Paleoenvironmental and sequence stratigraphic framework of the Cambrian–Ordovician transition in the Angosto del Moreno Area, Northwest Argentina

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Introduction

The Cambrian–Ordovician transition has been the focus of a series of biostratigraphic studies in Northwest Argentina (*e.g.,* Benedetto, 1977; Aceñolaza, 1983; Aceñolaza and Aceñolaza, 1992; Rao and Hunicken, 1995; Tortello and Aceñolaza, 1999). However, there is a remarkable absence of detailed stratigraphic sections and only a few studies deal with the associated sedimentary facies and the sequence stratigraphic framework of the Cambrian–Ordovician successions (Moya, 1998; Buatois and Mángano, in press). This has historically precluded a more accurate biostratigraphic zonation and placing of the Cambrian–Ordovician boundary. The aim of this paper is, therefore, to provide a paleoenvironmental and sequence stratigraphic framework for the Cambrian–Tremadocian succession exposed at the Angosto del Moreno area, in the southwest region of the Eastern Cordillera, Jujuy Province. Although this paper is focused on this particular section, information from other areas in Eastern Cordillera has been used for the recognition of allostratigraphic surfaces and stratal stacking patterns. We emphasize that integrated paleontologic (body and trace fossils), sedimentologic and sequence stratigraphic studies are essential in biostratigraphy. Paleontological data and biostratigraphic analysis is presented in Moya *et al.* (this volume).

The Cambrian–Ordovician succession at Angosto del Moreno: depositional environments, sequence stratigraphy and associated fauna

In contrast to other regions of Eastern Cordillera, the Angosto del Moreno succession is mostly undeformed and a continuous section can be measured (Moya and Albanesi, 2000). The base of the succession is represented by fine–grained, heterolithic deposits of the Campanario Formation, middle unit of the Cambrian Mesón Group (Figure 1). In the analyzed section, the Campanario Formation is 40 m thick and consists essentially of fine– to very fine–grained sandstone and mudstone with flaser, wavy and lenticular bedding deposited in intertidal areas of a macrotidal depositional system (Moya, 1998; Mángano and Buatois, 2000).

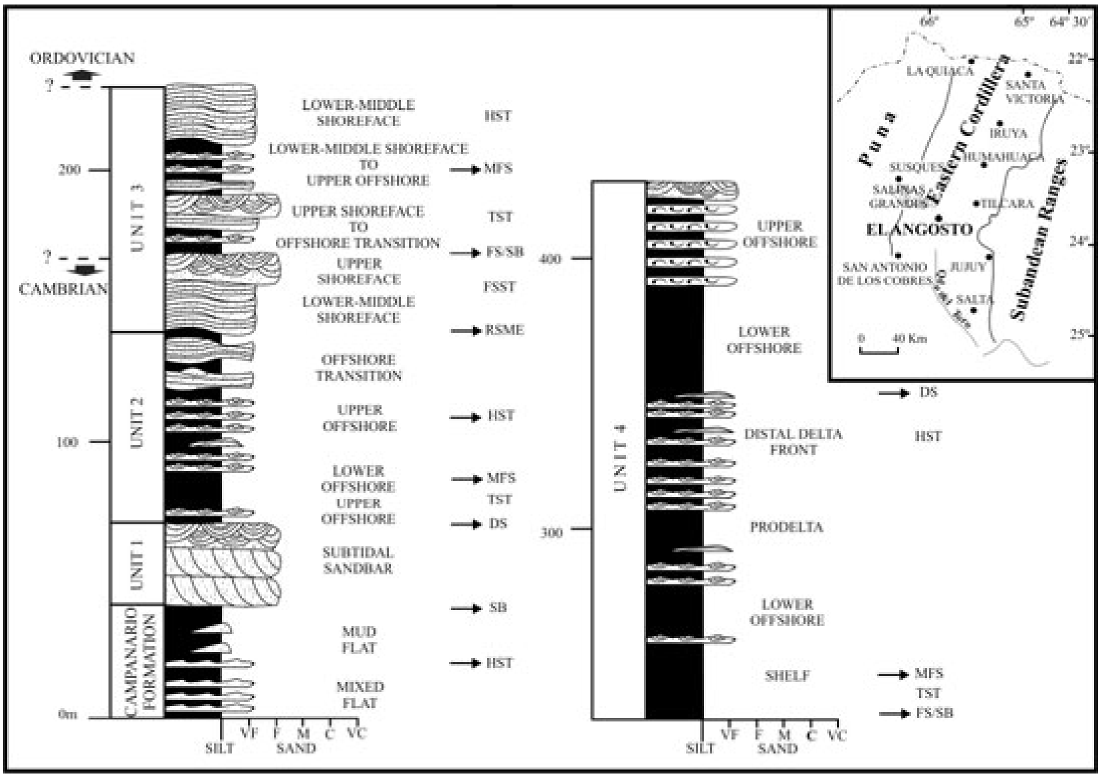

Figure 1. Location map and stratigraphic log of the Upper Cambrian–Tremadocian succession at Angosto del Moreno. TST, transgressive systems tract. HSST, highstand systems tract. FSST, falling stage systems tract. SB, sequence boundary. DS, drowning surface. RSME, regressive surface of marine erosion. FS/SB, amalgamated sequence boundary and flooding surface.

These fine–grained deposits are replaced upwards by a sandstone interval (unit 1) that traditionally has been referred to as the Padrioc Formation (Figure 1). This unit is 30 m thick and dominated by large scale tabular and trough cross-stratified, well-sorted, medium– to fine-grained quartzose sandstone beds that record deposition in subtidal sandbars. Correlation of this sandstone body is problematic due to the scarcity of body fossils. The presence of *Parabolina (Neoparabolina) frequens argentina* (Moya and Monteros, 2000) suggests that this unit is the basal sandstone of the Late Cambrian–Early Ordovician sedimentary cycle.

Tide–dominated sandstones of the Padrioc Formation are abruptly overlain by a mudstone–dominated succession (unit 2) (Figure 1). This unit is 70 m thick and is characterized by parallel laminated mudstone and thin, very fine–grained sandstone beds with combined–flow ripple cross–lamination and microhummocky cross–stratification. Thin to moderately thick, non–amalgamated, hummocky cross–stratified, fine to very fine–grained sandstone and shell beds occur towards the top of the interval. Fine–grained deposits contain an abundant trilobite fauna (see Moya *et al.,* this volume). Conodonts from the *Hirsutodontus hirsutus* Subzone of the *Cordylodus proavus* Zone were recovered from the shell beds (Moya and Albanesi, 2000; Moya *et al.,* this volume). The assemblage indicates a Late Cambrian age for this unit. This interval mostly represents alternating sediment fallout and storm deposition in wave–dominated, lower offshore to offshore transition environments. The lowermost parasequences display a retrogradational stacking pattern (transgressive systems tract), reflecting a transgressive episode that blanketed subtidal sandbar deposits of unit 1. Above the maximum flooding interval, the middle and upper intervals of unit 2 show an arrangement of progradational parasequence sets, representing a highstand systems tract.

Fine–grained deposits of unit 2 are abruptly overlain by another sandstone–dominated package (unit 3) (Figure 1). This unit is 90 m thick and can be divided into three distinct intervals, a lower sandstone–dominated interval, a middle mixed sandstone and mudstone interval and an upper sandstone–dominated interval. The lower and upper intervals are composed of hummocky cross–stratified, fine–grained sandstone. Sandstone beds are commonly amalgamated and internal second–order erosion surfaces separating hummocky cross–stratified laminasets are present. Proximal storm beds deposited in lower to middle shoreface environments are represented by thick amalgamated hummocky cross–stratified sandstones.

Hummocky cross–stratified sandstone bedsets occasionally pass upwards into fine–grained, trough cross–stratified sandstone units that record migration of three dimensional dunes in the upper shoreface. Amalgamation of hummocky cross–stratified beds and scarce bioturbation represented by opportunistic *Skolithos* suites indicate that the shoreface deposits of unit 3 were strongly storm–dominated. The middle member consists of interbedded parallel laminated mudstone and thin to rarely thick, fine– to very fine–grained sandstone beds with combined–flow ripple cross–lamination, microhummocky cross–stratification and hummocky cross–stratification. *Skolithos* occurs as endichnia in storm sandstone beds, while *Cruziana* is common as positive hyporelief and, very rarely, negative epirelief. Arthropod trackways are common on top of hummocky sandstone layers. This interval mostly records alternating sediment fallout and storm deposition in upper offshore to offshore transition environments, although shoreface deposits are locally present also. The lower interval most likely represents the incision of a sharp–based, forced regressive shoreface, which is included in the falling stage systems tract. The base of unit 3 is, therefore, a regressive surface of marine erosion and the sequence boundary is placed at the top of the lower interval. Lowstand deposits have not been identified and the sequence boundary is regarded as a co–planar surface or amalgamated flooding surface/sequence boundary. A subsequent transgressive–regressive cycle is detected within the middle and upper interval of unit 3. This cycle culminates with the progradation of the upper shoreface unit during a "normal" regression.

Unit 3 is abruptly overlain by fine–grained deposits (unit 4) (Figure 1). The contact between both units is a sequence boundary represented by a co–planar surface. In the analyzed section, unit 4 is approximately 200 m thick. The lower interval of unit 4 at Angosto del Moreno consists of parallel laminated mudstone with occasional intercalations of very thin, very fine–grained, silty sandstone beds with combined–flow ripple cross–lamination and microhummocky cross–stratification that become more common towards the top of this lower interval. Trilobites and graptolites are abundant in these fine–grained deposits (Moya *et al.,* this volume). The first record of *Anisograptus matanensis* is placed about 7 m above the base of unit 4, associated with scarce *Rhabdinopora* sp. *Anisograptus matanensis* is abundant through the succeeding 10 m, being the only graptolite found in these levels. It represents the *A. matanensis* Zone, the third graptolite zone of the Lower Tremadocian, according to the scheme proposed by Cooper *et al.* (1998). Interestingly, a new species of *Saltaspis* is recorded in the lowermost strata of unit 4, ranging up to 20 m from the base, in association with the graptolites mentioned.

The middle interval consists of interbedded parallel laminated mudstone and thin, very fine– to fine–grained sandstone beds with combined–flow ripple cross–lamination, microhummocky cross–lamination and, more rarely, hummocky cross–stratification. Trilobite traces, such as *Cruziana* and *Diplichnites*, are extremelly abundant, but *Skolithos* is rare. Physical sedimentary structures indicate alternation of sediment fallout and storm deposition. The presence of synsedimentary deformational structures indicates high sedimentarion rates in a relatively steep slope and a deltaic influence is inferred. Absence of dwelling traces of suspension feeders probably reflects high suspended, fine–grained sediment load due to deltaic discharge. The lower and middle intervals of unit 4 record a transgressive–regressive cycle. Transgressive deposits are present at the lowermost interval of unit 4. The maximum flooding surface occurs within the shelf deposits and is overlain by a progradational parasequence set that records deposition in prodelta to distal delta front environments of a wave–dominated deltaic system (highstand systems tract). The parallel laminated mudstones and thin shell beds of the upper interval represent the drowning of the deltaic system during a subsequent transgressive event. Despite particular efforts were addressed in search of conodonts (*ca.* 15 kg of calcarenites and calcareous coquinas completely digested by conventional acid etching techniques) no findings are registered at the moment.

Another outcrop occurs further south in the same area and has been analyzed by Gómez Martínez *et al.* (2002). This 120 m–thick interval occurs stratigraphically above the succession previously discussed. The trilobite *Kainella meridionalis* is present in these beds (Moya and Albanesi, 2000). Additionally, conodonts from the *Cordylodus angultus* Zone (Moya and Albanesi, 2000), which indicate a late Early Tremadocian age for this outcrop, were recovered.

Conclusions

This study provides a sequence stratigraphic and paleoenvironmental framework for the biostratigraphic data. Paleontologic information suggests that the Cambrian–Ordovician boundary may be located within the depositional sequence that comprises the middle and upper interval of unit 3. In particular, the sequence boundary at the top of the unit 3 may represent a significant hiatus. Therefore, the Cambrian–Ordovician boundary may be coincident with the contact between units 3 and 4. The lowermost Tremadocian graptolite zones may be absent in the basal interval of unit 4 at the studied section, reflecting a hiatus due to amalgamation between lowstand erosion and subsequent transgression. Further paleontologic sampling in this depositional sequence is essential for a more accurate delineation of the Cambrian–Ordovician transition.

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