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DEPOSITIONAL ENVIRONMENTS AND STRATIGRAPHY OF THE UPPER CAMBRIAN-LOWER ORDOVICIAN SANTA ROSITA FORMATION AT THE ALFARCITO AREA, CORDILLERA ORIENTAL, ARGENTINA: INTEGRATION OF BIOSTRATIGRAPHIC DATA WITHIN A SEQUENCE STRATIGRAPHIC FRAMEWORK

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Abstract: The Upper Cambrian-Tremadocian rocks exposed in the Alfarcito area of Cordillera Oriental, northwest Argentina reveal a series of transgressive-regressive cycles punctuated by incision of fluvio-estuarine valleys. An integrated sedimentologic, biostratigraphic and sequence stratigraphic study permits characterization of the sedimentary facies and stratal stacking patterns, and a revision of the stratigraphic framework of this succession. The Upper Cambrian-Tremadocian succession is included within the existing Santa Rosita Formation, which is formally subdivided here into six units, the Tilcara, Casa Colorada, Pico de Halcón, Alfarcito, Rupasca and Humacha members. This scheme recognizes the internal complexities of the formation, in that the Tilcara and Pico de Halcón members record sedimentation in areally-restricted incised valleys and contain structures indicative of tidal dominance, whereas the Casa Colorada, Alfarcito and Rupasca members typify wave-dominated open-marine environments, where background suspension-fallout was punctuated by oscillatory flows during storms. The Tilcara Member is incised into the underlying Mesón Group. The Casa Colorada Member reflects a basinwide Late Cambrian transgression and subsequent progradation and consists of lower to upper offshore deposits. The Pico de Halcón Member is incised into the Casa Colorada Member. The Alfarcito Member is divided into three distinctly upward-coarsening and-thickening intervals. The sandstone-dominated intervals are composed of lower to middle shoreface deposits with minor amounts of offshore transition and upper shoreface deposits. The heterolithic, fine-grained intervals record more distal deposition, ranging from the lower offshore to the offshore transition. The Rupasca Member is a dominantly fine-grained unit that records a major late early to early late Tremadocian transgression. The lower interval of this member consists of lower offshore to offshore-transition deposits, while the upper part is made up of shelf to lower offshore deposits. The Humacha Member is not exposed in the study area. The importance of integrating biostratigraphy within a sedimentologic and sequence-stratigraphic framework is underscored here, in that it enables us to construct a more accurate stratigraphic framework which permits a clear understanding of the sedimentary dynamics of this system.

Resumen: El análisis de las rocas del Cámbrico Superior-Tremadociano aflorantes en el área de Alfarcito, Cordillera Oriental, noroeste de Argentina, revela una serie de ciclos transgresivos-regresivos e incisiones de valles fluvio-estuarinos. Un estudio sedimentológico, bioestratigráfico y estratigráfico-

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secuencial integrado proporciona información para caracterizar las facies sedimentarias, analizar los patrones de apilamiento estratal y revisar el marco estratigráfico de estas sucesiones. La sucesión cámbrica-tremadociana es incluida en la Formación Santa Rosita, la cual es formalmente subdividida en seis miembros, Tilcara, Casa Colorada, Pico de Halcón, Alfarcito, Rupasca y Humacha. De este modo, este esquema retiene para el área de Alfarcito una unidad estratigráfica ampliamente aceptada como la Formación Santa Rosita y al mismo tiempo reconoce las complejidades internas de la misma, subdividiéndola en miembros. Los miembros Tilcara y Pico de Halcón registran depositación en valles incisos restringidos arealmente y contienen estructuras indicadoras de dominio mareal. Por el contrario, los miembros Casa Colorada, Alfarcito y Rupasca tipifican sedimentación en ambientes marinos abiertos dominados por el oleaje, donde la sedimentación por decantación alternó con flujos oscilatorios generados durante tormentas. El Miembro Tilcara está inciso en el subyacente Grupo Mesón. El Miembro Casa Colorada refleja una transgresión cámbrica tardía a escala de cuenca y la subsecuente progradación. En el área de estudio, esta unidad está representada por depósitos de offshore inferior a transición a offshore. El Miembro Pico de Halcón está inciso sobre el Miembro Casa Colorada. El Miembro Alfarcito está dividido en tres intervalos muy distintivos grano y estratocrecientes. Los intervalos arenosos están dominados por depósitos de shoreface inferior a medio con proporciones menores de depósitos de transición a offshore y shoreface superior. Los depósitos de los intervalos heterolíticos de grano fino registran depositación en un ambiente más distal, desde el offshore inferior a la transición al offshore. El Miembro Rupasca es una unidad dominantemente de grano fino, que registra una transgresión mayor de edad tremadociana temprana tardía a tardía temprana. El intervalo inferior del Miembro Rupasca consiste en depósitos de offshore inferior a transición a offshore, mientras que el intervalo superior consiste en depósitos de plataforma a offshore inferior. El Miembro Humacha no se encuentra expuesto en el área. La importancia de integrar estudios bioestratigráficos dentro de un marco sedimentológico y estratigráfico-secuencial es resaltada en este estudio. Este enfoque es esencial para construir un marco estratigráfico y correlaciones más precisas que ayuden a clarificar la nomenclatura estratigráfica de la cuenca.

Keywords: Facies analysis, sequence stratigraphy, biostratigraphy, shallow marine, Cambrian-Ordovician, Argentina.
Palabras Claves: Análisis de facies, estratigrafía secuencial, bioestratigrafía, marino somero, Cámbrico-Ordovícico, Argentina.

INTRODUCTION

Extensive lower Paleozoic outcrops are present in the Cordillera Oriental of northwest Argentina. In many areas, however, the Cambrian-Ordovician succession is strongly affected by faulting and continuous sections are difficult to locate. Undoubtedly, this has precluded a detailed understanding of the stratigraphic framework of these successions. In recent years, however, a number of studies have tried to integrate sedimentologic information within a lithostratigraphic and genetic stratigraphic framework. Also, most earlier lithostratigraphic attempts assumed a layer-cake stratigraphy and only recently the importance of areally restricted, valley-fill sequences has been recognized (*e.g.*, Astini, 1994, 2003; Moya, 1998; Buatois *et al.*, 2000; Buatois and Mángano, 2003, 2005; Mángano and Buatois, 2004; Astini *et al.*, 2004). This recent approach has been essential in order to re-evaluate and redefine lithostratigraphic units (*e.g.*, Mángano and Buatois, 2004; Astini *et al.*, 2004). Additionally, in the case of the open- marine deposits, the existence of a number of transgressive-regressive cycles of deposition, displaying similar lithofacies characteristics but having different ages, which had eluded earlier regional studies, is revealed to be a critical motif. Further complications result from the fact that very few prior paleontologic and biostratigraphic efforts had attempted to provide a genetic framework for the fossil content (*e.g.*, Moya *et al.*, 2003; Buatois *et al.*, 2003; Ortega and Albanesi, 2005) and, therefore, the precise significance of many biostratigraphic data remained uncertain. Ultimately, this precluded accurate correlations and resulted in a proliferation of lithostratigraphic units, whose relevance is dubious. Biostratigraphic studies within an adequate sequence stratigraphic framework are essential to delineate more precise correlations that will help to simplify stratigraphic nomenclature. Although sequence stratigraphy and lithostratigraphy represent distinct approaches to the stratigraphic record, a dynamic understanding of stratal architecture, stacking patterns, and regional distribution of rock units is critical in order to construct a more accurate stratigraphic framework for Cambrian-Ordovician units of northwestern Argentina.

Upper Cambrian-Tremadocian strata exposed in the Quebrada de Humahuaca region and adjacent areas illustrate some of these problems. Originally considered as having formed in fully open marine environments, more recent studies have suggested that these strata reflect a complex depositional history, encompassing a wide range of sedimentary environments, such as fluvial, tide-dominated estuarine, and wave-dominated shallow-marine (Buatois and Mángano, 2003). These deposits are currently referred to the Santa Rosita Formation, one of the classical lower Paleozoic units of northwest Argentina. Although a general facies analysis has been presented recently (Buatois and Mángano, 2003), detailed knowledge of the internal architecture and pattern of stratal packaging is still limited and the stratigraphy of this unit proves to be more complex than originally envisaged. Also, exposures in the Alfarcito area, along the western margin of Sierra de Tilcara (Fig. 1), the type localities of some of the units regarded here as subdivisions of the Santa Rosita Formation (*e.g.*, the Tilcara, Casa Colorada, Alfarcito, and Rupasca members), have never been revisited with the exception of a series of recent studies by Zeballo *et al.* (2003, 2005a,b) and Zeballo and Tortello (2005). In our analysis, we integrate different lines of evidence from sedimentology, biostratigraphy, ichnology, sequence stratigraphy and lithostratigraphy. Based on this integrated approach, we propose a revised stratigraphic scheme for these successions. Accordingly, the aim of this paper is to: (1) describe and interpret the sedimentary facies of the Santa Rosita Formation in the Alfarcito area, (2) analyze the implications of the stratal stacking patterns to detect transgressive-regressive cycles, and (3) revise the stratigraphic framework of these successions.

GEOLOGIC AND STRATIGRAPHIC SETTING

The lower Paleozoic units in northwest Argentina in general accumulated in a retroarc foreland basin developed along the margin of western Gondwanaland (Ramos, 1999; Astini, 2003). Towards the Puna region, siliciclastic strata interfinger with volcanic and volcaniclastic rocks of the magmatic arc of the Faja Eruptiva de la Puna Occidental (Coira *et al.*, 1982; Bahlburg and Breitkreuz, 1991; Moya *et al.*, 1993; Ramos, 1999). The oldest evidence of the volcanic arc is early Tremadocian (Moya *et al.*, 1993). Thus, the

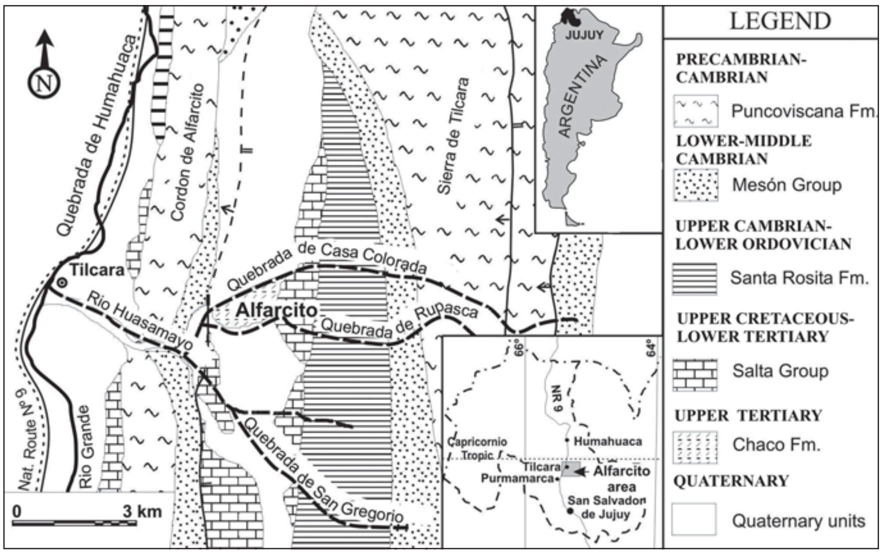


Figure 1. Geologic map of the Alfarcito area (modified from Zeballo *et al.*, 2003).
Figura 1. Mapa geológico del área de Alfarcito (modificado de Zeballo *et al.*, 2003).

tectonic setting of the Upper Cambrian is still uncertain. Lower Paleozoic strata were first deformed during the Middle to Late Ordovician Ocloyic Phase (Turner and Méndez, 1975), which resulted from the collision of the Antofalla-Belén-Arequipa terrane with Gondwanaland (Ramos, 1986, 2000; Forsythe *et al.*, 1993; Bahlburg and Hervé, 1997).

Astini (2003) integrated regional information on the Northwest Argentina Basin into a foreland basin model. In this scheme, five major zones can be distinguished: 1) the volcanic arc (Western Puna); 2) the tectonic wedge (Western Puna); 3) the foredeep (Eastern Puna); 4) the peripheral bulge (Cordillera Oriental), and 5) the back-bulge (Sierras Subandinas). Deep-marine turbidite systems fed from eastward prograding fan deltas were restricted to the foredeep region, while estuarine and deltaic systems with a source from the inner cratonic area dominated the back-bulge depositional zone. Deposition in the Cordillera Oriental region took place in ramp platforms formed in the forebulge area.

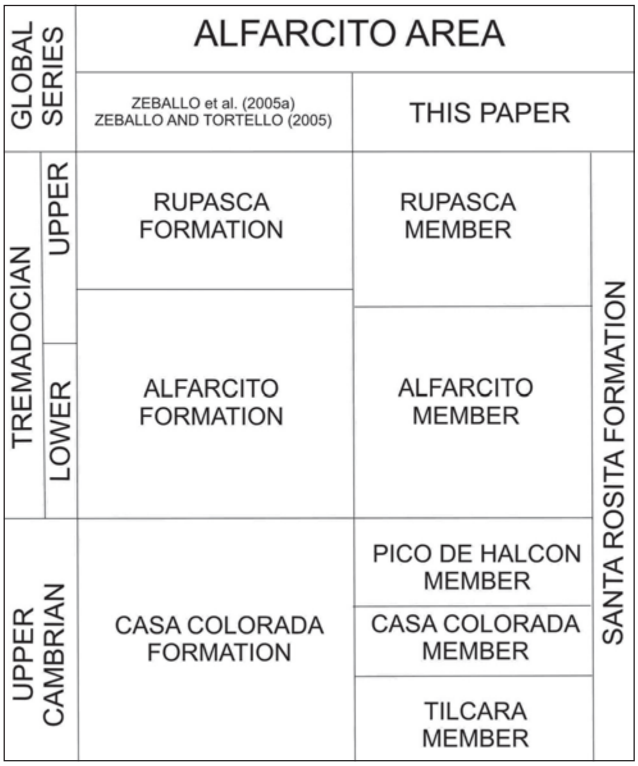


Figure 2. Stratigraphic nomenclature of the Cambrian-Ordovician rocks in the Alfarcito area, showing the correlation between the stratigraphic scheme used by Zeballo *et al.* (2003) and that proposed in this study.

Figura 2. Nomenclatura estratigráfica de las rocas del Cámbrico-Ordovícico del area de Alfarcito, mostrando la correlación entre el esquema estratigráfico usado por Zeballo *et al.* (2003) y el propuesto en este estudio.

The Santa Rosita Formation overlies the Cambrian Mesón Group and conformably underlies the Arenig Acoite Formation (Fig. 2). Both the Santa Rosita and Acoite formations are included in the Santa Victoria Group (Turner, 1960a). The contact between the Mesón Group and the Santa Rosita Formation has been interpreted variously as a regional unconformity resulting from the tectonic movements of the Iruyic Orogeny (*e.g.*, Turner, 1960a; Turner and Méndez, 1975; Moya, 1988), an unconformity due to a relative sea level fall (*e.g.*, Moya, 1998; Buatois *et al.*, 2000; Buatois and Mángano, 2003), or a conformable depositional transition (*e.g.*, Ruiz Huidobro, 1975; Fernández *et al.*, 1982; Tortello and Aceñolaza, 1999). In Cordón de Alfarcito, the contact is commonly strongly affected by faulting. However, in Quebrada de Rupasca and in other areas of the Cordillera Oriental as well, an unconformity due to valley incision produced by a relative sea level fall has been noted (Moya, 1998; Buatois and Mángano, 2003; Buatois *et al.*, 2003). The lower Paleozoic in the Alfarcito area is unconformably overlain by the Yacoraite Formation.

The Santa Rosita Formation and coeval units contain an abundant fossil fauna, composed of graptolites, trilobites, conodonts, brachiopods, gastropods, bivalves, cephalopods, echinoderms, ostracods, and acritarchs (*e.g.*, Harrington and Leanza, 1957; Waisfeld *et al.*, 1999; Rubinstein *et al.*, 2003; Brussa *et al.*, 2003; Waisfeld and Vaccari, 2003; Zeballo *et al.*, 2003, 2005a,b; Zeballo and Tortello, 2005). The Late Cambrian to Tremadocian age of the Santa Rosita Formation is well constrained, but the absence of detailed stratigraphic sections has historically precluded a more accurate biostratigraphic zonation and placing of the Cambrian-Tremadocian boundary (*cf.*, Rao and Hünicken, 1995; Rao, 1999). The maximum thickness of the Santa Rosita Formation, 2300 m, was recorded in the Sierra de Santa Victoria (Turner, 1960a), but detailed studies of the succession in that area have not been undertaken yet.

The stratigraphic nomenclature of Upper Cambrian to Tremadocian deposits in northwestern Argentina is inadequate. Several lithostratigraphic names were coined by Harrington (in Harrington and Leanza, 1957) as part of their classic study on Ordovician trilobites (Fig. 2), but lithologic descriptions were brief and no measured sections were provided. For the Alfarcito area, on the eastern side of Quebrada de Humahuaca, Harrington proposed the Casa Colorada shales, Alfarcito limestones and Rupasca shales to encompass what was then assumed to be entirely Tremadocian. The first two units were regarded as Lower Tremadocian, while the last was considered Upper Tremadocian. Harrington described the Casa Colorada shales as green, yellow and gray shale having a few thin sandstone interbeds carrying abundant *Parabolina argentina*. He defined the overlying Alfarcito limestones as consisting of thickly bedded limestone and calcareous sandstone with *Kainella meridionalis*, *Pseudokainella lata*, *Parabolinopsis mariana* and *Angelina hyeronimi*. The Rupasca shales were described by Harrington as dark gray shale having a few interbedded thin sandstones. According to this author, the trilobite fauna of this unit consists of *Pseudokainella keideli*, *Illaenopsis stenorhachis, Acerocarina glaber, Triarthrus tetragonalis, Parabolinopsis mariana, Parabolinella argentinensis* and *Plicatolina scalpta*. Harrington also introduced a stratigraphic scheme for the Sierra de Santa Victoria region, which hosts one of the thickest lower Paleozoic successions. He recognized the following units, from base to top: the Angosto Formation (lower Tremadocian), the Santa Cruz Formation (lower to upper Tremadocian), and the Acoite Formation (Arenigian). These units were questioned subsequently by Turner (1960a), who noted that the Angosto and Santa Cruz formations could not be distinguished in the field and coined the name Santa Rosita Formation for the whole Tremadocian succession.

In subsequent studies, the Santa Rosita Formation gained rapid acceptance and was extended to include coeval strata further south, including outcrops exposed in Quebrada de Humahuaca (*e.g.*, Turner and Méndez, 1975; Turner and Mon, 1979). However, López and Nullo (1969) gave formal formational rank to the units introduced by Harrington in the Alfarcito area and recognized them in adjacent zones along the Quebrada de Humahuaca. Their stratigraphic scheme was modified by Amengual and Zanettini (1974) who noted similarities between the lower and upper Tremadocian and assigned the whole stratal package to the Casa Colorada Formation, which became effectively a synonym of the Santa Rosita Formation. However, Moya (1988) recognized the internal complexities of this succession, retained Harrington´s units and added the Tilcara Formation as the basal unit and the Humacha Formation as the uppermost unit (see also Moya, 2003). This scheme was essentially adopted by Buatois and Mángano (2003), except they retained the widely accepted Santa Rosita Formation for the whole package and considered Tilcara, Casa Colorada, Alfarcito, Rupasca and Humacha as members (Fig. 1). We follow this scheme but introduce the Pico de Halcón Member (Fig. 2). Detailed biostratigraphic analysis of the Alfarcito area based on conodonts, graptolites and trilobites provides the temporal framework (see also Zeballo *et al.*, 2003, 2005a,b and Zeballo and Tortello, 2005). In the appendix the subdivision of the Santa Rosita Formation is formally proposed. The advantages of this approach are: 1) it retains for the area a widely accepted stratigraphic unit, such as the Santa Rosita Formation and 2) it recognizes its internal complexities by subdividing the succession into discrete members.

SEDIMENTARY FACIES, DEPOSITIONAL ENVIRONMENTS AND SEQUENCE STRATIGRAPHY

Description of the different sedimentary facies and interpretation of depositional environments in the Alfarcito area throughout the Santa Rosita Formation is summarized in Table 1. Sections were measured along several narrow creeks that drain the western slope of Sierra de Tilcara and individual rock units were walked out on the hillsides between the creeks. Additionally, sections measured in other areas of Quebrada de Humahuaca (e.g., Quebrada de Moya, Angosto del Morro de Chucalezna, Arroyo Sapagua, Quebrada de Abra Blanca, Quebrada del Salto Alto) and the western zone of Cordillera Oriental (e.g., Angosto del Moreno, Cangrejillos) were used for comparison and to check the regional extent of the units and discontinuity surfaces.

Environmental zonation of estuarine deposits follows the terminology of Dalrymple *et al.* (1992), while that of MacEachern *et al.* (1999) is adopted for open-marine wave-dominated environments. Overall the facies scheme is similar to that presented by Buatois and Mángano (2003), who recognized two main facies associations, one for the fluvio-estuarine deposits and the other one for the open-marine deposits (Fig. 3). The studied interval corresponds to the Cajas, Cardonal and Incamayo supersequences of Astini (2003).

Tilcara Member

The base of the Tilcara Member can be seen at the head of Quebrada de Rupasca where massive to rarely trough cross-bedded sandstone overlies planar cross-bedded quartzose sandstone of the Chalhualmayoc Formation. Maximum thickness recorded for this unit in the Alfarcito area is approximately 60 m (Fig. 4).

LITHOFACIES ASSOCIATION	LITHOFACIES	LITHOLOGY & SEDIMENTARY STRUCTURES	SEDIMENTARY PROCESSES & DEPOSITIONAL CONDITIONS	SEDIMENTARY ENVIRONMENT	DISTRIBUTION
Tide-Dominated Incised Valley	Massive to trough cross-bedded sandstone	Brown to gray, unbioturbated, massive to trough cross-stratified, thick-bedded, medium- to fine-grained sandstone. Current ripple cross-lamination in thinner sandstone beds. Scarce interbedded mudstone partings. Lenticular geometry. Convolute lamination and ball-and-pillow locally.	Tractive deposition from unidirectional currents. Scarce mud fall-out. Soft-sediment deformation.	Sandy braided fluvial system	Tilcara Member
	Massive or parallel laminated mudstone	Brown to gray, unbioturbated, massive to parallel laminated mudstone occasionally interbedded with very thin, very fine-grained silty sandstone. Lenticular bedding. Synaeresis and desiccation cracks. Laterally extensive intervals.	Suspension fall-out under low-energy conditions punctuated by tractive sand deposition due to tidal currents. Salinity fluctuations.	Middle estuarine mud flat	Tilcara and Pico de Halcón members
	Wavy-bedded sandstone and mudstone	White, ripple cross-laminated, very fine-grained quartzose sandstone interbedded with light gray mudstone. Wavy bedding. Straight and sinuous crested, symmetric and symmetric ripples. Mudstone drapes. Wrinkle marks and synaeresis cracks. Convolute lamination, ball-and-pillow and pseudonodules. Synaeresis cracks are common. Inclined heterolithic stratification. Rare trace fossils (depauperate *Cruziana* ichnofacies).	Erosion and sand deposition from tidal currents, mud fall-out during slack-water intervals, and subsequent reactivation and tractive sand deposition. Soft-sediment deformation. Salinity fluctuations.	Middle to outer estuarine mixed flat & Middle estuarine intertidal channels	Pico de Halcón Member
	Flaser-bedded, ripple-laminated and tabular cross-bedded sandstone	White, tabular cross-bedded and ripple cross-laminated, well-sorted, fine- and very fine-grained quartzose sandstone. Flaser bedding. Climbing and current ripple cross-lamination. Interference ripples. Near-symmetrical and asymmetrical ripples. Upper flow parallel stratification. Wrinkle marks and synaeresis cracks. Amalgamation surfaces, mudstone drapes, mudstone flakes and intraclasts. Herringbone cross-stratification. Rare to common trace fossils (depauperate *Cruziana* ichnofacies).	Erosion and sand deposition from tidal currents, mud fall-out during slack-water intervals, and subsequent reactivation and tractive sand deposition. Subordinate tidal currents strong enough to produce bedform migration. Salinity fluctuations.	Middle to outer estuarine upper subtidal to intertidal flats	Pico de Halcón Member
	Rhythmically laminated sandstone and mudstone	Greenish gray, very thinly laminated, greenish gray, mudstone and fine- to very fine-grained silty sandstone beds. Mudstone beds commonly silt-rich, although clay-rich intervals occur locally. Parallel lamination. Sandstone and mudstone couplets. Subordinate ripple-lamination. Wrinkle marks and synaeresis cracks. Symmetric cycles that thicken and coarsen, then thin and fine upward. Rare trace fossils (depauperate *Cruziana* ichnofacies).	Variations in tidal current speed during neap-spring tidal fluctuations. Salinity fluctuations.	Middle estuarine tidal rhythmites	Pico de Halcón Member
	Thick-bedded tabular cross-stratified sandstone	White, large scale tabular cross-stratified, well-sorted, medium- to fine-grained quartzose sandstone beds. Interbedded mudstone partings. Single and double mud drapes. Herringbone cross-bedding. Foresets grouped into bundle sets. Asymmetrical dunes. Smaller-scale ripples superimposed on the dunes. Bedsets may exhibit concave-upward geometry, defining sigmoidal cross-stratification and separated by erosional, subparallel to inclined reactivation surfaces. Rare trace fossils, although they may be common at reactivation surfaces (*Skolithos* ichnofacies).	Rapid, high energy, tidal currents. Significant subordinate tidal currents. Migrating two-dimensional dunes. Neap and spring tides.	Outer estuarine subtidal sandbar complex	Tilcara and Pico de Halcón members
Wave-dominated open marine	Black shale	Black, unbioturbated, thinly parallel laminated shale. Shale units laterally-extensive, displaying sharp bases.	Low energy, suspension fall-out deposition in the absence of waves and currents. Oxygen-depleted conditions.	Shelf	Alfarcito & Rupasca members

Table 1. Sedimentary facies of the Santa Rosita Formation in the Alfarcito area.
Tabla 1. Facies sedimentarias de la Formación Santa Rosita en el área de Alfarcito.

Wave-dominated open marine	Greenish gray mudstone	Greenish gray, massive or thinly parallel laminated mudstone. Mudstone units laterally-extensive, displaying sharp bases. Interbedded, gray, sharp-based, tabular, very thin, very fine-grained silty sandstone beds, exhibiting combined-flow ripple cross-lamination and symmetric to near-symmetric ripple tops. Subordinate very thin layers of normally graded siltstone. Rare trace fossils (distal *Cruziana* ichnofacies).	Low energy, suspension fall-out deposition punctuated by rare, storm events.	Lower offshore	Casa Colorada, Alfarcito & Rupasca members
	Mudstone with interbedded combined-flow rippled sandstone	Yellowish green and gray, parallel laminated mudstone with thin light gray, tabular, erosive-based, very fine-grained silty sandstone beds. Physical structures of interbedded sandstone layers highly variable. Common parallel lamination, combined-flow ripple cross-lamination and symmetrical to near-symmetrical ripples with rounded tops. Occasional microhummocky cross-stratification and current rippled cross-lamination. Gutter casts relatively common. Small load casts and tool marks are present locally. Abundant trace fossils (archetypal *Cruziana* ichnofacies).	Alternating background suspension fall-out and distal storm deposition. Sediment fall-out in a low energy setting punctuated by sporadic storm flows.	Upper offshore	Casa Colorada, Alfarcito & Rupasca members
	Interbedded hummocky cross-stratified sandstone and mudstone	Regularly interbedded, yellowish green and gray, parallel laminated mudstone and thin to thick, light gray, erosive-based, fine- to very fine-grained sandstone with hummocky cross-stratification, combined-flow ripple cross-lamination and/or symmetrical to near-symmetrical ripples at the top. Sandstone beds laterally extensive, although displaying thickness variation. Hummocky cross-stratification dominant in the thickest sandstone beds. Combined-flow ripple cross-lamination dominant in the thinnest beds. Amalgamation of hummocky beds uncommon. Common shell lags and intraclast layers at the base of hummocky beds. Occasional unidirectional climbing-ripple cross-lamination overlying a hummocky zone. Combined-flow ripples with rounded profiles and interference ripples commonly present at the top of hummocky beds. Rare convolute lamination and wrinkle marks. Common gutter casts displaying a wide variety of morphologies. Rare tool marks and pot casts. Abundant trace fossils (archetypal *Cruziana* ichnofacies).	Alternation of quiet-water sediment fall-out and combined and pure oscillatory flows due to frequent storms. Accretionary growths of hummocks. Temporary reworking by waves as storms waned. Diverse erosional processes, such as oscillatory flows, unidirectional flows, vortex flows, and combined flows, involved in gutter cast generation.	Offshore transition	Alfarcito & Rupasca members
	Amalgamated hummocky cross-stratified sandstone	Light gray, hummocky cross-stratified, fine-grained sandstone forming amalgamated packages. Individual sandstone beds generally pinch out, but bedsets laterally persistent. Internal second-order erosion surfaces separating hummocky cross-stratified laminasets. Rare and thin mudstone partings. Scours, ball-and-pillow, and load casts common at the base of sandstones. Shells locally forming moderately thick layers at the base of sandstone beds and concentrations along truncation surfaces within the bed. Rippled tops rare. Rare trace fossils (*Skolithos* ichnofacies).	Episodic storm wave activity and wave-generated surges High-energy oscillatory and combined flows during frequent storms. Strong erosive flows and rapid influx of sand. Accretionary growths hummocks.	Lower-middle shoreface	Alfarcito Member
	Trough cross-bedded sandstone	Light gray, unbioturbated trough cross-bedded, well sorted fine- to medium-grained sandstone. Erosive bases and scours. Laterally extensive units.	Strong erosive events and variably oriented unidirectional currents leading to migration of 3D dunes.	Upper shoreface	Alfarcito Member

Table 1. *Continuation.*
Tabla 1. *Continuación.*

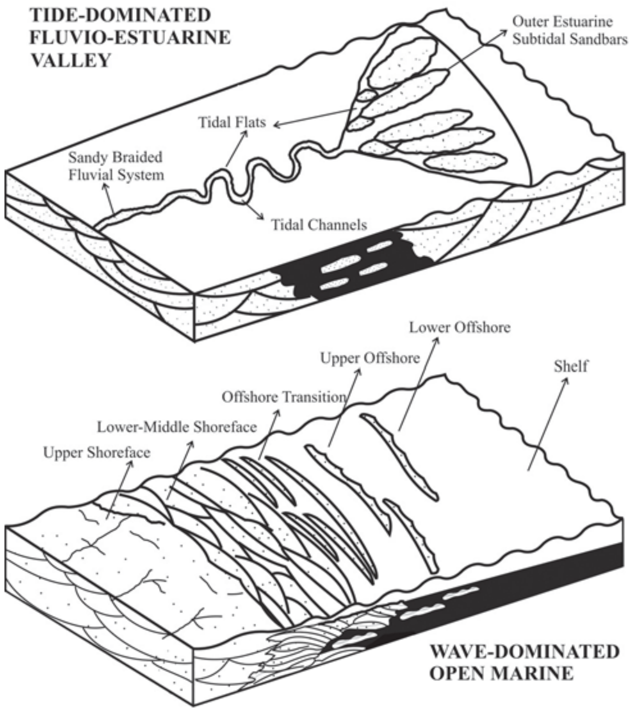


Figure 3. Depositional model of the Santa Rosita Formation, showing tide-dominated incised valley and wave-dominated open marine lithofacies associations (modified from Buatois and Mángano, 2003).
Figura 3. Modelo depositacional de la Formación Santa Rosita, mostrando las asociaciones de litofacies de valle inciso dominado por mareas y de mar abierto dominado por olas (modificado de Buatois y Mángano, 2003).

Stratal packages included here in the Tilcara Member were either unrecognized by Harrington (in Harrington and Leanza, 1957) or included within the Casa Colorada Member or the Mesón Group. The Tilcara Member is dominated by three main lithofacies: 1) massive to trough cross-bedded sandstone (sandy braided rivers); 2) massive or parallel-laminated mudstone with interbedded cross-laminated sandstone (estuarine tidal flats), and 3) thick bedded tabular cross stratified sandstone (subtidal sandbars).

The Tilcara Member represents the infill of a valley that was incised into the underlying Mesón Group during a relative fall of sea level (Moya, 1998; Mángano and Buatois, 2004). It is subdivided into three intervals: a lower sandstone-dominated interval, a middle mudstone-dominated interval and an upper sandstone-dominated interval. The massive to trough cross-bedded sandstone lithofacies comprises the lower interval, while the massive or parallel laminated mudstone and the thick bedded tabular cross stratified sandstone make up the bulk of the middle and upper interval, respectively. The lower sandstone-dominated interval records deposition in a sandy braided fluvial system. The middle mudstone-dominated interval is poorly exposed in the study area and consists of a symmetric cycle that thins and fines upward, and then, thickens and coarsens upward. This interval records sedimentation in tide-influenced regions of the valley, most likely the low-energy middle zone, characterized by fine-grained deposition. The upper sandstone-dominated interval represents tidal sedimentation at the seaward, high energy end of the valley. Therefore, the Tilcara Member illustrates the tripartite division (sand-mud-sand) commonly displayed by incised valleys filled during transgressive episodes. As noted by Rahmani (1988) and Dalrymple *et al*. (1992), this division results from energy distribution along estuarine valleys defining three major zones: an inner, river-dominated zone, a central zone where marine energy is dissipated by fluvial currents, and an outer zone dominated by marine processes. Fluvial sandstones in the lower interval represent lowstand strata, while the rest of the member comprises backstepping deposits of the transgressive systems tract, culminating in open-marine deposits of the Casa Colorada Member.

The absence of diagnostic fossils precludes a precise age determination for the Tilcara Member. Its stratigraphic position immediately below the Late Cambrian Casa Colorada Member indicates that the Tilcara Member is not younger than Late Cambrian (Mángano and Buatois, 2004).

Casa Colorada Member

The Casa Colorada Member is up to 85 m thick in the study area (Fig. 6). Notably, this unit is affected by a fault and poorly exposed in Quebrada de Casa Colorada. Two main lithofacies are dominant: 1) greenish gray mudstone (lower offshore) and 2) mudstone with interbedded combined-flow rippled sandstone (upper offshore).

In contrast to the associated tide-dominated Tilcara and Pico de Halcón members, the Casa Colorada Member records dominance of wave processes, representing the establishment of an open-marine, shallow platform affected by fairweather and storm waves. In this shallow sea, background sedimentation was punctuated by oscillatory flows during storms. The two lithofacies are stacked forming upward coarsening and thickening distal parasequences that record short-term

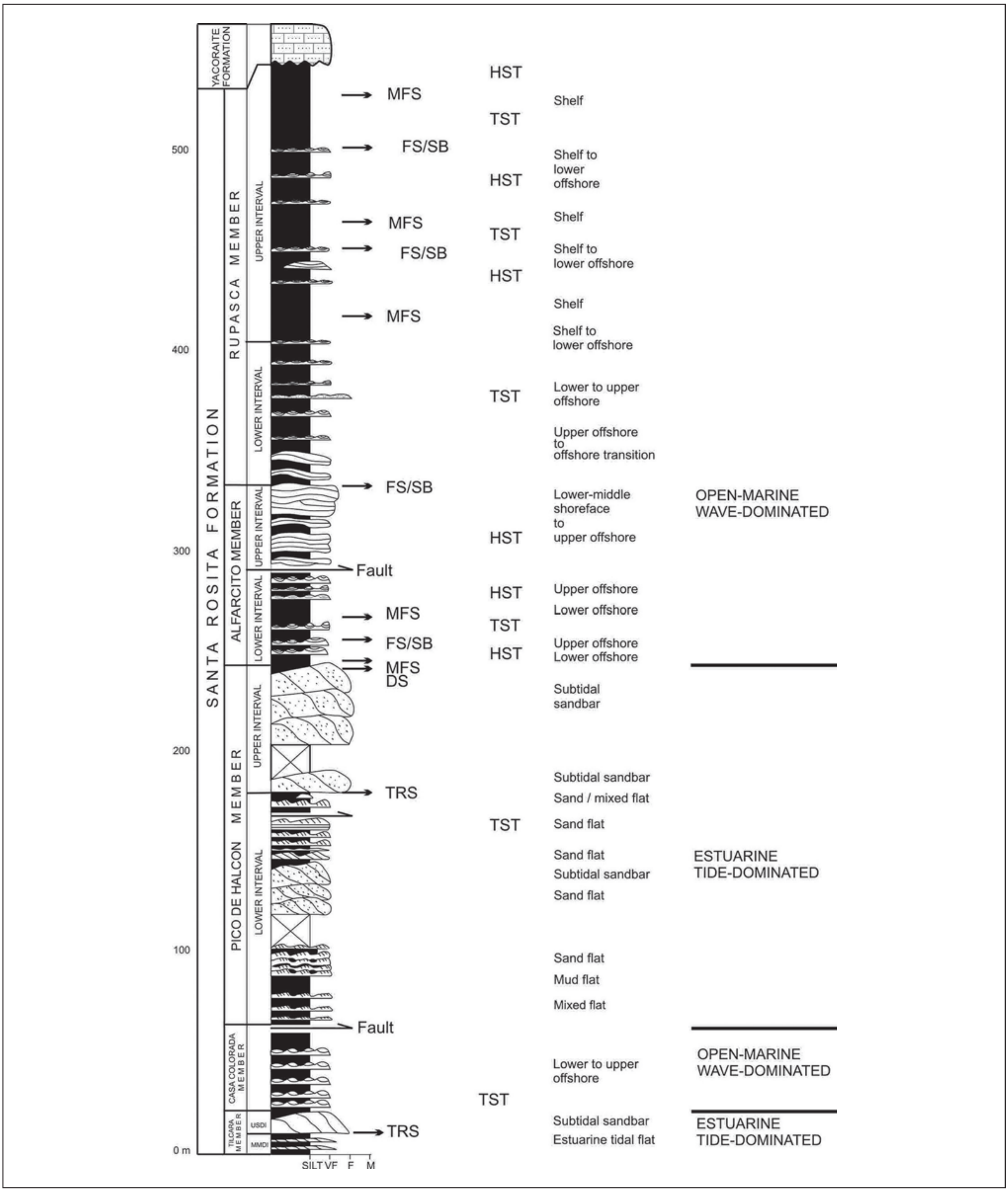


Figure 4. Stratigraphic section of the Santa Rosita Formation at Quebrada de Casa Colorada. TRS = tidal ravinement surface, DS = drowning surface, FS/SB = co-planar surface of marine flooding and sequence boundary, MFS = maximum flooding surface, TST = transgressive systems tract, HST = highstand systems tract. Tilcara Member: MMDI = middle mudstone-dominated interval, USDI = upper sandstone-dominated interval.

Figura 4. Sección estratigráfica de la Formación Santa Rosita en la quebrada de Casa Colorada. TRS = superficie de ravinamiento de mareas, DS = superficie de ahogo, FS/SB = superficie co-planar de inundación marina y límite de secuencia, MFS = superficie de máxima inundación, TST = cortejo depositacional transgresivo, HST = cortejo depositacional de nivel del mar alto. Miembro Tilcara: MMDI = intervalo medio dominado por pelitas, USDI = intervalo superior dominado por areniscas.

progradational pulses. The lowermost beds of the Casa Colorada Member record a basinwide transgression and the ultimate flooding of the estuarine valley, representing the late stage of the transgressive systems tract expressed by the Tilcara Member. The upper interval is represented by highstand deposits and consists of an aggradational to progradational parasequence set, which includes deposits that range from lower offshore into upper offshore.

The age of the Casa Colorada Member is constrained due to the recognition of the *Parabolina frequens argentina* trilobite zone, which suggests a Late Cambrian age (Zeballo and Tortello, 2005).

Pico de Halcón Member

The Pico de Halcón Member varies from 53 to 180 m in thickness. These strata were probably included in the Casa Colorada Member by Harrington, explaining the great thickness (250 m) he recorded for that unit. Strata exposed in Quebrada de Moya and Quebrada del Salto Alto previously included in the Tilcara Member by Buatois and Mángano (2003) are now referred to the newly defined Pico de Halcón Member. [*Derivatio nominis*: The name Pico de Halcón Member is derived from the science fiction short novel «Hawksbill Station» by Robert Silverberg. In that story Hawksbill (translated as: Pico de Halcón) is a Cambrian station where the political dissidents and all those who opposed authority were sent off by means of a time machine]. The lower interval is dominated by four lithofacies (Fig. 5a-e): 1) massive or parallel-laminated mudstone (mud flats), 2) wavy-bedded sandstone and mudstone (mixed flats), 3) flaser-bedded, ripple-laminated and tabular cross bedded sandstone (upper subtidal to intertidal flats), and 4) rhythmically laminated sandstone and mudstone (tidal rhythmites). A fifth lithofacies, thick bedded tabular cross stratified sandstone (subtidal sandbars), occurs less commonly and forms discrete packages (Fig. 5f-h). The upper interval of the Pico de Halcón Member consists primarily of this last lithofacies, forming intervals up to 40 m thick.

Regional observations suggest that the Pico de Halcón Member represents the infill of a valley incised into the underlying Casa Colorada Member during a relative fall of sea level. Valley morphology is also supported by the remarkable thickness variations of the Pico de Halcón Member in the Alfarcito area. The most diagnostic feature of the unit is the presence of structures indicative of tidal dominance in an estuarine setting. No lowstand deposits are recognized in the study area, suggesting the entire member forms the transgressive systems tract. Accordingly, the base of the Pico de Halcón Member is regarded as a co-planar surface or flooding surface/sequence boundary (FS/SB). The lower interval in the Alfarcito area records deposition mostly in the middle reaches of the valley. This middle zone is typically fine grained and is represented by a rhythmic alternation of very fine-grained sandstone and mudstone beds. These deposits are locally cut by intertidal runoff channels with inclined heterolithic stratification. These lithofacies are typically stacked forming upward thinning and fining parasequences, thought to record tidal-flat progradation. The upper interval represents the establishment of an outer estuary subtidal sandbar complex.

Overall the Pico de Halcón Member is characterized by backstepping middle to outer estuarine deposits that in turn are overlain by the open-marine deposits of the Alfarcito Member, forming a transgressive succession. The remarkable contrast between the areally restricted, tide-dominated deposits of the Pico de Halcón Member and the regionally extensive, wave-dominated deposits of the Casa Colorada and Alfarcito members is linked to valley morphology, in that a small cross-sectional zone along which tidal currents are forced may have amplified tidal range (*cf.* Wells, 1995).

The absence of diagnostic fossils precludes a precise age determination for the Pico de Halcón Member. However, regional correlations suggest a Late Cambrian age.

Alfarcito Member

The Alfarcito Member is 265 m thick, which corroborates the 260 m estimated by Harrington. Although he did not mention fine-grained mudstone interbedded with the coarse-grained deposits, the thickness estimated suggests that several successive transgressive-regressive cycles were included in the unit. In later studies in Quebrada de Moya and Angosto del Morro de Chucalezna, the heterolithic fine-grained deposits that are regarded here as the lowermost interval of the Alfarcito Member were included in the Casa Colorada Member (Aceñolaza, 1996a, 2003; Mángano *et al*., 2002; Rubinstein *et al*., 2003; Buatois and Mángano, 2003; Aráoz and Vergel, 2006). Notably, the Alfarcito Member is affected by a fault in Quebrada de Casa Colorada, where only the lower interval is exposed. In other areas, such as Quebrada de Rupasca, this unit is very well exposed and continuous (Fig. 6).

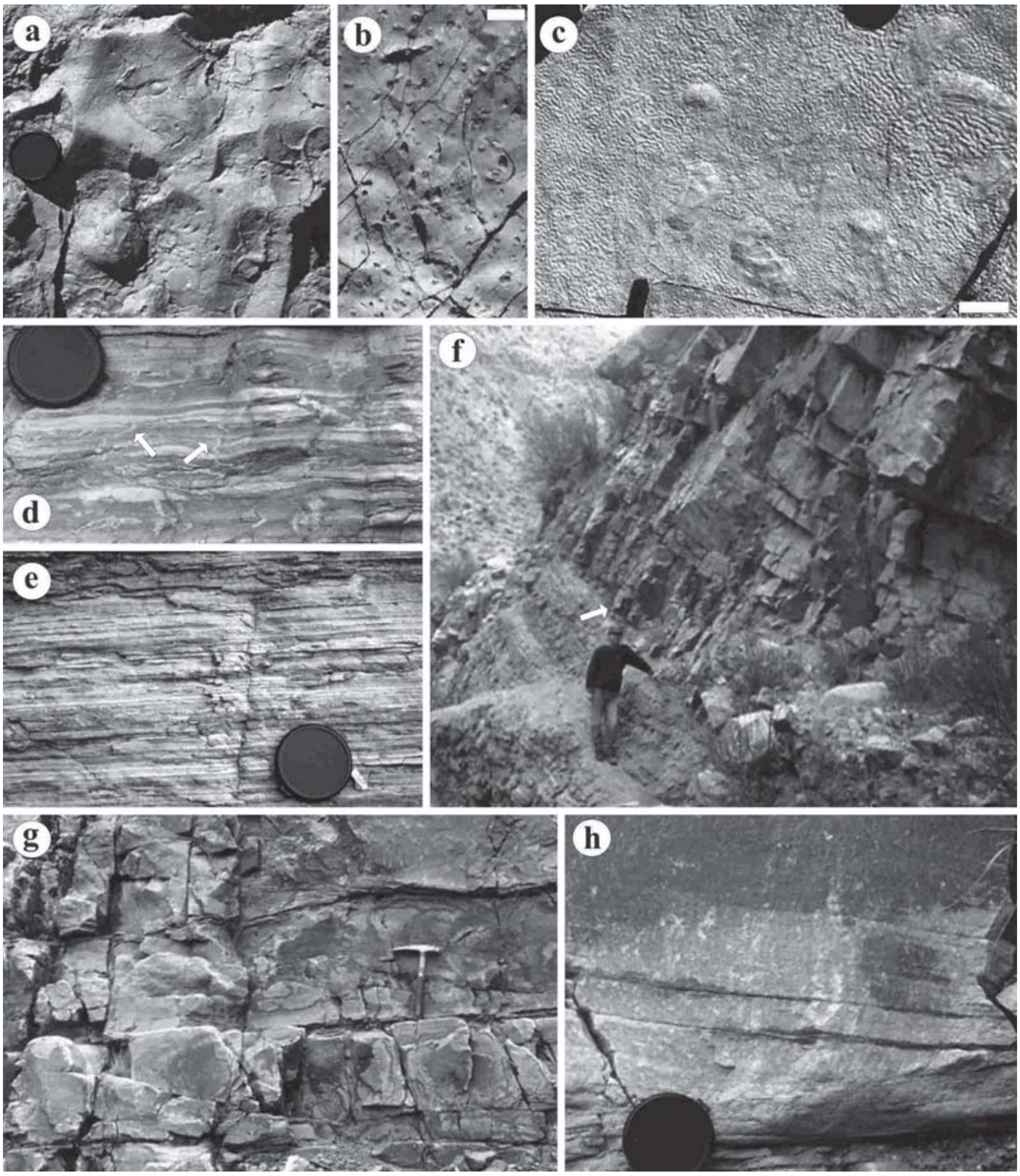


Figure 5. Sedimentary facies of the Pico de Halcón Member. a) Sandstone bedding plane showing interference ripples and synaeresis cracks. Estuarine intertidal sand flat. Quebrada de Rupasca. Lens cover = 5.5 cm. b) High density of *Skolithos linearis* on rippled sandstone top. Estuarine intertidal sand flat. Quebrada de Rupasca. Scale bar = 5 cm. c) Wrinkle marks and relict troughs. Estuarine intertidal sand flat. Quebrada de Rupasca. Scale bar = 5 cm. d) Sandstone and mudstone interbeds showing wavy and lenticular bedding and synaeresis cracks (arrows). Estuarine intertidal mixed flat. Quebrada de Casa Colorada. Lens cover = 5.5 cm. e) Interlaminated sandstone and mudstone. Estuarine tidal rhythmites. Quebrada de Casa Colorada. Lens cover = 5.5 cm. f) Contact between fine-grained middle estuarine deposits and lower estuarine subtidal sandbar deposits. The surface (arrow) is a tidal ravinement surface. Quebrada de Casa Colorada. g) Close-up of subtidal sandbar deposits showing large-scale, planar cross-stratification. Quebrada de Casa Colorada. h) Mud drapes along foresets. Subtidal sandbar complex. Quebrada de Casa Colorada. Lens cover = 5.5 cm.

Figura 5. Facies sedimentarias del Miembro Pico de Halcón. a) Plano de estratificación en una arenisca mostrando óndulas de interferencia y grietas de sinéresis. Planicie arenosa intermareal estuarina. Quebrada de Rupasca. Cubre lente = 5,5 cm. b) Alta densidad de *Skolithos linearis* sobre un tope de arenisca con óndulas. Planicie arenosa intermareal estuarina. Quebrada de Rupasca. Barra de escala = 5 cm. c) Marcas de corrugamiento y senos relícticos. Planicie arenosa intermareal estuarina. Quebrada de Rupasca. Barra de escala = 5 cm. d) Intercalaciones de arenisca y pelita con estratificación ondulosa y lenticular, y grietas de sinéresis (flechas). Planicie mixta intermareal estuarina. Quebrada de Casa Colorada. Cubre lente = 5,5 cm. e) Arenisca y pelita interlaminadas. Ritmitas mareales estuarinas. Quebrada de Casa Colorada. Cubre lente = 5,5 cm. f) Contacto entre los depósitos estuarinos medios de grano fino y los depósitos de barras arenosas submareales de estuario inferior. La superficie (flecha) es una superficie de ravinamiento de mareas. Quebrada de Casa Colorada. g) Detalle de los depósitos de barras arenosas submareales mostrando estratificación entrecruzada planar de gran escala. Quebrada de Casa Colorada. h) Pantallas de fango en capas frontales. Complejo de barras arenosas submareales. Quebrada de Casa Colorada. Cubre lente = 5,5 cm.

The original description as Alfarcito limestones is confusing because no true limestone occurs in the area. Rather, the Alfarcito Member is entirely siliciclastic. It can be divided into three very distinct upward coarsening and thickening intervals of regional extent across Quebrada de Humahuaca (Fig. 6). In the Alfarcito area, this three-fold subdivision is present, although the upper strata of the lower interval, the whole middle interval and the lower half of the upper interval have been removed by faulting in Quebrada de Casa Colorada. Each of these upward coarsening and thickening intervals can be in turn subdivided into a lower heterolithic fine-grained unit and an overlying sandstone-dominated unit (Fig. 6). These strata represent an open-marine, shallow, low-gradient platform, affected by fairweather and storm waves.

The heterolithic fine-grained unit of the lower interval consists of three main lithofacies: 1) greenish gray mudstone (lower offshore) (Fig. 7b); 2) mudstone with interbedded combined-flow rippled sandstone (upper offshore), and 3) interbedded hummocky cross-stratified sandstone and mudstone (offshore transition). The three lithofacies recognized are stacked forming upward coarsening and thickening distal parasequences that record short-term progradational pulses. Overall this heterolithic unit represents the upper part of a major transgressive-regressive cycle that started with the Pico de Halcón Member. However, high-resolution sequence stratigraphy analysis reveals further subdivisions (Mángano *et al.*, 2005). The lowermost beds of the Alfarcito Member record a basinwide transgression and the ultimate flooding of the estuarine valley, representing the late stage of the transgressive systems tract expressed by the Pico de Halcón Member. These transgressive deposits culminate in a maximum flooding surface that lies within lower offshore deposits that occur at the lowermost interval of the Alfarcito Member (Mángano *et al.*, 2005). In the Alfarcito area these transgressive deposits are overlain by lower offshore to upper offshore deposits forming a progradational parasequence set, which represents the highstand systems tract of this lower sequence. The top of this highstand package is marked by a co-planar surface or flooding surface/sequence boundary (FS/SB) and a change in the stacking pattern of parasequences, from progradational to retrogradational parasequence sets (Mángano *et al.*, 2005). The transgressive systems tract of this second depositional sequence consists of upper to lower offshore deposits stacked forming a retrogradational sequence set. The maximum flooding surface occurs in lower offshore deposits in the Alfarcito area. Highstand deposits of this second depositional sequence make up the upper strata of the heterolithic unit and consist of a progradational parasequence set, which includes deposits that range from the lower offshore into the offshore transition. Overall the heterolithic fine-grained unit of the lower interval coarsens towards the west where lower to middle shoreface deposits are represented outside the study area.

The sandstone-dominated uppermost part of the lower upward coarsening and thickening interval is characterized by the amalgamated hummocky cross-stratified sandstone lithofacies (lower to middle shoreface). The interbedded hummocky cross-stratified sandstone and mudstone (offshore transition) lithofacies is less common. This sandstone-dominated unit is approximately 30 m thick and most likely records the incision and rapid advance of a sharp-based, forced regressive shoreface, representing a falling stage systems tract (Fig. 7c). The base of this shoreface sandstone unit is a regressive surface of marine erosion. This forced regressive shoreface has been recognized further west in other areas of Quebrada de Humahuaca where its base is commonly marked by large-scale soft-sediment deformation structures (Buatois and Mángano, 2003). The top of lower interval is marked by a co-planar surface or flooding surface/sequence boundary (FS/SB).

The heterolithic fine-grained unit of the middle upward coarsening and thickening interval is 30 m thick and similar to the lower interval. These lithofacies are stacked forming wave-dominated, upward coarsening and thickening parasequences and record a transgressive-regressive cycle. No lowstand deposits have been observed. The lowermost parasequences display a retrogradational stacking pattern and record a transgressive systems tract, with dominance of lower offshore deposits. A maximum flooding surface and a change in parasequence stacking pattern from retrogradational to progradational mark the base of the highstand systems tract. Early highstand deposits are dominated by upper offshore to offshore transition lithofacies. When compared with coeval outcrops in Quebrada de Humahuaca, those from the Alfarcito area are finer-grained and more distal.

The sandstone-dominated unit of the middle upward coarsening and thickening interval is similar to that of the lower interval, but rather than sharp-based, it gradationally overlain the fine-grained deposits. It consists of two lithofacies: 1) interbedded hummocky cross-stratified sandstone and mudstone (offshore tran-

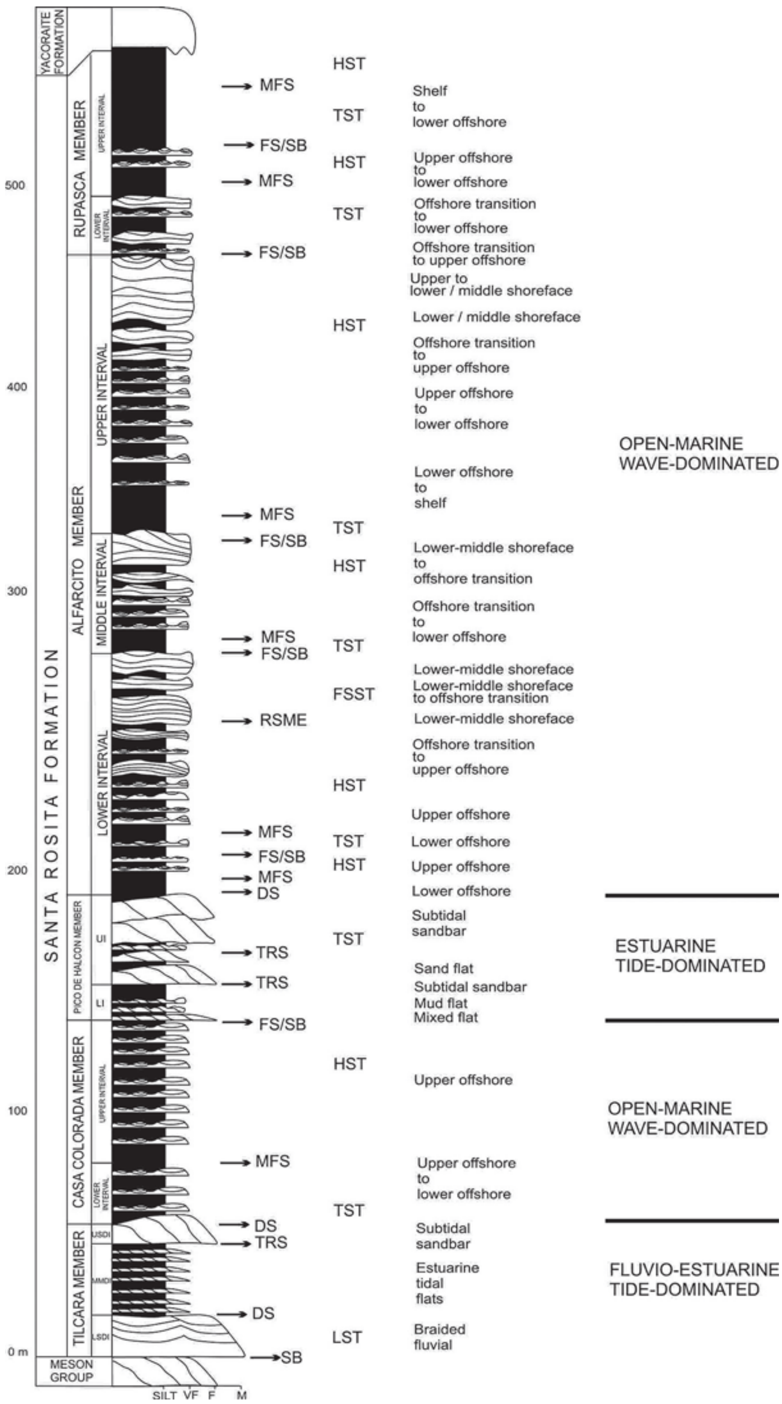


Figure 6. Stratigraphic section of the Santa Rosita Formation at Quebrada de Rupasca. TRS = tidal ravinement surface, DS = drowning surface, FS/SB = co-planar surface of marine flooding and sequence boundary, MFS = maximum flooding surface, RSME = regressive surface of marine erosion, LST = lowstand systems tract, TST = transgressive systems tract, HST = highstand systems tract, FSST = falling stage systems tract. Tilcara Member: LSDI = lower sandstone-dominated interval, MMDI = middle mudstone-dominated interval, USDI = upper sandstone-dominated interval. Pico de Halcón Member: LI = lower interval, UI = upper interval.

Figura 6. Sección estratigráfica de la Formación Santa Rosita en la quebrada de Rupasca. TRS = superficie de ravinamiento de mareas, DS = superficie de ahogo, FS/SB = superficie co-planar de inundación marina y límite de secuencia, MFS = superficie de máxima inundación, RSME = superficie regresiva de erosión marina, LST = cortejo depositacional de nivel del mar bajo, TST = cortejo depositacional transgresivo, HST = cortejo depositacional de nivel del mar alto, FSST = cortejo depositacional de caída de nivel del mar. Miembro Tilcara: LSDI = intervalo inferior dominado por areniscas, MMDI = intervalo medio dominado por pelitas, USDI = intervalo superior dominado por areniscas. Miembro Pico de Halcón: LI = intervalo inferior, UI = intervalo superior.

sition), and 2) amalgamated hummocky cross-stratified sandstone (lower to middle shoreface). This unit is 20 m thick, records progradation of a clastic wedge during normal regression, and therefore represents the last stage of the highstand systems tract.

The heterolithic fine-grained unit of the upper upward coarsening and thickening interval consists of three lithofacies: 1) black shale (shelf); 2) greenish gray mudstone (lower offshore), and 3) mudstone with interbedded combined-flow rippled sandstone (upper offshore). The sandstone-dominated unit of the upper upward coarsening and thickening interval is made up of four lithofacies: 1) mudstone with interbedded combined-flow rippled sandstone (upper offshore) (Fig. 8b); 2) interbedded hummocky cross-stratified sandstone and mudstone (offshore transition) (Fig. 8c-d); 3) amalgamated hummocky cross-stratified sandstone (lower to middle shoreface) (Fig. 8e), and 4) trough cross-bedded sandstone (upper shoreface) (Fig. 8f). The base of the upper interval is a co-planar surface or flooding

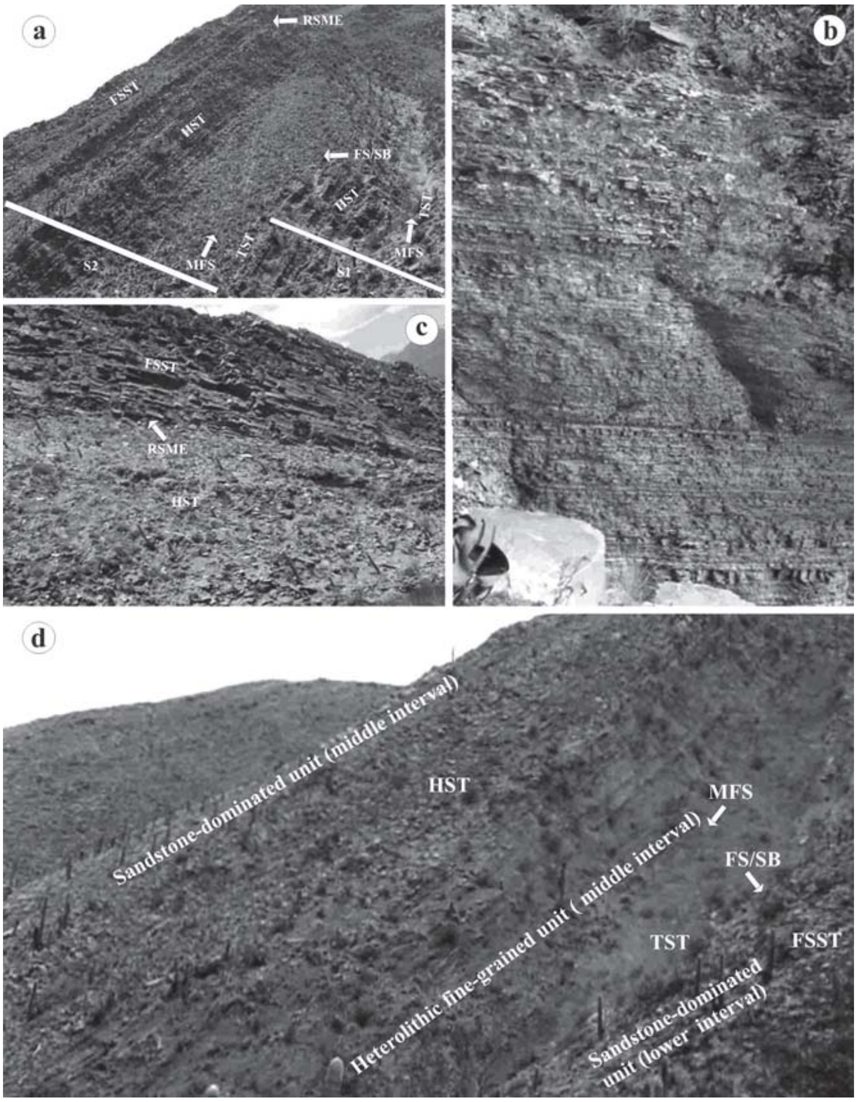


Figure 7. Facies and stratal stacking pattern of the lower and middle intervals of the Alfarcito Member at Quebrada de Rupasca. a) General view of the lower upward coarsening and thickening upward interval of the Alfarcito Member. Depositional sequence 1 (S1) is represented by transgressive systems tract (TST) and highstand systems tract (HST). This lower transgressive interval makes up the upper part of the depositional sequence that started with the Pico de Halcón Member. Depositional sequence 2 (S2) is represented by transgressive systems tract (TST), highstand systems tract (HST) and falling stage systems tract (FSST), the latter represented by the sandstone-dominated unit of the lower interval. The sequence boundary is a flooding surface/sequence boundary (FS/SB). A maximum

surface/sequence boundary (FS/SB). No lowstand deposits occur at the base of this interval. The transgressive systems tract is thin, with a maximum flooding surface located within the lowermost shelf interval close to the base of the heterolithic fine-grained unit. The remaining strata consist of a large-scale progradational succession, mostly reflecting gradual facies changes due to a normal regression. The bulk of this upward coarsening and thickening interval belongs to the highstand systems tract. More regional studies are requested to evaluate the existence of interbedded falling stage deposits reflecting more abrupt shoreface progradation. In contrast to regressive deposits in the Casa Colorada Member and the lower and middle intervals of the Alfarcito Member that contain lower to middle shoreface deposits as the most proximal components, the upper interval also includes upper shoreface deposits which are well exposed in Quebrada de Rupasca. This stratal stacking pattern indicates that the whole Alfarcito Member is a single large-scale regressive succession.

No body fossils were found in the lower interval of the Alfarcito Member, but trilobites occur in the middle interval and conodonts were recovered from the upper interval. The species *Parabolinella argentinensis* Kobayashi and *Dividuagnostus* sp. occur in the fine-grained heterolithic unit of the middle interval. *Parabolinella* is specious and has a wide stratigraphic range spanning the Upper Cambrian to the upper Tremadocian, so has great potential for establishing a biostratigraphic scheme in the region. However, based on an extensive collection of material from its type locality, Waisfeld and Vaccari (2003) showed that *Parabolinella argentinensis* does not display the wide

(Figure 7 - Continuation) flooding surface (MFS) separates the transgressive systems tract from the highstand systems tracts. A regressive surface of marine erosion (RSME) separates the highstand systems tract from the falling stage systems tract. b) Close-up of lower offshore deposits from the heterolithic fine-grained unit of the lower upward coarsening and thickening upward interval, showing dominance of mudstone with subordinate thin-bedded sandstone (distal tempestites). c) Close-up of the contact between the forced regressive shoreface and the underlying highstand deposits. The contact is expressed by a regressive surface of marine erosion (RSME). d) General view of the sandstone-dominated unit of the lower interval, the heterolithic fine-grained unit of the middle interval and the sandstone-dominated unit of the middle interval of the Alfarcito Member. The sandstone-dominated unit of the lower interval is interpreted as a forced regressive shoreface, representing a falling stage systems tract (FSST) that comprises the uppermost stratal package of the depositional sequence that started within the heterolithic fine-grained unit of the lower interval. The top of the sandstone-dominated unit of the lower interval of the Alfarcito Member is a flooding surface/sequence boundary (FS/SB). The middle interval of the Alfarcito Member make up a depositional sequence represented by a transgressive systems tract (TST) and a highstand systems tract (HST). A maximum flooding surface (MFS) separates the transgressive systems tract from the highstand systems tracts. The passage from the heterolithic fine-grained unit to the sandstone-dominated unit of the middle interval is gradational and reflects overall progradation.

Figura 7. Facies y patrón de apilamiento estratal en los intervalos inferior a medio del Miembro Alfarcito en la quebrada de Rupasca. a) Vista general del intervalo grano y estratocreciente inferior del Miembro Alfarcito. La secuencia depositacional 1 (S1) está representada por un cortejo depositacional transgresivo (TST) y un cortejo depositacional de nivel del mar alto (HST). Este intervalo transgresivo inferior conforma el tramo superior de la secuencia depositacional iniciada en el Miembro Pico de Halcón. La secuencia depositacional 2 (S2) está representada por los cortejos depositacionales transgresivos (TST), de nivel del mar alto (HST) y de caída de nivel del mar (FSST), este último representado por la unidad arenosa del intervalo inferior del Miembro Alfarcito. El límite de secuencia es una superficie de inundación /límite de secuencia (FS/SB). Una superficie de máxima inundación (MFS) separa el cortejo sedimentario transgresivo del de nivel del mar alto. Una superficie regresiva de erosión marina (RSME) separa el cortejo sedimentario de nivel del mar alto del de caída de nivel del mar. b) Detalle de los depósitos de *offshore* inferior de la unidad heterolítica de grano fino del intervalo inferior, mostrando el dominio de pelitas con intercalaciones subordinadas de delgadas capas de arenisca (tempestitas distales). c) Detalle del contacto entre el *shoreface* de regresión forzada y los depósitos de nivel alto subyacentes. El contacto está expresado por una superficie regresiva de erosión marina (RSME). d) Vista general de la unidad arenosa del intervalo inferior, la unidad heterolítica de grano fino del intervalo medio y la unidad arenosa del intervalo medio. La unidad arenosa del intervalo inferior es interpretada como un *shoreface* de regresión forzada, representando el cortejo sedimentario de caída de nivel del mar (FSST) que comprende el paquete estratal cuspidal de la secuencia depositacional iniciada en la unidad heterolítica de grano fino del intervalo inferior. El tope de la unidad arenosa del intervalo inferior del Miembro Alfarcito es una superficie de inundación /límite de secuencia (FS/SB). Los intervalos superiores del Miembro Alfarcito conforman una secuencia depositacional representada por los cortejos depositacionales transgresivos (TST) y de nivel de mar alto (HST). En el intervalo medio el pasaje de la unidad heterolítica de grano fino a la unidad arenosa es gradacional y refleja una tendencia de progradación.

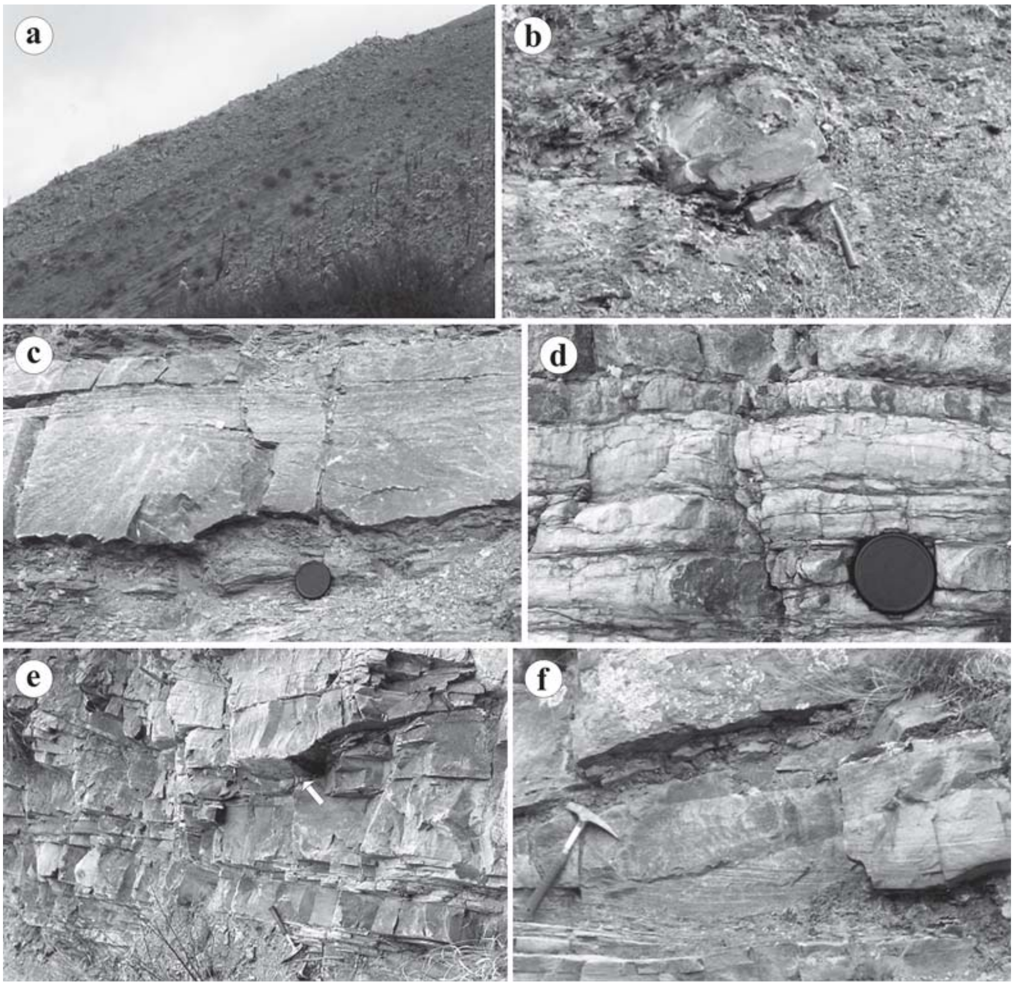


Figure 8. Facies of the upper upward-coarsening and -thickening interval of the Alfarcito Member. a) General view of the upper interval reflecting an overall transgressive-regressive cycle. Quebrada de Rupasca. b) Large gutter cast. Upper offshore. Quebrada de Rupasca. c) Hummocky cross-stratified sandstone bed with flute casts on the base. Offshore transition. Quebrada de Rupasca. Lens cover = 5.5 cm. d) *Skolithos* pipe rock. Sandstone tempestites. Offshore transition. Quebrada de Casa Colorada. Lens cover = 5.5 cm. e) Amalgamated hummocky cross stratified sandstone unit, showing large scour at the base of a lenticular hummocky cross-stratified bed (arrow) eroding into a tabular hummocky cross stratified sandstone. Lower to middle shoreface. Quebrada de Casa Colorada. f) Trough cross-stratified sandstone bed. Upper shoreface. Quebrada de Rupasca.

Figura 8. Facies del intervalo grano y estratocreciente superior del Miembro Alfarcito. a) Vista general del intervalo superior reflejando un ciclo transgresivo-regresivo. Quebrada de Rupasca. b) *Gutter cast* de grandes dimensiones. *Offshore* superior. Quebrada de Rupasca. c) Capa de arenisca con estratificación entrecruzada *hummocky* y calcos de flujo en la base. Transición al *offshore*. Quebrada de Rupasca. Cubre lente = 5,5 cm. d) *Pipe rock* de *Skolithos*. Tempestitas arenosas. Transición al *offshore*. Quebrada de Casa Colorada. Cubre lente = 5,5 cm. e) Arenisca con estratificación entrecruzada *hummocky* amalgamada, mostrando un gran *scour* en la base de la capa lenticular con estratificación entrecruzada *hummocky* (flecha) erosionando una capa tabular de arenisca con estratificación entrecruzada *hummocky*. *Shoreface* inferior a medio. Quebrada de Casa Colorada. f) Arenisca con estratificación entrecruzada en artesa. *Shoreface* superior. Quebrada de Rupasca.

morphologic variability suggested by Harrington and Leanza (1957) and therefore restricted its distribution to the material from this locality.

Dividuagnostus Koroleva has an extensive record in the Ordovician, with species ranging from the Arenigian to the Ashgillian. However, Nielsen (1997) tentatively included within this genus a group of early species (early Tremadocian-early Arenigian). Characteristics of the cephalon suggest that *Dividuagnostus* sp. belongs to this group based on cephalon morphology, including *Geragnostus (Micragnostus) neumanni* (Harrington and Leanza), which occurs in the *Kainella meridionalis* Zone in Iruya (Salta province). Although *Dividuagnostus* sp. is clearly distinct from *D. neumanni* and probably represents a new species. The presence of *Parabolinella argentinensis* and *Dividuagnostus* sp. in the fine-grained heterolithic unit of the middle interval suggests an early Tremadocian age.

The age of the upper interval of the Alfarcito Member is well constrained by the presence of the lower Tremadocian *Cordylodus angulatus* Zone in the sandstone-dominated middle unit.

Rupasca Member

The uppermost unit of the Santa Rosita Formation in the Alfarcito area is the Rupasca Member. The uppermost Humacha Member of the Santa Rosita Formation, a sandstone-dominated unit defined by Moya (1988) in the eponymous creek, does not seem to be exposed in the Alfarcito area. However, at the entrance of Quebrada de San Gregorio, the uppermost interval of the Rupasca Member becomes sandier, suggesting the onset of a progradational succession. The Rupasca Member is a dominantly fine-grained unit (Fig. 9a) and varies from 85 to 210 m in thickness due to truncation by the unconformity with the Cretaceous. At Quebrada de Rupasca, our measurements of 85 m (Fig. 6) are in agreement with the 80 m thick recorded by Harrington. A more complete succession is exposed in Quebrada de Casa Colorada (Fig. 4).

The lower interval of the Rupasca Member consists of three lithofacies: 1) greenish gray mudstone (lower offshore) (Fig. 9b); 2) mudstone with interbedded combined-flow rippled sandstone (upper offshore) (Fig. 9b); and (3) interbedded hummocky cross-stratified sandstone and mudstone (offshore transition). The upper interval is made up of two lithofacies: 1) black shale (shelf); and 2) greenish gray mudstone (lower offshore) (Fig. 9c). The base of the Rupasca Member is a coplanar surface or flooding surface/sequence boundary (FS/SB) and no lowstand deposits are present. However, in contrast to the rapid transgression recorded by the Alfarcito Member, the transgressive episode in the Rupasca Member appears much slower and continuous. In fact, at least three depositional sequences, consisting of thick (each up to 85 m thick) transgressive systems tracts and thinner (each less than 35 m thick) highstand systems tracts, are included. In all cases the time of maximum flooding lies within black shale packages. Shelfal deposition clearly occurs under anoxic conditions as suggested by the presence of thick unbioturbated and parallel laminated black shale packages, and a high concentration of organic matter in some concretions.

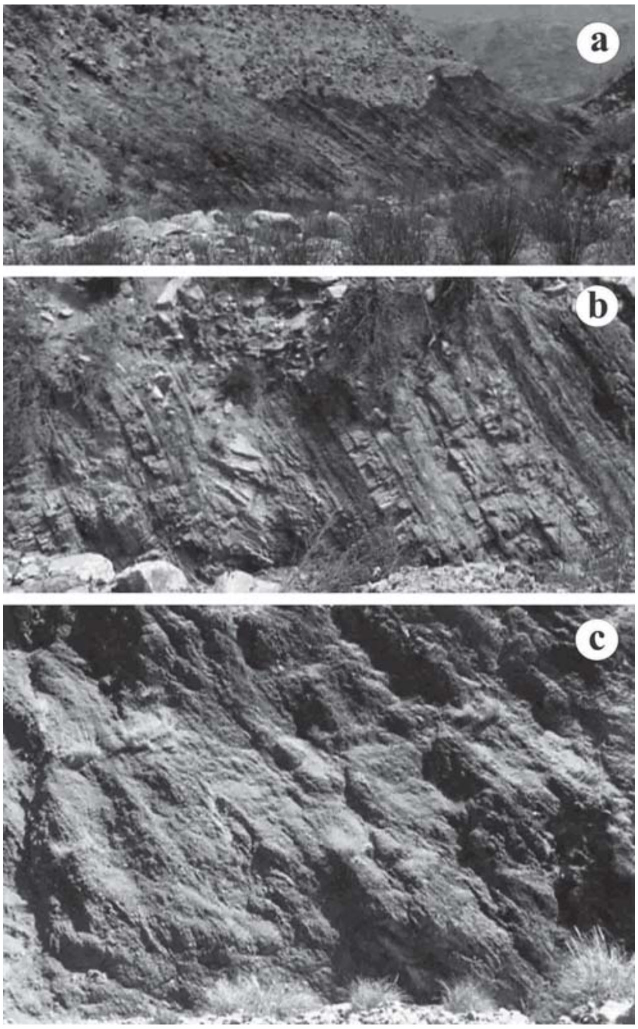


Figure 9. Facies of the Rupasca Member. a) General view. Quebrada de Rupasca. b) Thinly interbedded sandstone and mudstone. Lower to upper offshore. Lower interval. Quebrada de Casa Colorada. c) Mudstone-dominated interval. Lower offshore. Upper interval. Quebrada de Casa Colorada.

Figura 9. Facies del Miembro Rupasca. a) Vista general. Quebrada de Rupasca. b) Arenisca y pelita finamente interestratificada. *Offshore* inferior a superior. Intervalo inferior. Quebrada de Casa Colorada. c) Intervalo dominado por pelita. *Offshore* inferior. Intervalo superior. Quebrada de Casa Colorada.

Overall tendency is clearly transgressive with maximum flooding of the basin in the uppermost depositional sequence. This long-term transgressive tendency may reflect a tectonic signal, most likely increased subsidence linked to regional extension in the back-arc area. Transgressive deposition is also revealed by the common presence of shell and pebble lags at the base of some parasequences. The parasequences in the lower interval contain upper offshore to offshore transition sandstone tempestites having dense occurrences of *Skolithos* (pipe rock). This may reflect long transient time that allows extensive bioturbation, probably due to low rates of sedimentation linked to drowning of the source areas during transgression.

Specimens of the graptolite *Rhabdinopora flabelliformis flabelliformis* (Eichwald) were recorded together with conodonts of the *Cordylodus angulatus* Zone in the lowermost part of the Rupasca Member, suggesting that the onset of the Rupasca transgression occurred by the end of the early Tremadocian. The recognition of the *Paltodus deltifer* Zone in the overlying interval of the Rupasca Member, more specifically the *P. deltifer pristinus* Subzone, indicates that this unit ranges into the early late Tremadocian.

BIOSTRATIGRAPHIC FRAMEWORK

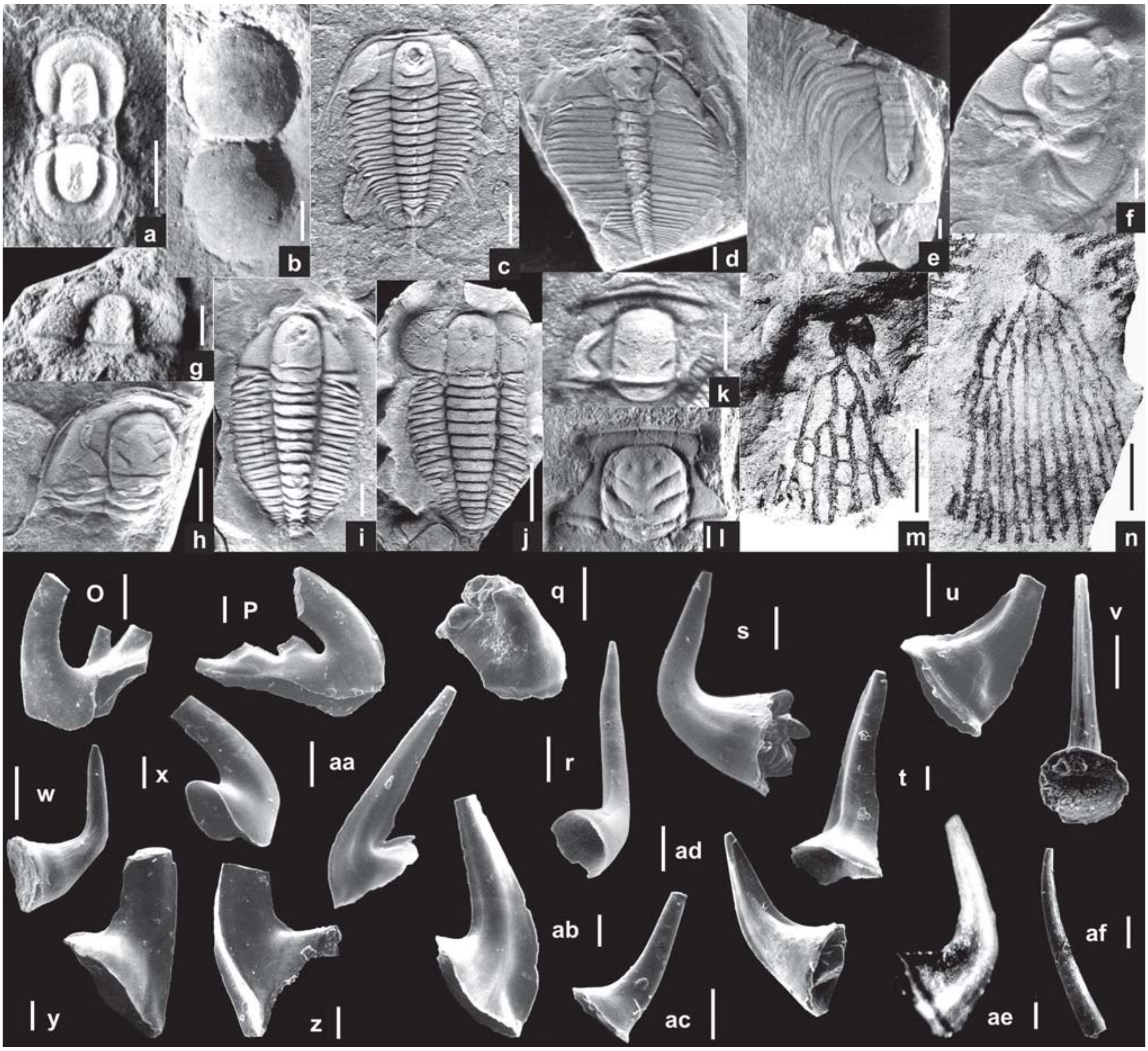
The trilobite, conodont and graptolite faunas of the Alfarcito area succession were previously described by Harrington and Leanza (1957), Zeballo and Tortello (2005), and Zeballo *et al.* (2003, 2005a,b). In particular, Zeballo *et al.* (2005a) analyzed the biozonal scheme that was introduced in a preliminary way by Zeballo *et al.* (2003). The following biostratigraphic units are recognized throughout sections of Quebrada de Casa Colorada, Quebrada de Rupasca, and Quebrada de San Gregorio, and most representative forms are shown in Figure 10.

Conodonts

***Cordylodus angulatus* Zone.** The lower Tremadocian *Cordylodus angulatus* Zone extends from the upper part of the Alfarcito Member (Zeballo *et al.*, 2005a,b) into the lowermost interval of the Rupasca Member according to the stratigraphic scheme presented here. At the Quebrada de Casa Colorada section, the base of this biozone is defined by the first appearance of the conodont *Rossodus tenuis* (Miller). In reference sections such as those from Newfoundland, this species is accompanied by the appearance of *C. angulatus* Pander (Ji and Barnes, 1994). However, the real range of *R. tenuis* needs full testing since it has been recorded in lower biozones from other North American localities (Miller *et al.*, 2003). At the Quebrada de San Gregorio section, the lowest records of C*ordylodus* sp. and *Teridontus nakamurai* (Nogami), are in the upper interval of the Alfarcito Member. However, these are not reliable guide taxa and could belong to the basal Ordovician *Iapetognathus* Zone or even uppermost Cambrian levels. Due to the lack of biostratigraphic markers in the lower part of the section, it is still not possible to propose a precise position for the global Cambrian/Ordovician boundary as defined by Cooper *et al.* (2001); notwithstanding that, regional correlations suggest this boundary lies close to the contact between the Pico de Halcón and Alfarcito members.

Conodonts of the *C. angulatus* Zone were recovered from calcareous coquinas, which also include

Figure 10. a) *Geragnostus* sp., complete specimen (CORD-PZ 30549). b) *Gymnagnostus* n. sp. A., complete specimen (CORD-PZ 30532). c) *Parabolina (N.) frequens argentina* (Kayser), complete specimen (CORD-PZ 30510). d) *Hapalopleura* sp., complete specimen (CORD-PZ 30871). e) *Onychopyge* sp., pygidium and partial thorax (CORD-PZ 30794). f) *Pseudokainella keideli* Harrington, cranidium and librigena (CORD-PZ 30864). g) *Pharostomina trapezoidalis* (Harrington), cranidium (CORD-PZ 30727). h) *Parabolinella* sp. A, cephalon (CORD-PZ 30739). i) *Leptoplastides granulosus* (Harrington), complete specimen (CORD-PZ 30926). j) *Peltocare norvegicum* (Moberg and Möller), complete specimen (CORD-PZ 30624). k) *Kainella* sp., cranidium (CORD-PZ 30532). l) *Bienvillia tetragonalis* (Harrington), cranidium (CORD-PZ 30559). m-n) *Rhabdinopora flabelliformis flabelliformis* (Eichwald), mature colonies with nematularium (m, CORD-PZ 30805; n, CORD-PZ 30801). o) *Cordylodus intermedius* Furnish (CORD-MP 8077/1). p) *Cordylodus angulatus* Pander (CORD-MP 8015/1). q) *Iapetognathus* sp. (CORD-MP 8082/1). r) *Teridontus nakamurai* (Nogami), a element (CORD-MP 8074/1). s) *Teridontus obesus* Ji and Barnes, a element (CORD-MP 8091/1). t) *Rossodus tenuis*. (Miller), e element (CORD-MP 8106/1). u) ?*Rossodus manitouensis* Repetski and Ethington, b element (CORD-MP 8100/1). v) *Semiacontiodus striatus* Zeballo, Albanesi and Ortega, c element (holotype) (CORD-MP 8092/70). w) *Semiacontiodus minutus* Zeballo, Albanesi and Ortega, c element (holotype) (CORD-MP 8094/36). x) *Drepanodus arcuatus* Pander, M element (CORD-MP 8108/1). y) *Paltodus deltifer pristinus* (Viira), M element (CORD-MP 8124/1). z) *Paltodus* cf. *subaequalis* (Pander), P element (CORD-MP 8125/1). aa) *Drepanoistodus alfarcitensis* Zeballo, Albanesi and Ortega, M element (holotype) (CORD-MP 8102/1). ab) *Drepanoistodus chucaleznensis* Albanesi and Aceñolaza, M element (CORD-MP 8129/1). ac) *Utahconus utahensis* (Miller), f element (CORD-MP 8079/6). ad) *Utahconus humahuacensis* Albanesi and Aceñolaza, f element (CORD-MP 8101/1). ae) *Variabiloconus variabilis* (Lindström), Sb element (CORD-MP 8047/16). af) *Phakelodus elongatus* (An) (CORD-MP 8110/1). Scale bars: trilobites = 1 mm except for C, E, H, J, = 5 mm; graptolites = 5 mm; conodonts = 0.1 mm.



(Continuación)

Figura 10. a) *Geragnostus* sp., ejemplar completo (CORD-PZ 30549). b) *Gymnagnostus* n. sp. A., ejemplar completo (CORD-PZ 30532). c) *Parabolina (N.) frequens argentina* (Kayser), ejemplar completo (CORD-PZ 30510). d) *Hapalopleura* sp., ejemplar completo (CORD-PZ 30871). e) *Onychopyge* sp., pigidio y torax parcial (CORD-PZ 30794). f) *Pseudokainella keideli* Harrington, cranidio y librígena (CORD-PZ 30864). g) *Pharostomina trapezoidalis* (Harrington), cranidio (CORD-PZ 30727). h) *Parabolinella* sp. A, céfalo (CORD-PZ 30739). i) *Leptoplastides granulosus* (Harrington), ejemplar completo (CORD-PZ 30926). j) *Peltocare norvegicum* (Moberg y Möller), ejemplar completo (CORD-PZ 30624). k) *Kainella*? sp., cranidio (CORD-PZ 30532). l) *Bienvillia tetragonalis* (Harrington), cranidio (CORD-PZ 30559). m-n) *Rhabdinopora flabelliformis flabelliformis* (Eichwald), colonias adultas con nematulario (m, CORD-PZ 30805; n, CORD-PZ 30801). o) *Cordylodus intermedius* Furnish (CORD-MP 8077/1). p) *Cordylodus angulatus* Pander (CORD-MP 8015/1). q) *Iapetognathus* sp. (CORD-MP 8082/1). r) *Teridontus nakamurai* (Nogami), elemento a (CORD-MP 8074/1). s) *Teridontus obesus* Ji y Barnes, elemento a (CORD-MP 8091/1). t) *Rossodus tenuis*. (Miller), elemento e (CORD-MP 8106/1). u) ?*Rossodus manitouensis* Repetski y Ethington, elemento b (CORD-MP 8100/1). v) *Semiacontiodus striatus* Zeballo, Albanesi and Ortega, elemento c (holotipo) (CORD-MP 8092/70). w) *Semiacontiodus minutus* Zeballo, Albanesi and Ortega, elemento c (holotipo) (CORD-MP 8094/36). x) *Drepanodus arcuatus* Pander, elemento M (CORD-MP 8108/1). y) *Paltodus deltifer pristinus* (Viira), elemento M (CORD-MP 8124/1). z) *Paltodus* cf. *subaequalis* (Pander), elemento P (CORD-MP 8125/1). aa) *Drepanoistodus alfarcitensis* Zeballo, Albanesi and Ortega, elemento M (holotipo) (CORD-MP 8102/1). ab) *Drepanoistodus chucaleznensis* Albanesi and Aceñolaza, elemento M (CORD-MP 8129/1). ac) *Utahconus utahensis* (Miller), elemento f (CORD-MP 8079/6). ad) *Utahconus humahuacensis* Albanesi and Aceñolaza, elemento f (CORD-MP 8101/1). ae) *Variabiloconus variabilis* (Lindström), elemento Sb (CORD-MP 8047/16). af) *Phakelodus elongatus* (An) (CORD-MP 8110/1). Escalas gráficas: trilobites = 1 mm, excepto C, E, H, J, = 5 mm; graptolitos = 5 mm; conodontes = 0,1 mm.

possible reworked elements from underlying strata; *e.g.*, *T. nakamurai*, *T. obesus* Ji and Barnes, *Drepanodus arcuatus* Pander, *Phakelodus elongatus* (An), *Problematoconites perforatus* Müller and *Coelocerodontus* sp. Allochthonous conodonts are probably present, which implies reworking and transport processes previous to the final deposition. A few taxa, such as *Iapetognathus* sp. and *Cordylodus* sp., are recorded as isolated findings. Among new conodont species for the Cordillera Oriental, Zeballo *et al.* (2005a) described and illustrated complete apparatuses of *Drepanoistodus alfarcitensis* Zeballo *et al.*, *Drepanoistodus chucaleznensis* Albanesi and Aceñolaza, *Semiacontiodus striatus* Zeballo *et al.*, *S. minutus* Zeballo *et al.*, and *Utahconus humahuacensis* Albanesi and Aceñolaza.

The *Cordylodus angulatus* Zone is widely represented in different continents. This biozone was previously reported in the Cordillera Oriental by Rao and Hünicken (1995), Rao (1999), and Tortello *et al.* (1999) from a unit commonly referred to as the Cardonal Formation at Sierra de Cajas (Jujuy province) and by Rao and Tortello (1998) for the Cardonal Formation at Quebrada de Incamayo (Salta province). The *C. angulatus* Zone is well represented in the Volcancito Formation (upper Filo Azul Member) in the Famatina region (La Rioja province) (Albanesi *et al.*, 1999; 2005). This biozone includes the *R. manitouensis* Zone of North American schemes (*cf.* Miller *et al.*, 2003), whose characteristic conodont species have been recorded in the carbonate La Silla Formation and equivalent San Jorge Formation of the Cuyania terrane, at San Juan and La Pampa provinces, respectively (Lehnert, 1995; Albanesi *et al.*, 2003).

Collections from the Santa Rosita Formation include mixed elements from both the warm and the cold-water realms that begin to differentiate progressively during the Tremadocian (Miller, 1984). Considering previous interpretations for Tremadocian conodont faunas of the Cordillera Oriental (Rao, 1999), these faunas could be assigned to the low-mid latitude transitional faunal realm as defined by Dubinina (1991).

***Paltodus deltifer* Zone (*Paltodus deltifer pristinus* Subzone).** *Paltodus deltifer pristinus* (Viira) appears for the first time in shell beds from the lower part of the Rupasca Member and species caracterizes the *P. deltifer pristinus* Subzone of the *P. deltifer* Zone (lower upper Tremadocian), following the scheme proposed by Löfgren (1997) for the Baltoscandian region. The lack of records of *P. deltifer deltifer* (Lindström) is in support of our interpretation that the upper subzone of the *P. deltifer* Zone is absent in the study area. Identified species that ranges through this part of the section include: *Teridontus nakamurai* (Nogami), *Semiacontiodus minutus* Zeballo *et al.*, *Drepanodus arcuatus* Pander, *Drepanoistodus chucaleznensis* Albanesi and Aceñolaza, *Phakelodus elongatus* (An), *Coelocerodontus* sp., *Variabiloconus variabilis* (Lindström), *Paltodus* cf. *subaequalis* (Pander) and *Utahconus humahuacensis* Albanesi and Aceñolaza.

The *P. deltifer* Zone was previously documented in the Precordilleran region by Keller *et al.* (1994), Lehnert (1995), Albanesi *et al.* (1998), and Cañas *et al.* (2002), through the interval spanning the contact between the La Silla and San Juan formations. Heredia (1995) identified this zone in the basal conglomerate of the Empozada Formation near Mendoza. In the Famatina area this biozone has been identified in the shaly Bordo Atravesado Formation, with typical species proceeding from shell tempestite levels that are interbedded with the lower black shales (Albanesi *et al.*, 2005). In the Cordillera Oriental this zone has been identified in coeval strata within the Santa Rosita Formation, in different localities from the eastern belt at Nazareno (Manca *et al.*, 1995) and Chucalezna (Albanesi and Aceñolaza, 2005), and in the western belt at Sierra de Aguilar (Rao and Flores, 1998).

The biostratigraphic interval represented by the Rupasca Member corresponds, at least in part, to the upper Tremadocian «Low Diversity Interval», well documented in North America (Ethington *et al.*, 1987). During this time span the conodont faunas are replaced by low-diversity communities after the widely recognized *Ceratopyge* shallowing event, which implies a global extinction event (Albanesi and Bergström, 2004).

Trilobites

***Parabolina frequens argentina* Zone.** This biozone was identified in the uppermost strata of the Casa Colorada Member (Zeballo and Tortello, 2005). The index species *Parabolina (Neoparabolina) frequens argentina* (Kayser) was recorded in association with undetermined ostracods and *Parabolinella argentinensis* Kobayashi, *Onychopyge* sp., *Beltella* sp., *Angelina* sp. and *Plicatolina scalpta* Harrington and Leanza. *Parabolinella* ranges from the Late Cambrian to the late Tremadocian. *Onychopyge* is represented by several species in northwestern Argentina, such as *O. riojana* Harrington from the Famatina area, *O. argentina* Harrington and Leanza and *O.*

longispina Harrington and Leanza from Sierra de Santa Victoria, and *O. harringtoni* Benedetto from Sierra de Cajas. The described faunal association suggests a latest Cambrian age. Vaccari *et al.* (2004) reported discovery of the oldest known euthycarcinoid (Arthropoda) in an erratic block from the Casa Colorada Member, at Garganta del Diablo (Río Huasamayo).

The intercontinental correlation of the *P. frequens argentina* Zone was presented by Zeballo and Tortello (2005). It is present in diverse localities in northwestern Argentina (Harrington and Leanza, 1957; Aceñolaza, 1968; Benedetto, 1977; Aceñolaza, 1983; Salfity *et al.*, 1984; Moya *et al.*, 1994; Tortello and Rao, 2000; Tortello and Esteban, 2003), as well as the Famatina area (Tortello and Esteban, 1999).

***Bienvillia tetragonalis - Conophrys minutula* Zone.** This zone was originally defined by Harrington and Leanza (1957) as *Triarthrus tetragonalis - Shumardia minutula.* At the Alfarcito area this interval is represented by *B. tetragonalis* (Harrington) and associated forms, such as *Leptoplastides granulosus* (Harrington), *Parabolinella* sp. B, *Pseudokainella keideli* Harrington, *Pharostomina trapezoidalis* (Harrington), *Peltocare norvegicum* (Moberg and Möller), *Hapalopleura* sp., *Asaphellus* sp., *Apatokephalus* sp., *Gymnagnostus* n. sp. A, and *Geragnostus* sp. (Harrington and Leanza, 1957; Moya *et al.*, 1994). Besides northwest Argentina, the *Bienvillia tetragonalis-Conophrys minutula* Zone has been documented in Bolivia (Pøibyl and Vanìk, 1980; Branisa, 1965), Mexico (Robison and Pantoja-Alor, 1968), and Norway (Henningsmoen, 1957).

Graptolites

***Rhabdinopora flabelliformis flabelliformis* assemblage.** The appearance of graptolites is recorded slightly above the base of the Tremadocian Stage, which is marked elsewhere by the appearance of the conodont *Iapetognathus fluctivagus* Nicoll *et al.* The early Tremadocian *Rhabdinopora praeparabola*, *R. flabelliformis parabola*, *Anisograptus matanensis* and *R. flabelliformis anglica* graptolite zones and species ranges have been well described (Cooper *et al.*, 1998; Cooper, 1999). The presence of various subspecies of *Rhabdinopora flabelliformis* Eichwald is recorded from the *R. flabelliformis parabola* Zone.

Rhabdinopora spp. are common in the Cordillera Oriental (*e.g.*, Turner, 1960 a,b; Moya *et al.*, 1994; Ortega and Rao, 1995; Aceñolaza, 1996b). However, most of them require a systematic revision. Specimens of *R. flabelliformis flabelliformis* Eichwald with conodonts of the *Cordylodus angulatus* Zone were recorded in the lowermost interval of the Rupasca Member at Quebrada de San Gregorio (Zeballo *et al.*, 2005a,b), according to our present stratigraphic scheme. Subspecies documented by these authors range from the *A. matanensis* Zone to the basal part of the *Adelograptus* Zone. Graptolites were collected from rippled sandstone beds occurring in the lowermost interval of this unit. Mature rhabdosomes with a three-vaned nematularium dominate our collection, while siculae, early astogenetic stages and young colonies are scarce suggesting a selection by hydraulic processes. The interval with *R. flabelliformis flabelliformis* is placed 10 m below strata bearing conodonts of the *Paltodus deltifer* Zone (*P. deltifer pristinus* Subzone), suggesting a probable correlation with the *R. flabelliformis anglica* Zone (late early Tremadocian) or the *Adelograptus* Zone (early late Tremadocian) of the scheme proposed by Cooper (1999).

Rhabdinopora flabelliformis flabelliformis is a widely distributed species, which can be found from inner shelf up to mid-lower slope environments, and it is present in both the didymograptid and isograptid biofacies (Cooper, 1999). The presence of monospecific rhabdosomes in rippled sandstone beds suggests probable transport of specimens.

DISCUSSION

Variations in accommodation space and sediment supply are the major controls on facies stacking pattern in the early sequence stratigraphic models (e.g. Posamentier *et al.*, 1988; Posamentier and Vail, 1988; Van Wagoner *et al.*, 1990). However, subsequent studies addressed the role of other factors, such as basin physiography, as controls on the stratal architecture of systems tracts (*e.g.*, Posamentier and Allen, 1993a,b; Posamentier and Weimer, 1993). Of primary importance is the distinction between ramps and basins with discrete shelf/slope breaks. While eustasy and subsidence/ tectonic uplift seem to determine the timing of sequence boundaries, basin physiography and sediment supply combine to determine stratal architecture (Posamentier and Allen, 1993a). Appreciation of the role of sediment supply is also essential to avoid potential miscorrelations in areas of major sediment supply variations, where progradational, aggradational and retrogradational parasequence sets may develop at the same time along depositional strike (Church and Gawthorpe, 1997).

Regional correlations in Northwest Argentina can be attained by integrating sedimentologic and biostratigraphic data within a sequence stratigraphic framework. However, correlation at the scale of fourth- and fifth-order sequences (*i.e.* parasequences and high-frequency sequences of Mitchum and Van Wagoner, 1991) is typically beyond biostratigraphic resolution. Accordingly, sequence stratigraphy may allow detailed correlations within time slices represented by biozones. The duration of the Tremadocian is approximately 10 Ma. Tremadocian conodont and graptolite zones have a duration that ranges from slightly less that 1 Ma to almost 5 Ma (Webby *et al.*, 2004), while third-, fourth- and fifth-order sequences form at 1-2 Ma, 0.1-0.2 Ma and 0.01-0.02 Ma cyclicity, respectively (Mitchum and Van Wagoner, 1991). At least eight third-order sequences have been identified within the Santa Rosita Formation spanning the Late Cambrian to early late Tremadocian. Ongoing field work indicates that these sequences can be correlated along depositional strike and dip into other parts of Cordillera Oriental.

Sedimentologic evidence supports the establishment of a low gradient ramp system during the Tremadocian (Buatois and Mángano, 2003). The absence of normal grading and the scarcity of unidirectional current indicators in sandstone beds in the Santa Rosita Formation argue against influence of turbidity currents, which is a common mechanism for sand emplacement during storms in high-gradient shelves (e.g. Mángano and Buatois, 1996). Also, apparently few lateral facies variations within individual shallow-marine parasequences have been observed along depositional dip, supporting the establishment of a low-gradient shelf setting during the Tremadocian.

As noted by Posamentier and Allen (1993b), interplay between eustasy and subsidence is crucial to understand sequence architecture in foreland basins. Astini (2003) cautioned against correlation using global sea level curves because of the role played by arc-load or tectonically-induced flexure in the foredeep and peripheral bulge regions, noting that only in the back-bulge region may global eustatic signals be detected. In any case, basinwide transgressive deposits allow intra-basinal correlation in Cordillera Oriental. Two major transgressive events and associated maximum flooding surfaces can be traced throughout the entire basin during the Late Cambrian-Tremadocian cycle. The Late Cambrian transgressive episode led to the establishment of open-marine environments represented in the Alfarcito area and in Quebrada de Humahuaca by the Casa Colorada Member. Further to the west (*e.g.*, Angosto del Moreno, Sierra de Cajas) and south (*e.g.*, Parcha), this event is represented by the Lampazar Formation (Buatois *et al.*, 2003; Astini, 2003; Albanesi and Ortega, 2005). The second transgressive episode is of late early to early late Tremadocian age. In the Alfarcito area, this event is represented by the Rupasca Member, correlative with the Saladillo Formation further south (*e.g.*, Parcha) (Albanesi and Ortega, 2005). In some areas of the basin (*e.g.*, Angosto del Moreno), these strata are truncated by the Tumbaya unconformity (Moya, 1997), which has been linked to peripheral bulge arching and exposure (Astini, 2003).

The transgressive events recorded in the heterolithic fine-grained units of the Alfarcito Member may be correlated to Quebrada de Humahuaca and, in some cases, in the adjacent regions. For example, the early Tremadocian transgressive deposits represented by the heterolithic fine-grained unit of the lower interval occur in the Quebrada de Humahuaca area. In both the Alfarcito area and in Quebrada de Humahuaca, this transgressive episode represents the flooding of the Pico de Halcón incised valley and the establishment of open marine conditions. This transgressive episode is also present in the Angosto del Moreno area (Buatois *et al.*, 2003). In that area, however, these strata occur above open-marine, wave dominated deposits rather than tide-dominated estuarine deposits, suggesting preservation of Upper Cambrian marine deposits in interfluve areas unaffected by the Pico de Halcón incision. The heterolithic fine-grained unit of the middle interval of the Alfarcito Member can be traced into the Quebrada de Humahuaca area and the Angosto del Moreno area. Correlation of these transgressive episodes towards the southern basin margin (*e.g.*, Parcha) is problematic. Open-marine deposits recorded by the Alfarcito Member were likely cannibalized due to successive erosional events due to valley incision represented by the Cardonal and Devendeus formations. Astini (2003) noted that nearshore deposits are absent in the Lampazar Formation at Parcha. The absence of progradational deposits at the upper interval of this unit suggests that highstand deposits of the Lampazar Formation were erosionally removed during incision of the Cardonal Formation.

Deposits of the lowstand systems tract are absent in the Alfarcito area, with the exception of those preserved towards the base of the Tilcara Member. In the case of the incised valley deposits of the Pico de Halcón Member, lowstand fluvial deposits have been recognized in adjacent areas, such as Quebrada de Moya, commonly along the axis of the paleovalley. While working in outcrops of the Western Interior of Canada, Ainsworth and Pattison (1994) asked themselves «where have all the lowstands gone?» to conclude that lowstand deposits occur as shoreface units that are attached to or in direct contact with the underlying highstand deposits. These shoreface deposits are now referred to as «forced regression shorefaces» and are included in the falling stage systems tract (Plint and Nummedal, 2000). In the Santa Rosita Formation, an incised, sharp-based, forced regressive shoreface has been detected in the sandstone-dominated unit of the lower interval of the Alfarcito Member. Recognition of forced regressive shorefaces is not always straightforward and requires careful regional mapping because these deposits may be confused with those of the underlying highstand systems tract that reflects normal regression. The sandstone unit of the lower interval of the Alfarcito Member is erosionally incised into the underlying finer-grained deposits, revealing a regressive surface of marine erosion (Figs. 4, 6, 7A,C). As a consequence of erosion and rapid basinward progradation of shoreface deposits, transitional facies are commonly missing (*cf.* Plint, 1988; Posamentier and Morris, 2000). Also, Buatois and Mángano (2003) noted that soft-sediment deformation structures are abundant at the base of the forced regressive Alfarcito shoreface in some sections (*e.g.*, Quebrada de Moya). Extensive presence of these structures suggests rapid loading of large volumes of sand after generation of the regressive erosion surface (Fitzsimmons and Johnson, 2000). Local sharp facies changes were also detected at the upper interval of the Alfarcito Member. This may suggest that part of this upper prograding interval may reflect a forced regression, but additional work is required to test this hypothesis.

There is a marked contrast in the thickness of the transgressive and highstand systems tracts between the Rupasca Member and the Casa Colorada and Alfarcito members in that in the Rupasca Member, transgressive systems tracts are thicker than highstand systems tracts. This is consistent with the overall deepening trend reflected by this unit and records a continuous, transgressive episode by the late Tremadocian. Deepening is also revealed by coeval outcrops in Eastern Puna where the Chiquero Formation contains approximately 2000 m of fine-grained turbidites and hemipelagic shales (Benedetto *et al.*, 2002). Deep-marine deposits reveal a major change by comparison to the early Tremadocian Las Vicuñas Formation of Western Puna and the Taique Formation of Eastern Puna which record sedimentation in shallow marine settings (Moya *et al.*, 1993; Astini, 2003). Regional evidence, therefore, suggests increased subsidence rates, probably related with back-arc extension.

By contrast, deposits attributable to transgressive systems tracts are thin, a few meters thick, in the Casa Colorada and Alfarcito members. This may prompt the following question: «where have most of the transgressive systems tracts gone?» In the case of the Casa Colorada Member, transgressive deposits are mostly represented by the estuarine infill of the Tilcara paleovalley, which represents a «hidden» Cambrian stratigraphy for the area, while the interfluve areas were reworked, with little deposition (Mángano and Buatois, 2004). Coeval incised valleys have been detected further south in the Parcha area (Sococha Formation of Astini, 2003). The same interpretation can be made for the heterolithic fine-grained unit of the lower interval of the Alfarcito Member which overlies estuarine deposits herein included in the Pico de Halcón Member. However, in the Alfarcito area no estuarine valleys associated with the heterolithic fine-grained units of the middle and upper intervals of the Alfarcito Member have been detected. On the other hand, coeval units (Cardonal and Devendeus formations) in the Parcha area are mostly valley fill deposits (Astini, 2003). Also, tide-dominated facies, suggestive of tidal amplification due to valley morphology, are common in the Cardonal Formation. It may be that some of the valley incision surfaces (sequence boundaries) in the Parcha area may become the co-planar surfaces recorded in the Alfarcito Member in the Alfarcito area and adjacent regions. In short, our analysis reveals the pitfalls of the standard «layer-cake stratigraphy» approach to the lower Paleozoic of northwest Argentina and suggests that stratigraphic hiatus in open marine deposits are more common than envisaged by current schemes. This model has strong implications for biostratigraphic studies in the Northwest Argentina Basin because it predicts the existence of several hiatus in the Upper Cambrian-Tremadocian succession.

CONCLUSIONS

1) The Upper Cambrian-Tremadocian succession at the Alfarcito area is placed in the Santa Rosita Forma-

tion. This formation is subdivided formally into six members, the Tilcara, Casa Colorada, Pico de Halcón, Alfarcito, Rupasca and Humacha members. This revised stratigraphic scheme has the advantage of retaining for the study area a widely accepted stratigraphic unit (*i.e.* the Santa Rosita Formation) while recognizing its internal complexities with members that can be traced laterally across most of Cordillera Oriental.

2) While the Tilcara and Pico de Halcón members commonly contain structures indicative of tidal dominance and record deposition in incised valleys, the Casa Colorada, Alfarcito and Rupasca members typify sedimentation in wave-dominated open-marine environments, where background suspension fallout sedimentation was punctuated by oscillatory flows during storms.

3) The Casa Colorada Member reflects a basin-wide Late Cambrian transgression and subsequent incipient progradation. The Alfarcito Member records three main transgressive-regressive episodes during the early to early late Tremadocian. The Rupasca Member is a dominantly fine-grained unit that records a major, late early to early late Tremadocian transgression.

4) The importance of integrating biostratigraphic studies within a sedimentologic and sequence stratigraphic framework is underscored in this study. This approach is essential to construct a more accurate stratigraphic framework and delineate more precise correlations.

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APPENDIX

Proposed Stratigraphic Subdivision

The Santa Rosita Formation is here formally subdivided into six members (following the International Stratigraphic Guide, Salvador, 1994): the Tilcara, Casa Colorada, Pico de Halcón, Alfarcito, Rupasca and Humacha members. The Tilcara Member is not well exposed in the Alfarcito area. Accordingly, the type section is placed outside of the study area based on observations in the Quebrada de Humahuaca area. Outcrops of the Humacha Member were not identified in the Alfarcito area and the type section is located in the eponimous creek.

Tilcara Member

Type section: Quebrada de Abra Blanca.
Type area: Quebrada de Humahuaca.
Facies: Trough cross-stratified sandstone, parallel laminated mudstone, interlaminated sandstone and mudstone and thick-bedded tabular cross-stratified sandstone.
Thickness: 60 m at the type section.
Boundaries: The base is placed where trough cross-stratified sandstone replaces large-scale planar cross-stratified sandstone of the Chalhualmayoc Formation. The boundary marks the incision of a fluvial-estuarine valley. The expression of this surface is highly variable throughout the basin (Mángano and Buatois, 2004). The top is placed where thinly interbedded mudstones and sandstones with combined-flow ripples that make up the lower interval of the Casa Colorada Member replace thick-bedded tabular cross-stratified sandstones that characterize the upper interval of the Tilcara Member. The boundary marks the change from restricted, tide-dominated deposits to open-marine, wave-dominated deposits.
Fossils: No fossils were found.
Age: Late Cambrian?

Casa Colorada Member

Type section: Quebrada de Rupasca.
Type area: Alfarcito.
Facies: Greenish gray mudstone and mudstone with interbedded combined-flow rippled sandstone.
Thickness: 85 m at the type section.
Boundaries: The base is placed where thinly interbedded mudstones and sandstones with combined-flow ripples overly thick-bedded tabular cross-stratified sandstones that characterize the upper interval of the Tilcara Member. The boundary marks the change from restricted, tide-dominated deposits to open-marine, wave-dominated deposits. This surface is not well exposed in the Alfarcito area, but is present in the Quebrada de Humahuaca area (*e.g.*, Quebrada de Abra Blanca). In Quebrada de Rupasca, it is approximately at 60 m above the base of the measured section. The top is placed where thick-bedded planar cross-stratified sandstones, wavy-bedded sandstone and mudstone, and flaser-bedded, ripple-laminated sandstone overly interbedded mudstone and thin-bedded sandstone with combined-flow ripples. The boundary marks the incision of a tide-dominated estuarine valley. At Quebrada de Rupasca, it is approximately at 145 m above the base of the measured section.
Fossils: Trilobites: *Onychopyge* sp. (Fig. 10e), *Parabolina (Neoparabolina) frequens argentina* (Kayser) (Fig. 10c), *Parabolinella* sp. A (Fig. 10h), *Plicatolina scalpta, Beltella* sp., *Angelina* sp.
Age: Late Cambrian.

Pico de Halcón Member

Type section: Quebrada de Casa Colorada.
Type area: Alfarcito.
Facies: Parallel laminated mudstone, wavy-bedded sandstone and mudstone, flaser-bedded, ripple-laminated and tabular cross-bedded sandstone, rhythmically laminated sandstone and mudstone and thick-bedded tabular cross-stratified sandstone.
Thickness: 120 m at the type section.
Boundaries: The base is placed where thick-bedded planar cross-stratified sandstones, wavy-bedded sandstone and mudstone, and flaser-bedded, ripple-laminated sandstone replace interbedded mudstone and thin-bedded sandstone with combined-flow ripples of the Casa Colorada Member. The boundary marks the incision of a fluvial-estuarine valley and is well exposed in Quebrada de Rupasca and is also well exposed in different areas of Quebrada de Humahuaca (*e.g.*, Quebrada de Abra Blanca). The top is placed where mudstone intervals interbedded with thin-bedded sandstones having combined-flow ripples overly thick-bedded planar cross-stratified sandstones. This boundary marks the change from restricted, tide-dominated deposits to open-marine, wave-dominated deposits.
Fossils: No fossils were found.
Age: Late Cambrian.

Alfarcito Member

Type section: Quebrada de Rupasca.
Type area: Alfarcito.
Facies: Black shale, greenish gray mudstone, mudstone with interbedded combined-flow rippled sandstone, interbedded hummocky cross-stratified sandstone and mudstone, amalgamated hummocky cross-stratified

sandstone and trough cross-bedded sandstone.
Thickness: 265 m at the type section.
Boundaries: The base is placed where thinly interbedded mudstones and sandstones with combined-flow ripples overly thick-bedded planar cross-stratified sandstones of the Pico de Halcón Member. The boundary marks the establishment of open marine conditions. At Quebrada de Rupasca, it is approximately at 265 m above the base of the measured section. The top is placed where interbedded mudstone, combined-flow rippled sandstone and hummocky cross-stratified sandstone overly trough cross-stratified sandstone and amalgamated hummocky cross-stratified sandstone. At Quebrada de Rupasca, it is approximately at 530 m above the base of the measured section.
Fossils: Trilobites: *Parabolinella argentinensis* Kobayashi, *Dividuagnostus* sp., *Bienvillia tetragonalis* (Harrington) (Fig. 10l), *Gymnagnostus* n. sp. (Fig. 10b), *Hapalopleura* sp. (Fig. 10d), *Leptoplastides granulosus* (Harrington) (Fig. 10i). Conodonts: *Cordylodus angulatus* Pander (Fig. 10p), *Cordylodus intermedius* (Furnish) (Fig. 10o), *Cordylodus* sp., *Drepanodus arcuatus* Pander (Fig. 10x), *Drepanodus*? cf. *concavus* (Branson and Mehl), *Drepanoistodus alfarcitensis* Zeballo, Albanesi and Ortega (Fig. 10aa), *Drepanoistodus chucaleznensis* Albanesi and Aceñolaza (Fig. 10ab), *Iapetognathus* sp. (Fig. 10q), *Monocostodus sevierensis* (Miller), *Phakelodus elongatus* (Miller) (Fig. 10af), *Rossodus tenuis* (Miller) (Fig. 10t), *Semiacontiodus minutus* Zeballo, Albanesi and Ortega (Fig. 10w), *Semiacontiodus striatus* Zeballo, Albanesi and Ortega (Fig. 10v), *Utahconus utahensis* (Miller), *Utahconus humahuacensis* Albanesi and Aceñolaza (Fig. 10ad), *Teridontus nakamurai* (Nogami) (Fig. 10r), *Teridontus obesus* Ji and Barnes (Fig. 10s).
Age: Early Tremadocian to late early Tremadocian

Rupasca Member

Type section: Quebrada de Casa Colorada.
Type area: Alfarcito.
Facies: Black shale, greenish gray mudstone, mudstone with interbedded combined-flow rippled sandstone and interbedded hummocky cross-stratified sandstone and mudstone.
Thickness: 210 m at the type section.
Boundaries: The base is placed where interbedded mudstone, combined-flow rippled sandstone and hummocky cross-stratified sandstone overly trough cross-stratified sandstone and amalgamated hummocky cross-stratified sandstone of the Alfarcito Member. At Quebrada de Rupasca, it is approximately at 530 m above the base of the measured section. The top is not observed in the study area.
Fossils: Trilobites: *Apatokephalus* sp., *Asaphellus* sp., *Bienvillia tetragonalis* (Harrington), *Geragnostus* sp. (Fig. 10a), *Gymnagnostus* n. sp., *Hapalopleura* sp., *Kainella*? sp. (Fig. 10k), *Leptoplastides granulosus* (Harrington), *Parabolinella* sp. B, *Peltocare norvegicum* (Moberg and Möller) (Fig. 10j), *Pharostomina trapezoidalis* (Harrington) (Fig. 10g), *Pseudokainella keideli* (Harrington) (Fig. 10f). Conodonts: *Cordylodus angulatus* Pander, *Cordylodus intermedius* (Furnish), *Cordylodus* sp., *Coelocerodontus* sp., *Drepanodus arcuatus* Pander, *Drepanodus*? cf. *concavus* (Branson and Mehl), *Drepanoistodus alfarcitensis* Zeballo, Albanesi and Ortega, *Drepanoistodus chucaleznensis* Albanesi and Aceñolaza, *Paltodus deltifer pristinus* (Viira) (Fig. 10y), *Paltodus* cf. *subaequalis* (Pander) (Fig.10z), *Phakelodus elongatus* (Miller), *Problematoconites perforatus* Müller, *Rossodus tenuis* (Miller), ?*Rossodus manitouensis* Repetski and Ethington (Fig. 10u), *Semiacontiodus striatus* Zeballo, Albanesi and Ortega, *Semiacontiodus minutus* Zeballo, *Teridontus nakamurai* (Nogami), *Teridontus obesus* Ji and Barnes, *Utahconus utahensis* (Miller), *Utahconus humahuacensis* Albanesi and Aceñolaza, *Variabiloconus variabilis* (Lindström) (Fig. 10ae). Graptolites: *Rhabdinopora flabelliformis flabelliformis* (Eichwald) (Fig. 10m-n).
Age: Late early to early late Tremadocian.

Humacha Member

Type section: Quebrada de Humacha.
Type area: Quebrada de Humahuaca.
Facies: Amalgamated hummocky cross-stratified sandstone, greenish gray mudstone, mudstone with interbedded combined-flow rippled sandstone and interbedded hummocky cross-stratified sandstone and mudstone.
Thickness: Approximately 200 m (according to Moya, 2003, fig. 4)
Boundaries: Base and top not observed in the type section.
Fossils: No record based on the fact that the unit is not exposed in the Alfarcito area.
Age: Late late Tremadocian.