Geologica Acta, Vol.1, Nº1, 2003, 85-94
Available online at www.geologica-acta.com

Biogenic and physical sedimentary structures in latest Cambrian-earliest Ordovician mudrock facies (Famatina Range, Northwestern Argentina)

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ABSTRACT

Lamination is a common feature in shales and other mud-dominated rocks. When combined with other geological evidence, the diverse lamination types can provide important information about sedimentary processes and depositional environments. Petrographic and Scanning Electron Microscope studies performed in the latest Cambrian-earliest Ordovician lower Member of the Volcancito Formation (Famatina Range) have revealed three distinct types of lamination in mudrocks. Thick horizontal lamination (> 0.5 mm thick) is characterized by dark clay laminae alternating with calcite and quartz-rich light colored silt laminae. Silty laminae show micro-scours at the base, and unidirectional micro-ripple cross-lamination. This type of lamination is dominant in the lower part of the succession, and it is interpreted as formed by bottom flowing currents, probably induced by storms. Wavy lamination shows clear undulation surfaces at megascopic scale. In thin section, wavy lamination is composed by alternating black organic-rich laminae less than 0.2 mm thick, and lighter colored carbonate-rich clay and fine silt laminae (0.1-0.2 mm thick). This second type of lamination is observed at the lower and middle parts of the sequence and it is interpreted as produced by benthic microbial mat development (probably cyanobacteria). Thin horizontal lamination (< 0.5 mm thick) is characterized by dark organic and clay-rich laminae alternating with lighter colored quartz-rich silty laminae. This lamination may be associated with suspension settling from dilute suspended fine-grained sediment flows. Thin horizontal lamination is predominant at the upper part of the succession. Changes in lamination and sedimentary processes observed from base to top of the studied succession record a major deepening event in the basin during the latest Cambrian - earliest Ordovician, which finally triggered the deposition of a thick lower Tremadoc black shale package. This event was also responsible of a significant faunal change through the sequence. The representing fauna of the *Parabolina frequens argentina* Biozone changes upwards from predominant benthic trilobites (e.g. *Parabolinella, Angelina hyeronimi* (KAYSER), *Shumardia erquensis* KOBAYASHI, *Onyclopyge*, etc.) to pelagic trilobites (exclusively *Jujuyaspis*), which occur associated with planktonic graptolites (*Rhabdinopora*). Changes in facies pattern and faunal components record a relative sea level rise, which resulted in a major transgression at the base of the Ordovician.

KEYWORDS **Late Cambrian-Early Ordovician. Mudrocks. Biogenic and physical lamination. Famatina Range. NW Argentina.**

INTRODUCTION

The study of sedimentary structures in modern sediments has provided important criteria that are commonly used to understand ancient depositional environments recorded by sedimentary rocks. Most studies have focused on coarse-grained sediments despite the fact that fine-grained rocks (mudrocks) comprise from 45 to 55% of sedimentary sequences (Tucker, 1991). This lack of attention given to mudstones probably results from the relative difficulty to study their sedimentary structures. Whereas the nature of sedimentary structures in sands and sand-

FIGURE 1 **a-b. Location map of the study locality in the Volcancito river section of the Famatina range in northwestern Argentina. c. Stratigrafic section of the Lower Member of the Volcancito Formation at its type locality.**

stones often can be described from field observations, examination of sedimentary structures in mudstones generally requires the use of special techniques (Kuehl et al., 1988; O' Brien, 1989; Pike and Kemp, 1996 and O'Brien et al., 1998).

Horizontal lamination is the megascopic sedimentary structure most commonly observed in mudstones (Potter et al., 1980). A lamina is the smallest megascopic layer in a sedimentary succession, usually less than 10 mm thick (Campbell, 1967). Microscopic examination of sedimentary laminae has revealed a variety of structures, including graded bedding, micro-cross-lamination, convolute bedding and wavy bedding (Stow and Bowen, 1980; Schieber, 1986; Kuehl et al., 1988; O' Brien, 1990, 1996). These features have been associated with different sedimentary processes operating in the shale formation (Schieber, 1986; O' Brien, 1990; O' Brien et al., 1998). Sedimentary processes such as bottom flowing currents or those associated with suspension settling and microbial mat development, are mentioned by O'Brien (1996) as shale generating processes.

This study deals with lamination types and sedimentary processes in the Lower Member mudrocks of the Volcancito Formation (latest Cambrian – earliest Ordovician, Famatina Range, northwest Argentina). New data on the usefulness of the laminated mud for depositional environment determination in ancient sequences are presented.

GEOLOGICAL SETTING

The Volcancito Formation represents the basal unit of the Ordovician basin in the Famatina Range, northwestern of Argentina (Fig. 1). This basin was formed along the western margin of early Paleozoic Gondwana. The section studied corresponds to the type profile of the Lower Member of the Volcancito Formation, which is an approximately 160 m thick, mixed carbonate and siliciclastic succession, with notorious development of carbonate grainstones. This unit unconformably overlies a dominantly fine-grained, slightly metamorphosed and folded Late Precambrian-Early Cambrian sequence, and underlies a thick, graptolite-rich black shale package (the Middle Member of the Volcancito Formation).

The Lower Member of the Volcancito Formation in the type locality comprises, from base to top (Fig. 1c): (1) 30 m of laminated marlstones with abundant trilobites and brachiopods and thin massive and laminated skeletal intraclastic grainstones (2-35 cm thick), that show rare hummocky cross-stratification; (2) 70 m of marlstones, shales and massive skeletal intraclastic grainstones, with unidentifiable trilobite and brachiopod fragments and (3) 60 m of shales with trilobites and graptolites and scarce massive and laminated skeletal intraclastic grainstones. This sequence represents sedimentation in a mixed carbonate-clastic shelf environment. The carbonate layers are most probably storm-induced deposits, although scarce typical hummocky cross-stratification can be observed.

Widespread trilobite remains of the *Parabolina frequens argentina* Biozone and scarce undetermined brachiopods occur on bedding planes of the lower part of the succession (Tortello and Esteban, 1997, 1999; Tortello, in this volume). The upper shales contain invertebrate fauna consisting of the trilobite *Jujuyaspis keideli* KOBAYASHI and the rhabdinoporid graptolites *Rhabdinopora flabelliformis* cf. *socialis* (SALTER) and *R.f.* cf. *norvegica* (BULMAN) (Tortello and Esteban, 1999).The studied succession has also yielded an important conodont fauna within the carbonate layers (Albanesi et al., 1999), which allowed to place the precise position of the Cambrian-Ordovician boundary. In addition, the presence of algae *(Nuia siberica* MASLOV and *Girvanella*) in the carbonate layers was reported by Astini et al. (1999) and Astini and Dávila (2000).

DESCRIPTION OF THE MUDSTONE FACIES. LAMINATION TYPES

Sampling and analytical techniques

Twenty mudrock samples representing ten different stratigraphic levels were randomly collected from the Lower Member of the Volcancito Formation, which crops out in its type locality, on the western side of Volcancito river (Fig. 1). Each sample was studied by petrographic microscope and scanning electron microscope (SEM) techniques. All the facies photos shown in this paper correspond to perpendicular to bedding cut sections (photomicrographs) or broken surfaces (SEM images). Mineralogy was determined by X-ray diffraction.

Marlstones and shales are the most widespread facies in the studied section. The marlstones are thick, dark gray wavy laminated beds, which often occur from the lower to middle part of the succession. Calcite and quartz (dominant), feldspars (subordinate), muscovite and chlorite (scarce) and montmorillonite (very subordinate) make up this facies. Shales are gray to green, thinly laminated and occur from the middle to upper part of the sequence. Quartz and feldspars (dominant), muscovite and kaolinite (subordinate), montmorillonite and hornblenda (very subordinate) constitute these shales.

Three types of lamination occur in the marlstones and shales of the Lower Member of the Volcancito Formation: thick, wavy and thin. Laminae are identified in thin sections based on size, shape, composition, and orientation of constituent particles. In the field only thick and wavy lamination can be recognized macroscopically.

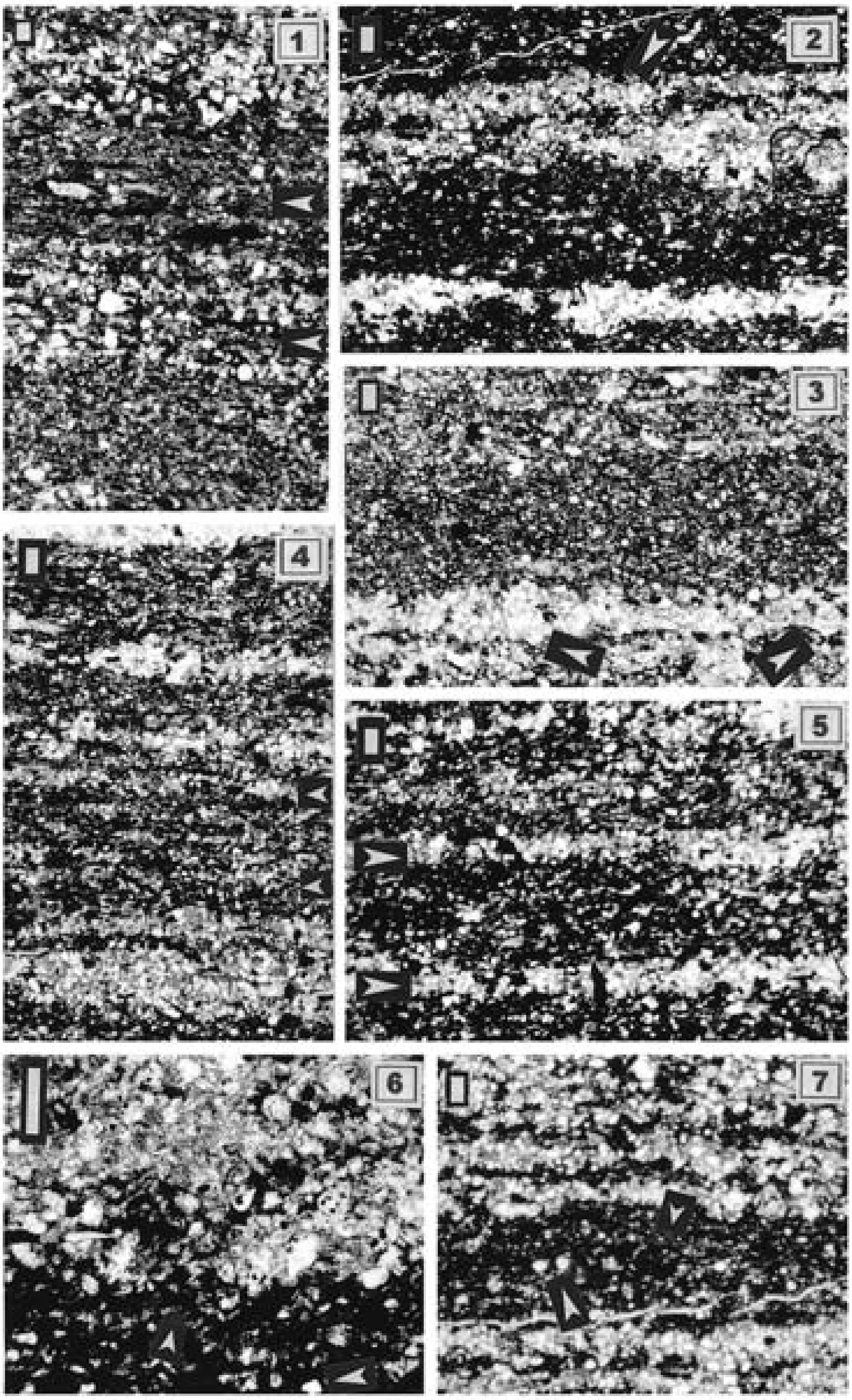

FIGURE 2 **Thin section photomicrographs of typical lamination types. 1-3. Thick horizontal lamination. 1. Non-graded laminae, light layers are quartz- and carbonate- rich (arrows), darker layers contain more organic matter and micrite grains. Sample VC1. Scale= 1 mm. 2. Lamina containing micro-cross lamination (arrow). Sample VC2. Scale= 1 mm. 3. Cut and fill feature on bedding plane (arrows). Samples VC4. Scale= 1 mm. 4-5. Thin horizontal lamination. Alternating layers of organic- rich clay (dark) and silt (light). Notice that silt layers (arrows) are composed of only a few quartz grains. Samples VC8 and VC10. Scale= 1 mm. 6-7. Wavy lamination. Notice that dark laminae display undulatory contacts (small arrows) and silt grains (large arrows). Samples VC3 and VC6. Scale= 1 mm.**

Thick horizontal lamination

Thick lamination is characterized by mostly horizontal, alternating dark and light laminae. Darker layers are finer grained than adjacent lighter layers and contain abundant montmorillonite as well as variable amounts of unidentifiable organic matter, micrite and quartz. Light layers are characterized by very fine sand to coarse silt-size grains of calcite and quartz. Scarce feldspars, opaque cubic minerals (pyrite?) and micas also occur. Small skeletal fragments of brachiopod valves and trilobites are also observed in these light layers. In this thickly laminated facies, single layers commonly are thicker than 0.5 mm and they are not internally graded (Fig. 2.1). Contacts are parallel and sharp; however, thin-section magnified views reveal micro-scour at the base of the silty layers. These micro-scours result in uneven contacts between some laminae (Fig. 2.3). Micro-cross lamination and thinning of some light laminae have also been observed (Fig. 2.2).

Wavy lamination

Wavy lamination is characterized by alternating light and dark laminae, displaying undulatory surfaces and less than 0.2 mm thick single laminae (Fig. 2.7). Lamination is given by changes in composition: dark laminae represent unidentifiable organic matter, whereas light coloured laminae are carbonate-rich with subordinated quartz, plagioclase and muscovite. The organic-rich laminae are laterally continuous and wavy; in contrast interlaminated carbonate laminae are generally discontinuous. A few silt size quartz grains are found mixed with the more abundant fine-grained organic material (Figs. 2.6-7). Filamentous calcite bodies up to 20 mm in diameter (Figs. 3.1-2 and 3.4) and calcite crystals (Fig. 3.3) in the organic-rich layers were observed with scanning electron microscope (SEM).

Thin horizontal lamination

Thin lamination displays horizontal alternating dark and light laminae commonly less than 0.5 mm in thickness (Fig. 2.4). In thin section, this lamination shows dark organic and clay-rich laminae, alternating with lighter colored fine silt layers. The light laminae are rich in quartz and contain minor organic matter and clays. Laminae are parallel and continuous with sharp contacts (Fig. 2.5). Silty layers are exceedingly thin, sometimes only one or a few grains in thickness (Fig. 2.4), while micro-scours similar to those of thick lamination are absent.

INTERPRETATION OF LAMINATION TYPES

There is a vertical change in the dominant type of lamination observed in the the Lower Member mudrocks of the Volcancito Formation (Fig. 1c). The thick horizontal lamination is dominant in the lower part of the studied succession, and the wavy lamination in the lower to middle part, where greenish gray marlstones occur. Thin horizontal lamination is predominant in the upper shales. A compositional change is also observed in the sequence, since the lower part of the succession is characterized by carbonate-rich fine-grained sediment, changing upwards to a dominantly siliciclastic facies assemblage. These vertical changes in the type of lamination and clastic composition indicate different conditions for the fine-grained sedimentation in the Famatina Basin during the Cambrian-Ordovician transition.

The thick horizontal lamination is interpreted as formed by unidirectional bottom flowing currents, probably induced by storms. Current influence is indicated by the presence of micro-ripple cross-lamination and parallel to subparallel lamination. Micro scale scours on bedding plane surfaces are an additional evidence for the episodic character of sedimentation. Low velocity bottom flowing currents could account for lateral thinning of some coarser-grained laminae. The physical sedimentary structures found in these thick laminated marlstones are also reported in modern shale facies. Rine and Ginsburg (1985) have observed in recent argillaceous sediments of the Suriname coast the presence of micro cross-lamination and parallel to subparallel lamination formed by wave generated currents. Scour and fill is other associated structure.

Similar features occur in some shales of the Volcancito Formation when viewed in thin section. Schieber (1986) has reported parallel and cross-lamination in the Mid- Proterozoic shales of Montana. This author interpreted these rocks as formed in only a few tens of meters deep subtidal environments, where storms disrupted bottom sediment. Micro-ripple cross-lamination and scour features have also been observed by O' Brien (1990) in the thickly laminated Jurassic Shales of Yorkshire, UK. These structures have been interpreted as indicative of shallow water marine conditions dominated by low-velocity bottom currents. The same evidences associated with storm activity have been reported from the Silurian Williamson Shales (New York State, USA; O' Brien et al., 1998).

In addition, the carbonate layers (skeletal intraclastic grainstones) interbedded with marl and shale facies in the studied succession also agree with the episodic character of sedimentation. Astini and Davila (2000) interpreted the grainstone beds as storm layers deposited in a shelf environment, below the average fair-weather wave base. However, the few hummocky cross-stratification units preserved in these beds also suggest that sedimentation mostly took place below storm wave base. Moreover, the fossil content of thick laminated marlstones in the lower

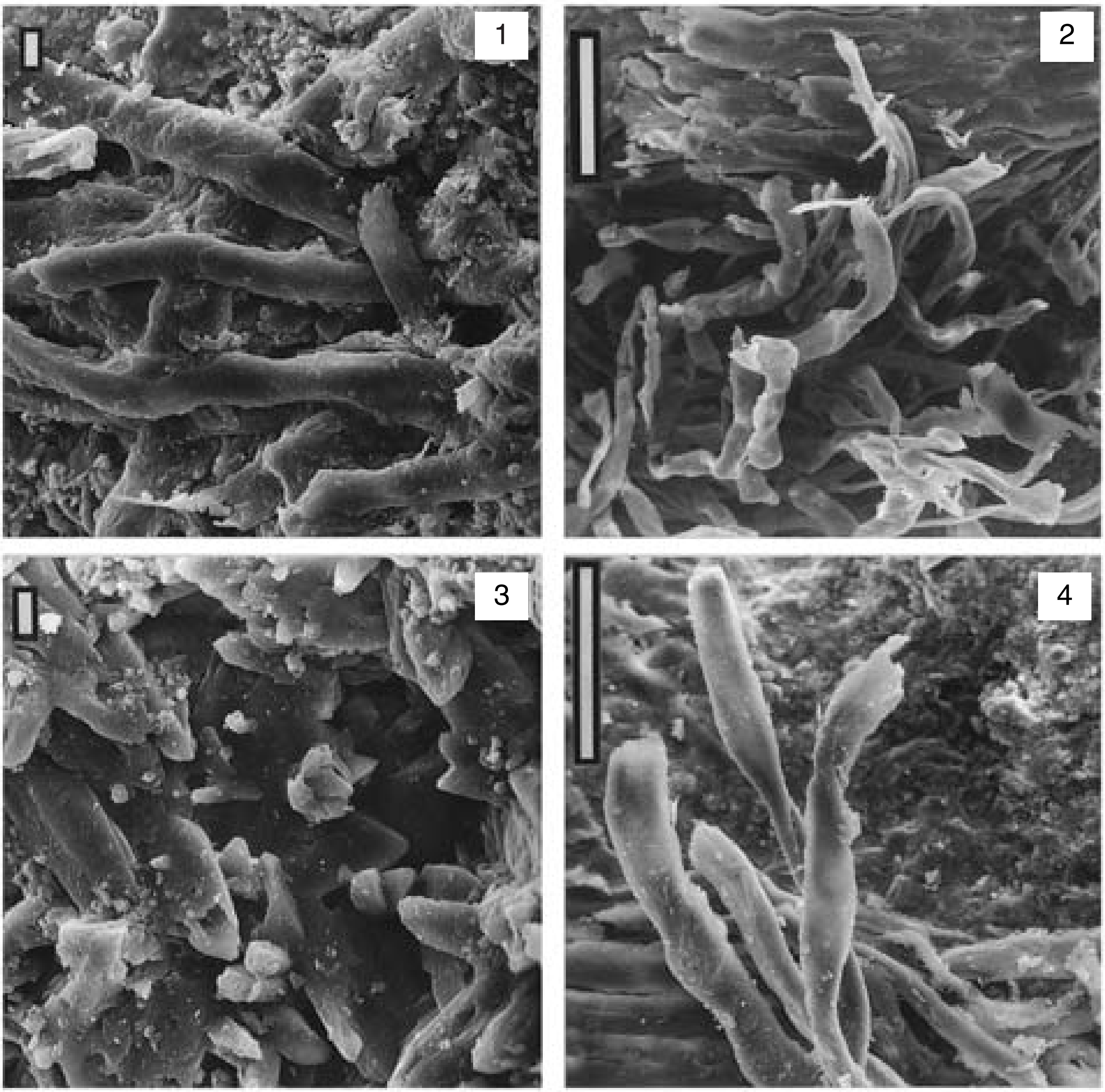

FIGURE 3 **Scanning electron photomicrographs of the organic- rich laminae in the wavy laminated marlstones. 1. Notice the presence of intertwined smooth and isodiametric calcite filaments. Sample VC6. Scale= 10 mm. 2 and 4. Group of filamentous calcite bodies. Sample VC3. Scale= 100 mm. 3. Calcite crystals mixed with organic matter in the darker lamina. Sample VC6. Scale= 10 mm.**

levels of the sequence (*Parabolina frequens argentina* Biozone, Tortello this volume), indicates shallower marine environments within the continental shelf.

The presence of wavy lamination consisting of alternating thin, light carbonate-rich and dark organic-rich laminae can be explained by microbial mat development. Although indirect indications of microbial activity (wavy lamination and silt trapping) have been observed in thin sections, recent SEM examination provides direct evidence of the participation of microbial mats in the formation of these marlstones. Remains of microbial mats are represented by calcite filaments up to 20 μm in diameter (Figs. 3.1-2 and 3.4), which can be attributed to filamentous microorganisms, probably cyanobacteria.

Bauld (1981) has described modern, commonly laminated organo-sedimentary structures developed at the sediment-water interface. These carpet-like structures (sometimes called algal mats) are built by benthic microbial communities, usually dominated by filamentous cyanobacteria. Schieber (1986) has interpreted the wavy to crinkly kerogen-rich laminae found in the carbonaceous silty shale of the Newland Formation (Mid-Proterozoic, Montana) as the main evidence of a possible microbial mat origin. He demonstrated that the wavy character of laminae and the patterns of particle trapping and "false cross-lamination" provide evidence for this interpretation. Other features that can serve as microbial mat indicators are organic laminae showing domal buildups, cohesive behavior and mica enrichment (Schieber, 1999). A similar structure has been found by O' Brien (1990) in the Toarcian Jet Rock from Yorkshire (UK).

The significance of wavy lamination in interpreting sedimentary processes is well illustrated by Kauffman (1981) in his study of the *Posidonienschifer* of Germany, which supports a model "that proposes an extensive fungal mat situated a few centimetres above the interface, entrapping anaerobic waters below".

Other possible origins for organic matter accumulation in the sediments are detritic or planktonic. When organic matter is detrital and transported by currents, the difference in specific weight between quartz silt and fragments of organic matter should result in effective sorting of organic matter and silt grains. Carbonaceous material and silt should be concentrated in discrete laminae (Schieber, 1986). If organic matter is deposited from suspension, even parallel laminae rather than wavy laminae result. In contrast, benthic origin of the organic matter is proved by silty sedimentary particles scattered within the laminae, which were deposited during mat growth (Oschmann, 2000). The observations presented here support the view that the wavy laminae in the Volcancito Formation formed as offshore benthic microbial mats, rather than accumulating from a planktonic rain of microbial matter or from fragments of intertidal microbial mats transported into the basin.

Absence of macrofauna and bioturbation within the wavy laminated strata and dark coloration of sediments, suggest that the microbial communities which built these mats were dominated by anaerobic organisms. Some cyanobacteria may occur in anaerobic habitats (Cohen et al., 1975) and others may produce anoxic conditions beneath of the mat surface, due to anaerobic decay of mat material, with formation of "anoxic" minerals (e.g. pyrite, siderite, ferroan dolomite; Schieber, 1999).

Shales with thin horizontal lamination illustrate features associated with suspension settling from suspended low density turbid flows. As noted above, these shales are also characterized by common thin well-sorted, non-graded, silt layers, with parallel and sharp upper and lower contacts. These features do not suggest sedimentation by bottom flowing turbidity currents, which would disrupt fine lamination and produce evidence of graded beds or cut and fill structures. Three possible mechanisms to produce this type of lamination have been mentioned by O'Brien (1996): 1) hemipelagic settling, 2) deposition from "detached turbid layers", and 3) deposition from dust clouds blown out into the basin.

Thin lamination, similar to that of the Lower Member of the Volcancito Formation shales, is found in recent sediments deposited from dilute suspended fine-grained sediment flows, from which silt particles rained down onto the sea floor sediment forming a thin layer only a few grains thick. Upon dissipation of a turbid layer, conditions returned to normal sedimentation.

Stanley (1983) proposed a "detached turbid layer" model to explain the thin lamination present in some Mediterranean fine-grained sediments. The laminae in these deposits are not texturally graded and neither bedforms nor load structures occur, whereas bioturbation is scarce. The same features associated with detached turbid layers activity have been reported in Middle and Upper Devonian Black Shales of New York State by O' Brien (1989). These rocks have a depositional fabric characterized by thin, parallel laminae of alternating fine organic-rich clay layers and coarse silty clayey layers, deposited under anaerobic conditions in a density stratified sea. Suspension settling in areas further offshore with deeper and quiet marine water is suggested as the dominant sedimentary process, responsible of this fine lamination type (O' Brien, 1990).

The fossil content of the thinly laminated shales suggests deeper water (outer shelf), than in the underlying marlstones. Rhabdinoporid graptolites e.g. *Rhabdinopora flabelliformis* cf. *socialis* (SALTER) and *R. f.* cf. *norvegica* (BULMAN) associated with pelagic trilobites (*Jujuyaspis keideli* KOBAYASHI) occur in these shales. Recent studies of the earliest Ordovician graptoloids suggest that *Rhabdinopora flabelliformis socialis* and *R.f. norvegica* "…represent morphotypes of populations occupying an environment marginal to that of the most abundant and diverse graptolite populations..." (i.e. the continental slope; Cooper et al., 1998).

Changes in lamination and sedimentary processes observed from base to top in the Lower Member of the Volcancito Formation, record a major deepening event in the basin during the latest Cambrian-earliest Ordovician (Fig. 4). This process resulted in the deposition of a thick package lower Tremadoc graptolites-rich black shales (= Middle Member of the Volcancito Formation). This event was also responsible of a significant upward faunal shift from the dominance of benthic organisms (subordinate braquipods and the widespread trilobites *Parabolinella, Angelina hyeronimi* (KAYSER), *Shumardia erquensis* KOBAYASHI, *Onychopyge, Plicatolina scalpta* HARRINGTON and LEANZA and *Rhadinopleura eurycephala* HARRINGTON and LEANZA) to that of pelagic

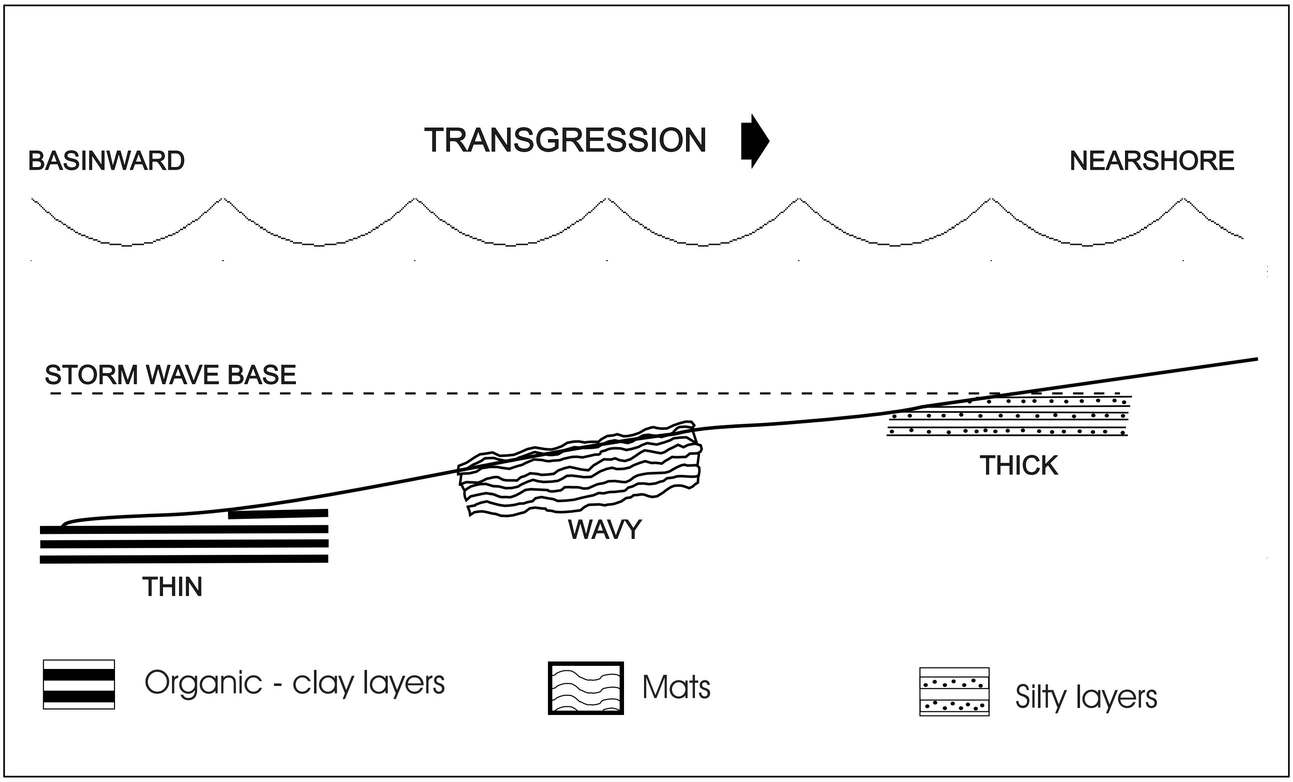

FIGURE 4 **Sketchy model with distribution of mudrock lamination type and depositional setting in the Lower Member of the Volcancito Formation .**

forms (the trilobite *Jujuyaspis* and the graptolite *Rhabdinopora*).

Changes in facies pattern and faunal components record a relative sea level rise which resulted in a major transgression in the Cambrian-Ordovician boundary interval. This transgressive event reached a maximum during the lower Tremadoc, with the deposition of a thick package of graptolite-rich black shales (= Middle Member of the Volcancito Formation). The Famatinian transgression may be correlated with the "*Dictyonema* Shale transgression " or with the transgressive phase following the Acerocare Regressive Event (Erdtmann, 1986), which is proposed by the International Working Group on the Cambrian-Ordovician Boundary (COBWG II) as the interval suitable do define this boundary horizon (Cooper and Nowlan, 1998).

CONCLUDING REMARKS

Lamination types and associated small (micro) scale features may be used to identify sedimentary processes. Microscopic studies in the Lower Member of the Volcancito Formation mudrocks (latest Cambrian-earliest Ordovician) reveal three different types of lamination. 1) thick horizontal lamination (> 0.5 mm thick), that is characterized by dark clay laminae alternating with calcite and quartz-rich silt laminae. Silty laminae show micro-scours at the base, and unidirectional micro-ripple cross-lamination. 2) wavy lamination (< 0.2 mm thick) with alternating black organic-rich laminae and lighter colored carbonate-rich clay and silt laminae displaying undulatory contacts. Finally, 3) thin horizontal lamination (< 0.5 mm thick) that is characterized by dark organic and clay-rich laminae alternating with lighter colored quartz-rich silty layers, showing parallel and sharp contacts.

The vertical sequence thick wavy-thin lamination found in these mudrocks reflects variations in the sedimentary processes, which operated on a shelf marine environment. Thick horizontal lamination indicates the influence of bottom flowing currents (most probably induced by storms), wavy lamination is produced by benthic microbial mats development (mainly cyanobacteria), and thin lamination is produced in a relatively deeper environment in which suspension settling was dominant. The fossil record reflects such a change in the environmental conditions of the basin. The benthic fauna of the lower part of the sequence (trilobites of the *Parabolina frequens argentina* Biozone) is interpreted as evidence of deposition in a relatively shallower water zone. The wavy lamination type, which prevails in the lower to middle part of the member, suggests a change in the sedimentary environment that enhanced colonization of the sea floor by filamentous cyanobacteria which were responsible for the development of microbial mats. Finally, the upper mudrocks with pelagic trilobites (*Jujuyaspis*) and planktonic graptolites (*Rhabdinopora*) indicate deeper water conditions on the shelf environment.

Thus, changes in facies pattern and faunal components in the Lower Member of the Volcancito Formation record a deepening event in the Famatina Basin during the latest Cambrian - earliest Ordovician, which may correspond with a relative sea level rise. This sea level change resulted in a major transgressive event at the base of the Ordovician and possibly was related with the transgressive phase following the "Acerocare Regressive Event" (Erdtmann, 1986).

ACKNOWLEDGEMENTS |

I thank Florencio Aceñolaza and the Instituto Superior de Correlación Geológica for logistical and financial support; Graciela Mas for X-ray diffraction analysis; Franco Tortello and Luis Buatois for their comprehensive and careful reading of an earlier version of the manuscript and Julio Pantaleón for the drafting work. Reviews by Concha Arenas Abad, and editorial review by Lluís Cabrera greatly improved the content and shape of the manuscript.

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Manuscript received October 2001;
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