanesi 2005, Benedetto 2007, B. Waisfeld, J.L. Benedetto and G. Ortega, written communications). The Casayok Sandstones (= Santa Rosita Formation) had been regarded as entirely Tremadocian (e.g. Harrington and Leanza 1957, Fernández *et al*. 1982). Subsequent studies, however, demonstrated that this sedimentary cycle started by the Late Cambrian (e.g., Benedetto 1977, Moya *et al*. 1994, Moya and Albanesi 2000, Waisfeld and Vaccari 2003, Zeballo and Tortello 2005, Zeballo *et al*. 2005, Buatois *et al*. 2006).

- Pico de Halcón Member: Previously included within the Chalhualmayoc Formation (Fernández *et al*. 1982, Fernández 1983), this unit is present in Cerro Crestón where it is approximately 50 m thick, although its basal contact is not exposed (Fig. 2). Two main sedimentary facies have been recognized: (1) planar cross bedded and ripple cross-laminated sandstone and mudstone; and (2) thick bedded, planar cross bedded sandstone. The former is dominant in the lower half of the Cerro Crestón section while it tends to interbed with the latter in the upper half. It consists of interbedded light-grey, planar cross bedded and ripple cross-laminated, well sorted, fine- to very fine grained quartzose sandstone and parallel-laminated mudstone. Mud drapes (Fig. 3A) and syneresis cracks are abundant. Wavy bedding and convolute lamination are common. Microhummocky cross-stratified, very fine-grained sandstone with interference and symmetric ripples at the top occurs towards the uppermost part of the interval (Fig. 3B). Individual sandstone beds are 10-20 cm thick and mudstone intervals are 5-20 cm thick. *Skolithos linearis*, *Planolites montanus, Palaeophycus tubularis, Rusophycus carbonarius, Dimorphichnus* isp., and poorly preserved specimens of *Cruziana semiplicata* are present. *Skolithos linearis* commonly crosses thin microhummocky sandstone beds and penetrates into the underlying mudstone. Bioturbation intensity is variable (BI = 0-3).

There is a clear tendency to an upward increase in ichnodiversity and degree of bioturbation through the interval.

This facies is similar to facies C of Buatois and Mángano (2003) identified in the Quebrada de Humahuaca area. Tidal currents in upper subtidal to intertidal flat environments are the most likely depositional process and environmental setting for this facies. However, presence of microhummocky cross-stratified beds indicates subordinate storm action. Occurrence of *Skolithos linearis* penetrating mudstone suggests rapid consolidation of fine sediment and formation of relatively firm substrates. Syneresis cracks suggest salinity fluctuations, which is consistent with deposition in middle to outer zones of the estuary (Buatois and Mángano 2003).

The second facies consists of white, large-scale planar cross bedded, well sorted, medium- to fine grained quartzose sandstone beds. Mudstone partings are present locally. Herringbone cross bedding and trough cross bedding occur in places. Foresets are commonly grouped into bundled sets. Asymmetrical dunes are preserved on top of some beds. Bedsets may exhibit concave upward geometry, defining sigmoidal cross bedding and are separated by erosional, subparallel to inclined reactivation surfaces (Fig. 3C-D). This facies is generally nonbioturbated, but monospecific assemblages of *Skolithos linearis* or *Diplocraterion* isp. occur locally (BI = 0-3).

This facies is similar to facies F of Buatois and Mángano (2003) recognized in the Quebrada de Humahuaca area. The presence of reactivation surfaces, sigmoidal cross-bedding and herringbone cross-bedding suggests rapidly changing, high-energy, tidal currents (Buatois and Mángano 2003). This facies is interpreted as recording migrating two- and three-dimensional dunes within a subtidal sandbar complex developed in the mouth of a tide-dominated estuary.

The Pico de Halcón Member has been interpreted as having formed in a north-south trending, incised tide-dominated, fluvio-estuarine valley based on outcrops exposed in Quebrada de Humahuaca and adjacent areas (Buatois and Mángano 2003, Buatois *et al*. 2006). The base of the unit is not exposed in the Azul Pampa area, so informa-
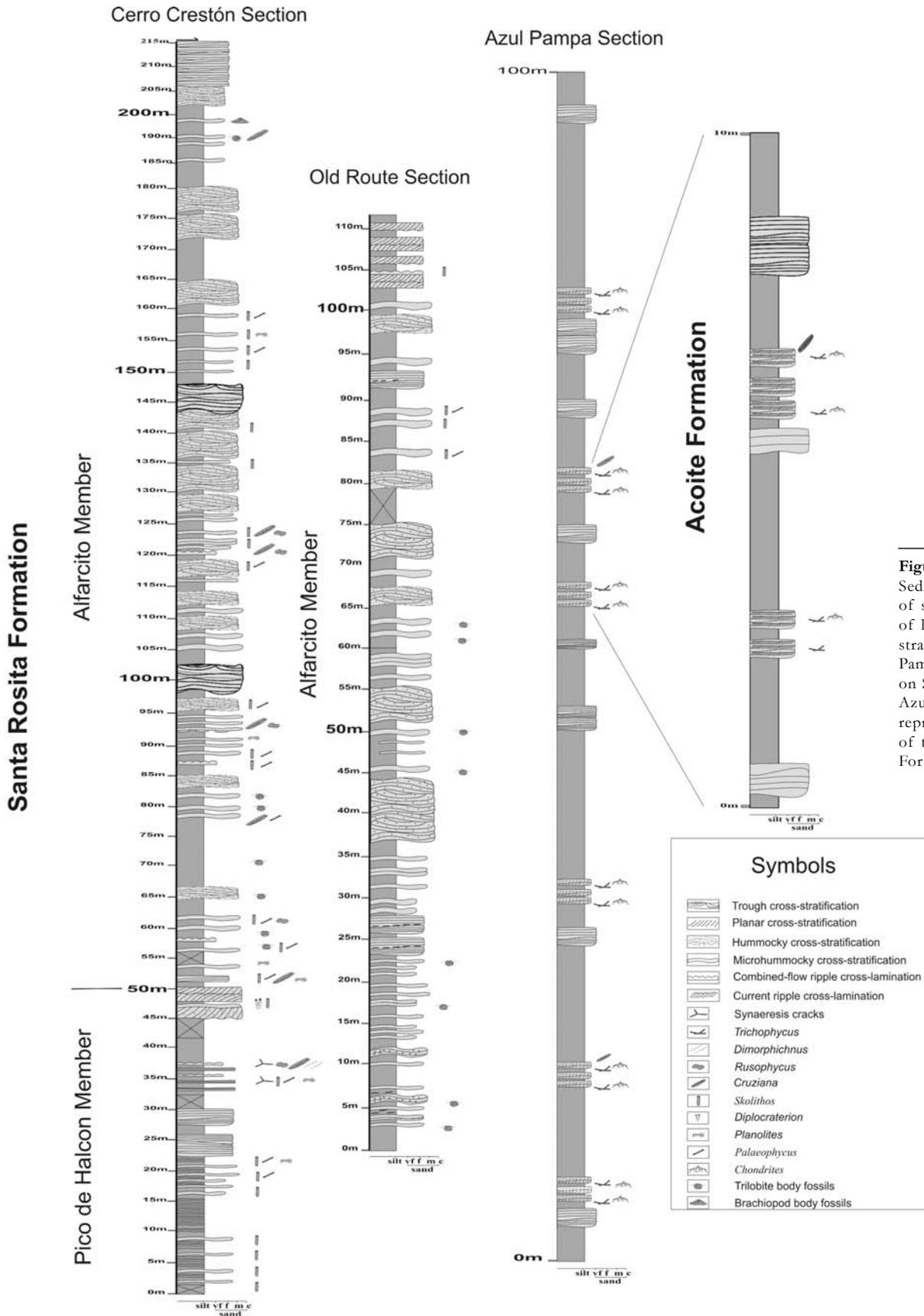
Figure 2: Sedimentologic logs of selected sections of lower Paleozoic strata in the Azul Pampa area (based on Such 2005). The Azul Pampa section represents only part of the Acoite Formation.
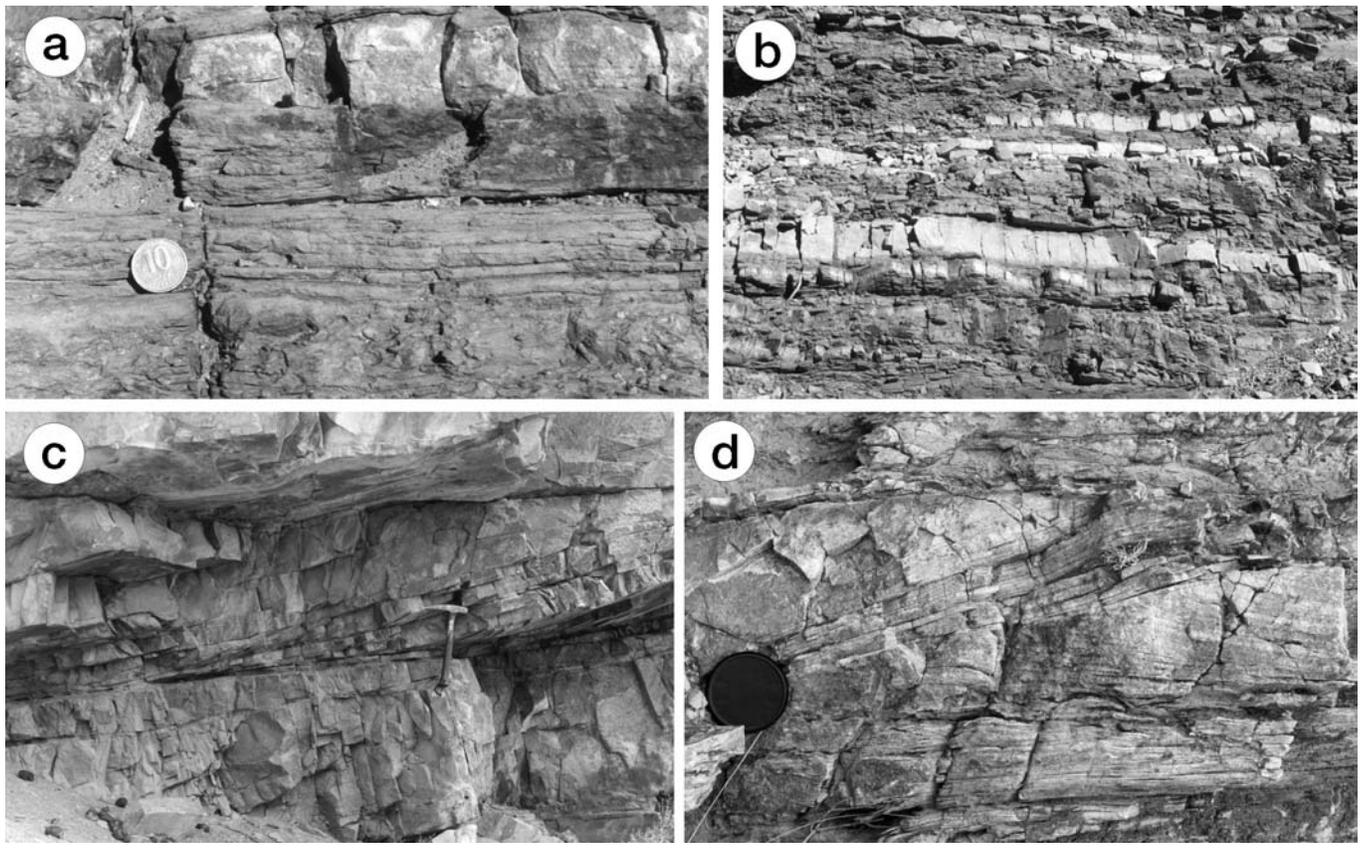
Figure 3: Sedimentary facies of the Pico de Halcón Member in the Azul Pampa area. a) Thin-bedded very fine-grained sandstone with mud drapes underlying a thick-bedded microhummocky cross-stratified sandstone. Middle to outer estuary. b) Interbedded mudstone and microhummocky cross-stratified, very fine-grained sandstone. Middle to outer estuary. c) Medium- to fine grained sandstone beds with bedsets defining large-scale sigmoidal cross stratification and separated by subparallel to inclined reactivation surfaces. Outer estuary subtidal sandbar. d) Planar cross bedded, medium- to fine grained sandstone beds showing two different dipping directions. Outer estuary subtidal sandbar. All photographs are from the Cerro Crestón locality. Lens cap diameter = 5.5 cm. Coin diameter = 1.8 cm.

tion on the incision surface is not available. The Cerro Crestón section most likely represents deposition in the middle and outer regions of the valley. The retrogradational vertical facies stacking pattern and the upward increase in ichnodiversity and degree of bioturbation suggests a transgressive infill, which is characteristic of incised estuarine valleys (Zaitlin *et al.* 1994). Large subtidal sandbars are particularly common in the seaward area of tide-dominated systems where tidal currents can be intense (Dalrymple *et al.* 1992, Dalrymple and Choi 2007).

- Alfarcito Member: This member crops out in Cerro Crestón where a relatively continuous, approximately 165 m thick succession is present (Fig. 2). The top of this unit is not exposed, however. Additional, scattered outcrops occur nearby the old road between 65°25'03.5"W and 22°58'55.6"S. The unit consists of five main facies: (1) mudstone; (2) mudstone with interbedded combined-flow cross-laminated rippled sandstone; (3) interbedded hummocky cross-stratified sandstone and mudstone; (4) amalgamated hummocky cross-stratified sandstone; and (5) trough cross-bedded sandstone.

Facies 1 consists of dark greenish-grey, tabular, parallel laminated mudstone (Fig. 4A). Light-greenish grey, sharp-based, tabular, thin (5-15 cm), very fine-grained silty sandstone beds, with combined-flow ripple cross-lamination, microhummocky cross-stratification and symmetric to near-symmetric ripple tops, are interbedded in places. Thick (up to 50 cm) hummocky cross-stratified beds occur rarely (Fig. 4A). Trilobites are locally present. Bioturbation is rare in this facies (BI = 0-1), commonly represented by scarce indistinct burrows on the base of sandstone beds. This facies compares with facies I of Buatois and Mángano (2003), which represents dominantly low energy, suspension fall out deposition punctuated by infrequent storms in lower offshore environments.

Facies 2 consists of parallel-laminated, dark greenish-grey mudstone with thin (individual layer are between 10 and 15 cm) light greenish gray, tabular, erosive-based, very fine grained silty sandstone. These sandstones display a wide variety of structures, such as parallel lamination, combined-flow ripple cross lamination, symmetrical to near-symmetrical ripples with rounded tops, microhummocky cross-stratification and hummocky cross-stratification. Wrinkle marks, gutter casts, load casts and tool marks are variably common. Trilobites are locally present and graptolites are rare. This facies contains a diverse assemblage of
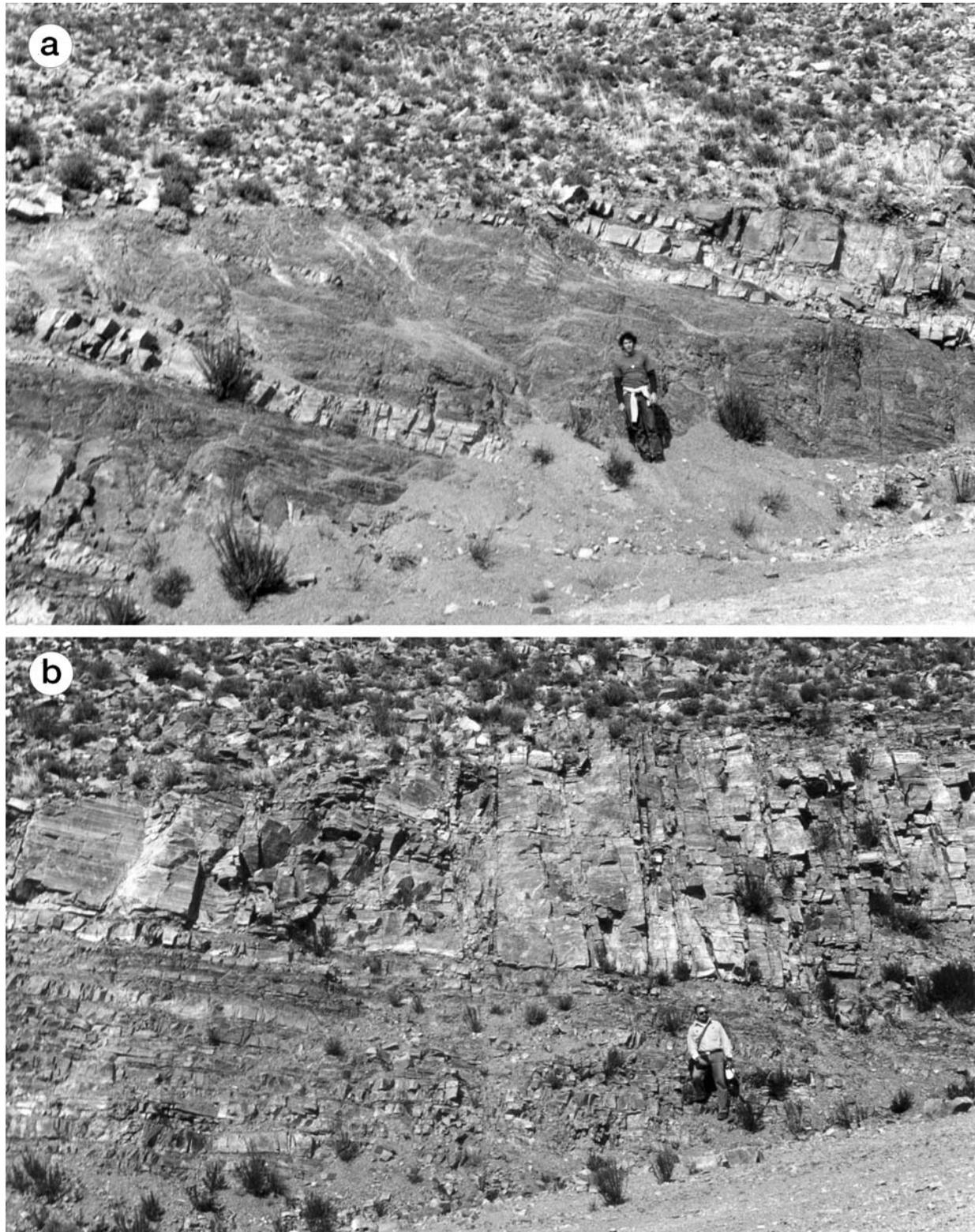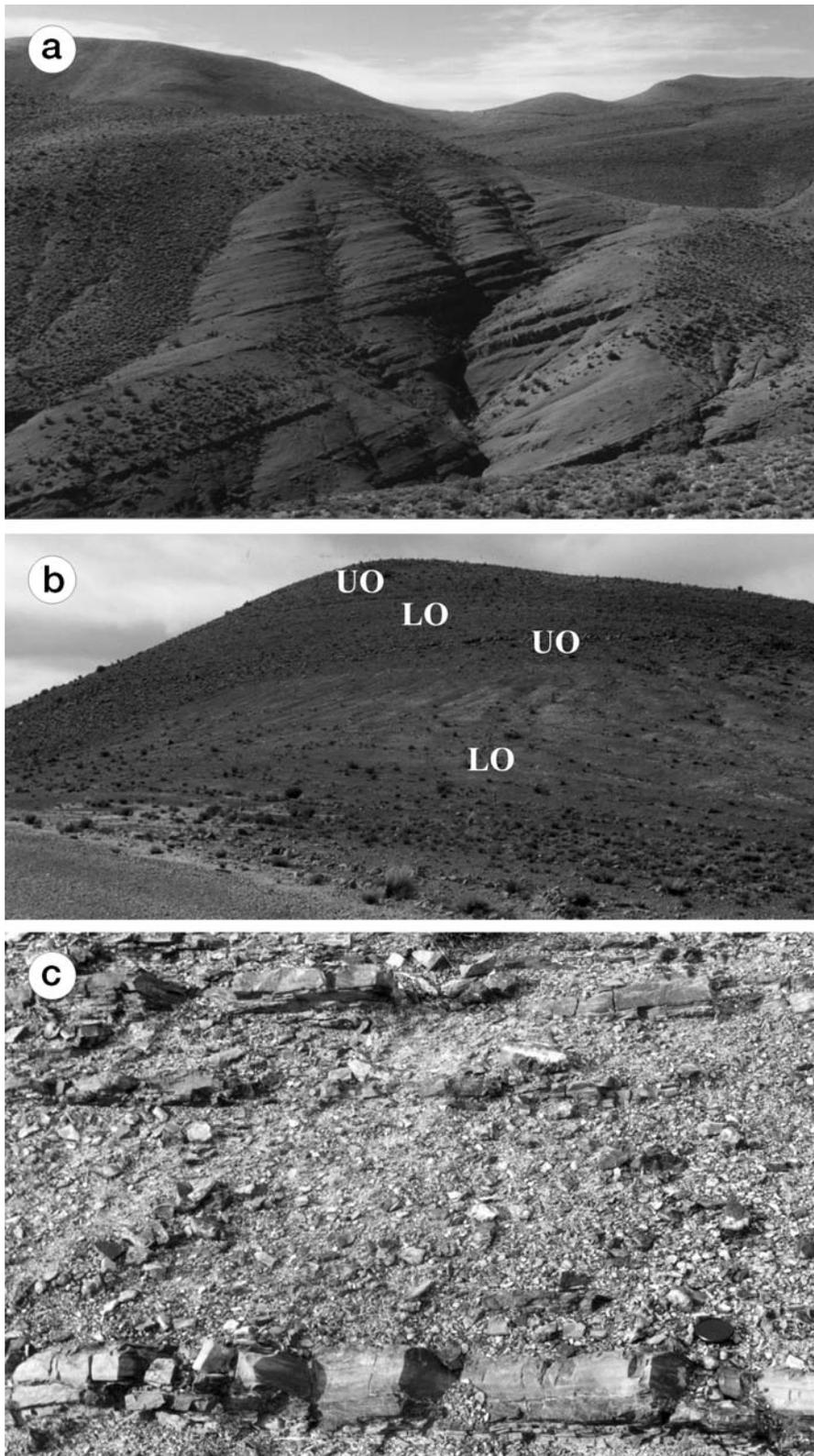
Figure 4: Sedimentary facies of the Alfarcito Member in the Azul Pampa area. a) Parallel-laminated mudstone with a thick hummocky cross-stratified sandstone bed reflecting an unusually large storm. Lower offshore. b) Regularly interbedded, fine- to very fine-grained hummocky cross-stratified sandstone and parallel-laminated mudstone (offshore transition) that pass upwards into amalgamated, hummocky cross-stratified, fine-grained sandstone (lower/middle shoreface). All photographs are from the old roadcut.

trace fossils, including *Skolithos linearis, Planolites montanus, Palaeophycus tubularis, Rusophycus carbonarius, R. moyensis, Rusophycus* isp., *Dimorphichnus* isp. and *Cruziana semiplicata*. However, because most of these trace fossils are preserved in lithologic interfaces,

degree of bioturbation is low to moderate (BI = 0-3). This facies is similar to facies J of Buatois and Mángano (2003), which records low-energy, suspension fall out deposition alternating with storm events in upper offshore environments.

Facies 3 consists of regularly interbedded, light greenish-grey, fine- to very fine-grained hummocky cross-stratified sandstone and parallel-laminated mudstone (Fig. 4b). Sandstone beds commonly contain combined-flow ripple cross lamination and symmetrical to near-symmetrical ripples occur at their tops. Sandstone beds are 20-55 cm thick and mudstones are 5-10 cm thick. Sandstone beds are laterally extensive, but display thickness variation. Gutter casts and tool marks are common. Soft sediment deformation structures, such as pseudonodules and ball and pillow, are locally abundant. Trilobites occur locally. *Skolithos linearis* and *Palaeophycus tubularis* are dominant, but trilobite trace fossils are also present (*Rusophycus moyensis, Cruziana semiplicata*). As in the case of facies 2, degree of bioturbation is low to moderate (BI = 0-2). This facies is similar to facies K of Buatois and Mángano (2003), which records the alternation of quiet-water sediment fall-out and combined and pure oscillatory flows mostly formed due to storms in an offshore transition setting.

Facies 4 consists of light greenish-grey, amalgamated hummocky cross-stratified, fine-grained sandstone (Fig. 4b). Each sandstone bed (35-50 cm thick) commonly pinches out, but sets of amalgamated beds (up to 2.5 m thick) are laterally persistent at the scale of hundreds of meters. Due to amal-

Figure 5: Sedimentary facies of the Acoite Formation in the Azul Pampa area. a) Alternating dark- and light-green, parallel-laminated mudstone (shelf) locally interbedded with intervals of parallel laminated mudstone and very thin to thin, very fine-grained silty sandstone beds (lower offshore). b) Parallel-laminated mudstone with scarce, very thin to thin, very fine-grained silty sandstone (lower offshore) (LO) locally interbedded with intervals containing thicker sandstone beds (upper offshore) (UO). c) Parallel-laminated mudstone alternating with thin, very fine-grained silty sandstone beds having combined-flow ripples and micro-hummocky cross-stratification (lower offshore). Lens cap diameter = 5.5 cm. All photographs are from the Azul Pampa locality.

gamation, internal second-order erosion surfaces separating hummocky cross-stratified laminasets are present. Millimeter-thick mudstone partings locally occur between sandstone beds. Scours, ball-and-pillow, pseudonodules, and load casts occur at the base of sandstones in places. Fragmented brachiopods, trilobites and crinoids occur forming layers at the base of beds. Trace fossils are rare and restricted to vertical burrows (*Skolithos linearis*) forming relatively dense occurrences (BI = 0-4). This facies is similar to facies L of Buatois and Mángano (2003) and records repeated storms and fairweather waves in lower to middle shoreface environments.

Facies 5 consists of light greenish-gray, 30-50 cm thick, tabular, erosive-based, trough and planar cross-bedded, fine-grained sandstone. Trace fossils are absent. A similar facies has been described by Buatois *et al.* (2006) in the Alfarcito Member in its type area. It is attributed to migration of two- and three-dimensional dunes in areas of channels and bars formed in an upper shoreface environment. The upper shoreface is subjected to multidirectional current flows in the build up and surf zones, where currents parallel to the shoreline interact with shoreline-normal currents producing variably-oriented subaqueous dunes (e.g. Clifton *et al.* 1971, Pemberton et al. 2001).

The Alfarcito Member in the Quebrada de Humahuaca and Alfarcito areas has been interpreted as formed in an open marine, shallow, low-gradient platform, affected by fairweather and storm waves (Buatois and Mángano 2003, Mángano *et al.* 2005, Buatois *et al.* 2006). A similar scenario is envisaged for the Azul Pampa area, including environments ranging from upper shoreface to lower offshore. Amalgamated and essentially nonbioturbated hummocky cross-stratified units indicate that the shoreface deposits of the Alfarcito Member were strongly storm-dominated. In comparison with coeval strata exposed further south and described previously (Buatois and Mángano 2003, Mángano *et al.* 2005, Buatois *et al.* 2006), deposits in the Azul Pampa area seem to have been formed in shallower water. Shelf black shale, such as that locally present south of the study area, is absent. Additionally, although upper shoreface

sandstones are present in the Alfarcito area, this facies seems to be more abundant in Azul Pampa. Overall, the sand-mud ratio of the Alfarcito Member in Azul Pampa is higher than in Quebrada de Humahuaca and Alfarcito, indicating a higher proportion of more proximal shoreface and offshore transition facies with respect to more distal offshore and shelf fines.

The sedimentary facies described are stacked forming regionally-extensive, wave-dominated, coarsening-upward parasequences like those documented by Mángano *et al.* (2005) south of the study area. Each parasequence reflects short-term seaward migrations of the shoreline separated by drowning events recording minor omission surfaces. The base of the Alfarcito Member is a low-energy drowning surface, representing flooding of the Pico de Halcón estuarine valley (Buatois and Mángano 2003). While most of the progradational events have been regarded as normal regressions, the sandstone-dominated part of the lower upward-coarsening and-thickening interval was considered as resulting from a forced regression in the Quebrada de Humahuaca and Alfarcito area (Buatois *et al.* 2006). A similar situation is apparent in the Cerro Crestón section where a rapid shift in facies was detected in direct association with soft sediment deformation structures. This surface is interpreted as a regressive surface of marine erosion that records the incision of a sharp-based, forced regressive shoreface (falling stage systems tract of Plint and Nummedal 2000).

Acoite Formation: Outcrops of the Acoite Formation are located nearby the Azul Pampa locality, forming a NW belt that can be traced for about 8 km (Fig. 1). This unit has been analyzed in detail in the Western Cordillera Oriental by Astini and Waisfeld (1993) and Astini *et al.* (2004). Its lower to middle Arenigian age is well established based on trilobites, graptolites, brachiopods and palynomorphs (Ottone *et al.* 1992, Toro 1994, 1996, 1997, Ortega and Rao 1995, Waisfeld 1995, Benedetto 1998, Astini *et al.* 2004). In the Azul Pampa area, the unit is more than 1000 m thick. Three main facies have been recognized: (1) black shale; (2) greenish gray mudstone; and (3)

mudstone with interbedded combined-flow cross-laminated rippled and hummocky cross-stratified sandstone.

Facies 1 is by far the most abundant and consists of alternating dark- and light-green, parallel-laminated mudstone forming very thick intervals (tens of meters) (Fig. 5A). These mudstone packages can be traced laterally at the scale of several kilometers. Trace fossils are absent. This facies represents suspension fallout in low-energy, shelf environments.

Facies 2 consists of dark- and light-green, parallel-laminated mudstone alternating with scarce, very thin to thin (1-15 cm), light-green, very fine-grained silty sandstone beds (Fig. 5a-c). These sandstone beds contain climbing and combined-flow ripple cross-lamination and microhummocky cross-stratification. Bed tops are undulating, commonly displaying symmetric to near-symmetric ripples. *Thalassinoides* isp., *Chondrites* isp., *Skolithos linearis, Trichophycus venosus* and *Cruziana rugosa* are the dominant trace fossils. Degree of bioturbation is commonly moderate to relatively high (BI = 2-4). Although mud suspension fallout was the dominant process, the local presence of storm-generated sandstones with combined and oscillatory flow structures indicates deposition above storm wave base. This facies is, therefore, interpreted as lower offshore deposits.

Facies 3 occurs in lower proportion and consists of dark- and light-green, parallel laminated mudstone interbedded with thin to medium-bedded (10-25 cm), light-green, tabular, erosive-based, very fine grained silty sandstone beds with climbing and combined-flow ripple cross lamination, microhummocky cross-stratification and hummocky cross-stratification (Fig. 5b). Bed tops commonly contain symmetrical to near-symmetrical ripples. Trace fossil content and degree of bioturbation is similar to that of facies 2. As in facies 2, this facies records alternation of mud suspension fallout and storm-generated oscillatory flows. However, the presence of thicker sandstone beds and the overall higher amounts of sand indicate shallower water, more specifically upper offshore environments.

As in the case of the Alfarcito Member,
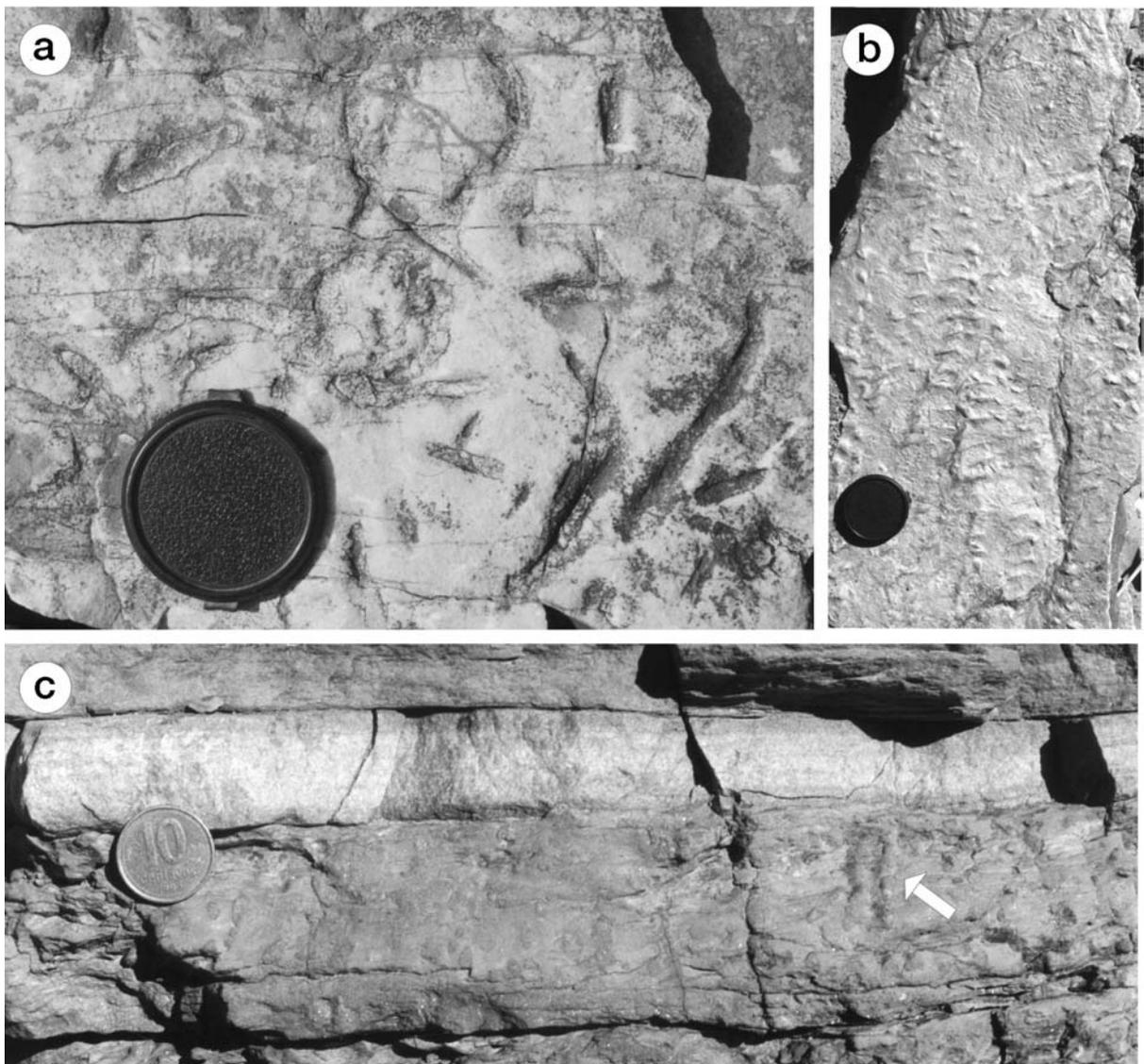
Figure 6: Selected trace fossils of the Pico de Halcón Member in the Azul Pampa area. a) Bedding plane view of *Diplocraterion* isp. b) *Dimorphichnus* isp. c) *Skolithos linearis* penetrating from thin storm sandstone into the underlying mudstone and passively filled with sand coming from the event bed. All photographs are from the Cerro Crestón locality. Lens cap diameter = 5.5 cm. Coin diameter = 1.8 cm.

deposits of the Acoite Formation accumulated in an open marine, low-gradient platform, affected by fairweather and storm waves. However, the Acoite Formation reflects deposition in more distal settings, ranging from the shelf to the upper offshore, and represents a maximum flooding event at the basin scale. The facies described are stacked forming regional, wave-dominated, coarsening-upward parasequences emplaced in a distal position. Strata from the Acoite Formation have been included within the Acoite supersequence (Astini 2003).

PALEOECOLOGICAL, ENVIRONMENTAL AND EVOLUTIONARY IMPLICATIONS OF THE ICHNOFAUNA

The paleobiologic, paleoecologic, sedimentologic and evolutionary significance of early Paleozoic ichnofaunas of northwestern Argentina has been the focus of recent study (Mángano and Buatois 2003b, Mángano *et al.* 2005). Earlier descriptions of trace fossil taxa from the Azul Pampa area (Aceñolaza and Fernández 1984, Fernández and Lisiak 1984) have been updated (Mán-

gano and Buatois 2003b) and selected ichnotaxa are illustrated in figures 6 and 7. The most significant aspects of the trace fossil distribution in the Azul Pampa region are summarized below.

`Absence or scarcity of biotur-`
`bation in high-energy settings:`
High-energy conditions dominate in shoreface and subtidal sandbar environments, usually precluding trace fossil preservation. Lower/middle shoreface deposits of the Alfarcito Member are only rarely bioturbated, while no trace fossils occur in the upper shoreface deposits at all. This is con-
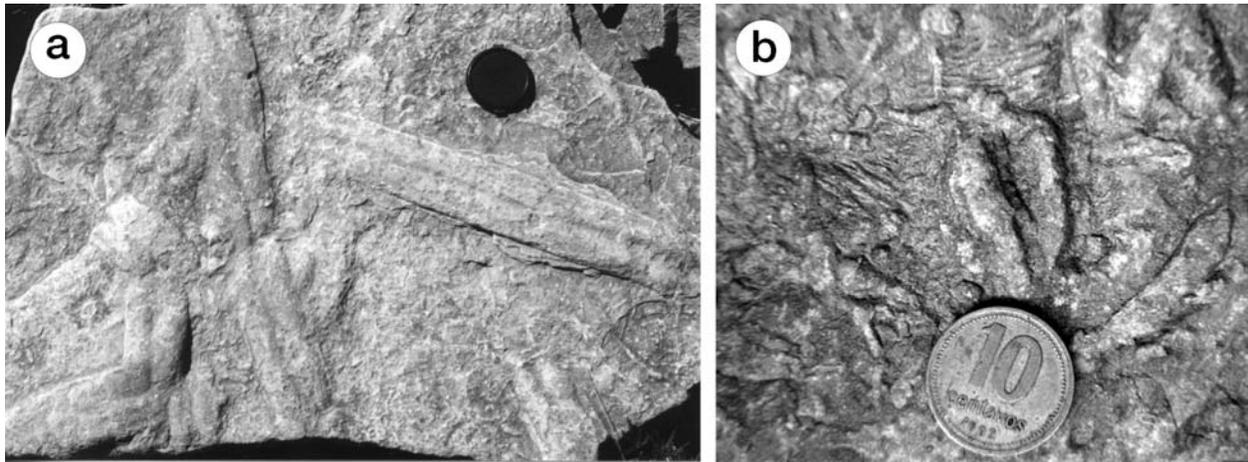
Figure 7: Selected trace fossils of the Alfarcito Member in the Azul Pampa area. a) *Cruziana semiplicata*. b) *Rusophycus* isp. All photographs are from the Cerro Crestón locality. Lens cap diameter = 5.5 cm. Coin diameter = 1.8 cm.

sistent with observations from this unit in the Quebrada de Humahuaca and Alfarcito region (Mángano *et al.* 2005, Buatois *et al.* 2006). In lower/middle shoreface environments, frequent storm-wave erosion precluded the establishment and/ or preservation of shallow- to midtier fairweather assemblages and, therefore, the trace fossil suites consist of vertical burrows (*Skolithos linearis*) that represent the activity of opportunistic colonization communities representing the *Skolithos* ichnofacies. The presence of rapidly migrating dunes and the strong scouring preclude establishment and/or preservation of biogenic structures in the upper shoreface. Subtidal sandbar deposits of the Pico de Halcón Member are also sparsely bioturbated, as is the case of outcrops of this unit in the Alfarcito area (Buatois *et al.* 2006). The ichnofauna is restricted to sporadic occurrences of monospecific assemblages of *Skolithos linearis* or *Diplocraterion* isp. (Fig. 6A), revealing bioturbation during short-term colonization windows. Similar ichnofaunas have been documented in other Cambrian-Ordovician subtidal sandbar deposits of northwest Argentina (Mángano *et al.* 1996, 2001, Mángano and Buatois 2003b, 2004b).

Increase in ichnodiversity along salinity gradients: Previous studies have documented rapid changes in ichnodiversity throughout the Santa Rosita Formation (Buatois and Mángano 2003, Mángano and Buatois 2003b). Alternations between tide-dominated (e.g. Pico de Halcón Member) and wave-dominated (e.g. Alfarcito Member) regimes are usually paralleled by dramatic changes in body and trace fossil diversity. Overall wave-dominated deposits tend to contain abundant and diverse body and trace fossil faunas, whereas tide-dominated deposits display poorly diverse trace fossil faunas and body fossils are scarce or simply absent (Mángano and Buatois 2006). This pattern further supports the interpretation of the Santa Rosita Formation as consisting of an alternation of laterally persistent, open-marine, wave-dominated strata punctuated by areally-restricted, tide-dominated incised fluvio-estuarine valleys (Buatois and Mángano 2003, Buatois *et al.* 2006). In the Pico de Halcón Member, a seaward increase in ichnodiversity is detected. The inner zone of the fluvio-estuarine valley is, in general, nonbioturbated and only a few trace fossils occur in the middle zone. Trace fossils are only abundant and relatively diverse in the outer zone of the estuary, essentially recording fully or almost fully marine conditions (Mángano and Buatois 2003b). Heterolithic facies of the outer estuarine zone contain ichnofaunas that are commonly dominated by trilobite trace fossils (Mángano and Buatois 2003b, Buatois and Mángano 2003). In the Azul Pampa area, a vertical increase in ichnodiversity is detected in the middle estuarine deposits that reveal progressively more marine conditions towards the top of the interval.

Abundance of firm substrates in Cambrian marginal-marine environments: Limited extent and depth of bioturbation during the Cambrian resulted in the widespread development of relatively firm substrates and the virtual absence of a mixed layer within the substrate (Droser *et al.* 2004, Jensen *et al.* 2005). This was particularly true during the Early Cambrian. Interestingly, the rapid formation of relatively firm substrates may have persisted during the rest of the Cambrian in stressful, restricted environments that lack intense bioturbation. Occurrence of *Skolithos linearis* penetrating estuarine mudstones (Fig. 6c) of the Pico de Halcón Member suggests quick consolidation of background fines and formation of relatively firm sediment. In contrast to firmground trace fossils at erosionally exhumed discontinuity surfaces, *Skolithos linearis* in the Pico de Halcón Member is unrelated to allostratigraphic surfaces. Burrows penetrate from thin tempestites into the underlying mudstone and are passively filled with sand coming from the event bed. Therefore, the only erosion involved was that related with scouring during the storm.

Increase in degree and depth of bioturbation through the Early Ordovician: Secular changes in bioturbation through the Ordovician have been the subject of much interest (e.g. Mángano and Buatois, 2003b; Mángano and Droser, 2004; Mángano *et al.*, 2005). In particular,

an increase in degree and depth of bioturbation through the Early Ordovician interval was recently noted for Upper Cambrian-Tremadocian deposits of the Santa Rosita Formation (Mángano and Buatois 2003b, Mángano *et al.* 2005), who contrasted the predepositional assemblages of Upper Cambrian-Lower Tremadocian with those in Upper Tremadocian storm-dominated upper offshore deposits. The older tempestites contain ichnofaunas reflecting a shallow-tiered community structure which defines an essentially bidimensional ichnofabric. By contrast, the younger tempestites exhibit a *Trichophycus* ichnofabric (= *Teichichnus* of Aceñolaza and Poiré 1998, 1999, or *Teichichnus-Trichophycus* of Albanesi and Aceñolaza 2005). This three-dimensional ichnofabric indicates more efficient ecospace utilization by deposit feeders that caused significant disruption of the primary sedimentary fabric. No Upper Tremadocian strata were identified in the Azul Pampa area. However, Arenigian upper offshore deposits having a pervasive *Trichophycus* ichnofabric occur in the Acoite Formation, supporting the proposed secular changes in bioturbation. Furthermore, the addition of middle-tier burrow systems attributed to *Thalassinoides* also contributes to increasing disruption of the primary sedimentary fabric.

CONCLUSIONS

1) The Mesón Group (Lower to Middle Cambrian) is the oldest unit in the Azul Pampa area and records shallow-marine sedimentation in a tide-dominated environment. More specifically, the Lizoite and Chalhualmayoc formations contain subtidal sandbar deposits while the Campanario Formation includes intertidal flat and channel deposits.

2) The abandonment of the older stratigraphic nomenclature (Casayok Sandstones and the Azul Pampa Formation) is recommended. These units are equivalent to the well-established and widely-accepted Santa Rosita Formation (Upper Cambrian to Tremadocian) and Acoite Formation (Arenigian), respectively.

3) The lower interval of the Santa Rosita Formation is represented by tide-domina-

ted estuarine deposits of the Pico de Halcón Member, whereas the upper interval is included in the Alfarcito Member and consists of wave-dominated shallow-marine deposits, ranging from the upper shoreface to the lower offshore.

4) The Acoite Formation records a basinwide maximum transgressive episode and is dominated by shelf deposits with subordinate offshore deposits.

5) Ichnologic information suggests an absence or scarcity of bioturbation in high-energy settings, an increase in ichnodiversity along salinity gradients, the abundance of firm substrates in Cambrian marginal-marine environments, and an increase in degree and depth of bioturbation through the Early Ordovician.

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