NEOPROTEROZOIC PERITIDAL FACIES OF THE VILLA MONICA FORMATION, SIERRA LA JUANITA, TANDILIA

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ABSTRACT

From field observations and petrographic studies, a complex association of peritidal carbonate and siliciclastic facies have been recognized in the Villa Mónica Formation (Neoproterozoic), Sierra La Juanita, outcropping at the quarries of Estancia La Siempre Verde, Estancia La Placeres and Estancia Don Camilo, where carbonate facies have not been described ´*in situ*` since their discovery in 1967. Three different detailed stratigraphic sections are fully described. On the one hand, calcareous facies (well-preserved head stromatolites) have developed in a shallow subtidal to lower intertidal environment. Laminated microbial mats, with millimetric to centimetric scale siliciclastic intercalations, were deposited in low-energy intertidal conditions. Short-lived continental input of quartzose clastic sediments did not obliterate the microbial colonies, which grow following a pattern of thin cycles. On the other hand, heterolithic facies, developed in high-energy intertidal conditions towards the top of the succession illustrate progressive change in the paleoenvironmental conditions which evolved from a shallow prograding carbonate platform, with periodical sea level oscillations, to siliciclastic tidal influenced littoral conditions with minor development of microbial mat deposits. The recognition of 'MISS'(*microbially induced sedimentary structures*) represented by microbial mats developed in siliciclastic facies was decisive for the evaluation of paleoenvironmental conditions and for the decision to assign heterolithic lithofacies described in this paper to the Villa Mónica Formation. These microscopical structures suggest and alternation of organic microbial activity with tractive and suspensive events. The coast line was probably oriented N-S with the deeper facies located to the west. A paleoenvironmental model is proposed for the area.

Keywords: *Paleogeography, stromatolites, tidal flats, Neoproterozoic , MISS.*

RESUMEN

Facíes Peritidales neoproterozoicas de la Formación Villa Mónica, Sierra La Juanita, Tandilia.
Una asociación compleja de facies carbonáticas y siliciclásticas peritidales ha sido reconocida en la Formación Villa Mónica (Neoproterozoico) aflorante en las Estancias La Siempre Verde, La Placeres y Don Camilo sobre la base de observaciones de campo y estudios petrográficos de detalle. Se describen tres secciones estratigráficas en las cuáles las facies carbonáticas no habían sido descriptas "*in situ*" desde 1967. Las facies calcáreas basales (estromatolitos columnares) se desarrollaron en ambientes intertidales profundos a subtidales someros. Estromatolitos laminares con intercalaciones siliciclásticas milimétricas a centimétricas se depositaron en condiciones intertidales de baja energía. El aporte esporádico de sedimentos clásticos no alcanzó a obliterar a las colonias microbianas que crecieron con un patrón cíclico de pequeña escala. Posteriormente, facies heterolíticas se desarrollaron en ambientes intertidales de alta energía hacia el techo de la secuencia marcando una evolución paleoambiental desde una plataforma carbonática somera y progradante con oscilaciones del nivel del mar hacia un ambiente siliciclástico litoral-mareal con un menor desarrollo de las colonias microbianas. El reconocimiento de las MISS (estructuras sedimentarias inducidas por la acción microbiana) que se desarrollan en las facias siliciclásticas fue decisivo para la evaluación de las condiciones paleoambientales de las facies heterolíticas en la parte superior de la secuencia. Estas estructuras microbianas sugieren una alternancia de actividad orgánica con episodios tractivos y suspensivos. La línea de costa estaba orientada en dirección N-S y las facies marinas más profundas se ubicaban hacia el oeste. Se propone un modelo paleoambiental para el área de estudio.

Palabras clave: *Paleogeografia, estromatolitos, planicie mareal, Neoproterozoico, MISS.*

INTRODUCTION

The Tandilia System is a complex mountain range, composed of basement rocks and an important sedimentary cover of Neoproterozoic to Early Ordovician age, dominated by siliciclastic and carbonate facies. Different deformational and diagenetic events have affected the sedimentary units (Iñíguez *et al.* 1989; Rapela, 2007; Zalba *et al.* 2007; 2010a and b; Pazos *et al.* 2008; Cingolani, 2011).

The Neoproterozoic Villa Mónica Formation is the oldest sedimentary unit of the Tandilia Basin with a Tonian to Cryogenian age (850 Ma.) according to Cingolani (2011). It was named and first described in detail by Poiré (1989, 1993) in the stratotype area of Sierras Bayas, within the Buenos Aires Province (Fig.1 and Chart 1). This lithostratigraphic unit was correlated with the La Juanita Formation, recognized in the Barker area by Iñíguez *et al.* (1989), located 100 km to the SE of Sierras Bayas. The outcrops of the Villa Mónica Formation are only up to 10 meters thick in the studied area. Nevertheless, the unit is regionally extended and in the Sierras Bayas strato-type area located to the NW, more than 50 m thick deposits have been described.

Carbonate deposits are also widespread in the basin, being represented by two different units, the Villa Mónica Formation and the Loma Negra Formation. The first unit is a magnificent example of a Neoproterozoic record of the activity of calcified bacterial-algal organisms growing as mats and biofilms (see also Riding, 2000, Nofke *et al.* 2001). Later, these rocks were dolomitized (Zalba *et al.* 2010b). The second unit is a 45 m thick, also Neoproterozoic, black to brownish homogeneous, micritic limestone and marl deposits with a palaeokarst surface developed to the top (Iñíguez *et al.* 1989; Poiré y Spalletti, 2005, Gaucher *et al.* 2005, 2008, 2009). This sequence is widely mined by the cement industry within the Tandilia System.

Microbial precipitation of calcium carbonate has played a vital role in the development of carbonate platforms since the beginning of the Proterozoic, as they were the first large-scale biotic rock builders (Schieber, 1998; Lehrman *et al.* 2001; Yu *et al.* 2001; Sherman *et al.* 2001; Whalen *et al.* 2002; Eren *et al.* 2002; Hass y Demeny, 2002; Masse *et al.* 2003; Vasconcelos *et al.* 2006, Nédélec *et al.* 2007). Marine dolomite formation was also related to the redox state of the oceans, implying that anoxic environments promote the formation of dolomite (Burns *et al.* 2000, Vasconcelos *et al.* 2006, Tunik *et al.* 2009). The influence of such environmental factors suggests that geological variations in the carbonate formation can explain the fluctuations in the carbonate mineral supersaturation state in seawater, affecting the accretion, abundance and preservation of these deposits in time and space (Riding, 2000).

Microbial mats are well known from stromatolites in carbonates back to 3.5 Ga (Walter, 1994, Riding, 2011). Practically all the reports on stromatolites in Proterozoic basins are from carbonate environments (Awramik, 1984; Walter *et al.* 1992) whereas reports from terrigenous clastic environments are exceptionally cited (Schieber, 1998). Siliciclastic deposits are not frequent suitable rocks for fossil preservation; nevertheless, some studies have detected biosignatures of Archean age in sandy deposits (Noffke, 2006).

This contribution studies the sedimentological and paleoenvironmental characteristics of microbial mats in siliciclastic rocks of the Villa Mónica Formation, Sierra La Juanita, near Barker, with new data from three stratigraphic sections and which were not described before in the geological literature except for a recent contributions of Porada y Bouougri (2008) and Zalba *et al.* (2010a) where mixed facies were recognized and presented in an integrated stratigraphic section.

Besides a detailed mineralogical and diagenetic contribution developed by Zalba *et al.* (2010 a and b) in the Villa Mónica Formation at the Sierra La Juanita, more sections located in open pits within the study area are described and added here to exemplify these rather hidden microbial mat deposits intercalated with siliciclastics.

The recognition of typical micro patterns and morphological characteristics in mixed facies made possible to distinguish between purely physical structures, e.g. graded structures, and biogenerated structures, e.g. wrinkle structures, oriented grains within mats, wavy structures in bedding planes, crinckly lamination, concavities and convexities on dark, wavy mat layers, which were grouped together with 'petees', 'old elephant skin structures', 'mat cracks', and several other ones and named 'MISS' (microbially induced sedimentary structures) by Nofkke *et al.* (2001). The importance of the recognition of 'MISS' is also in direct relationship with the paleoenvironment characteristics.

We will discuss new peritidal depositional environment features that helped to unveil the complex geological history of this sequence. Peritidal, stratiform, Precambrian stromatolites, very similar to the examples presented here, have been described by Hofmann (1975) in the Belcher Islands, Canada.

Well exposed outcrops of the studied lithofacies are geographically very restricted within the Barker area. The sediments of this Neoproterozoic unit have also undergone diagenetic processes, and in some cases, intense deformational effects that obscured the lithofacies recognition on the field. Due to this fact most of the rock descriptions were carried out in open pits. Three outcrops were selected for the study at the localities of: Estancia La Siempre Verde (Section A, Fig. 1), Estancia La Placeres (Section B, Fig. 1) and Estancia Don Camilo (Section C, Fig. 1).

Methodology

During field work, three sections with well exposed sedimentary rocks were measured and described with detailed sampling of all the lithological types, sedimentary structures and textures. Fifty thin sections were examined using opti-

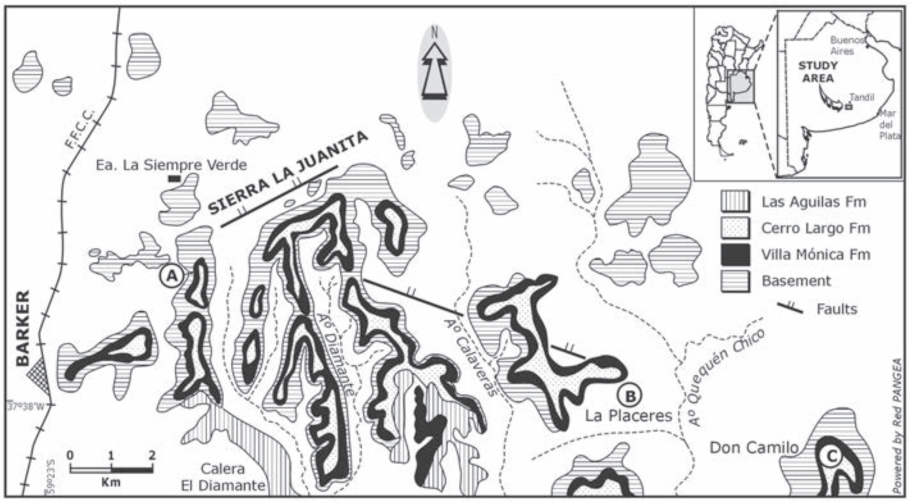

Figure 1: Geological map and location of studied sections.

TABLE 1: Stratigraphical scheme for the Tandilia Basin and regional correlation of main units.

Age / Area	Statigraphic units: Sierras Bayas		Statigraphic units: Barker		Sedimentary cycles
Early Ordovician				Balcarce Fm. (quartzite)	Batán
		Cerro Negro Fm. (claystone, marl and limestone)		Cerro Negro Fm. (Claystone, marl and limestone)	La Providencia
Neo Proterozoic	**Sierras Bayas Group**	Loma Negra Fm. (limestone)	**Sierras Bayas Group**	Loma Negra Fm. (limestone)	Villa Fortabat
		Olavarría Fm. (claystone)		Las Águilas Fm. (?) (breccia, claystone and quartzite)	Diamante
		Cerro Largo Fm. (quartzite)		Cerro Largo Fm. (quartzite)	Malegni
		Villa Mónica Fm. (dolomite, claystone and quartzite)		Villa Mónica Fm. (dolomite, claystone and quartzite)	Tofoletti
Paleo Proterozoic	Complejo Buenos Aires (granitoids)				

cal microscopy to determine textural and optical properties as well as mineral associations. Selected samples were tinted with Alizarin red and observed by optical microscopy on uncovered thin sections.

Analysed stratigraphic sections

At all studied sites, the base of the Villa Mónica Formation is clearly defined by quartzite deposits (Cuarcitas Inferiores), whereas its upper part is composed of carbonate, carbonate/siliciclastic, and heterolithic facies recognized for the first time by Zalba *et al.* (2010). The carbonate facies are represented by well preserved, columnar, brownish-yellowish stromatolitic boundstones and weathered brownish-yellowish microbial laminites according to the classifications of Dunham (1962) and Embry y Klovan (1971). Towards the top, siliciclastic and heterolithic facies are developed as alternating claystones, laminar mats associated with cyanobacteria activity and intercalated quarzitic sandstones, suggesting tidal influence in shallow areas.

A brief description of each section is provided in order to highlight the main characteristics of these infrequent preserved facies.

Estancia La Siempre Verde quarry. The Villa Mónica Formation is represented by predominantly siliciclastic basal facies (Cuarcitas Inferiores), 16 m thick -not studied here- overlain by minor calcareous deposits (dolostones, 4 m thick); carbonate/siliciclastics (2 m), and 1,5 meters of heterolithic facies (Fig. 1, Section A and Fig 2). To the top, in paraconcordance, 30 meters of quartzites are attributed to the Cerro Largo Formation (Cuarcitas Superiores).

Calcareous deposits (carbonate facies) are represented by well-developed dolomite columnar head stromatolites with diagenetic quartz megacrystals developed in dissolution cavities. Here, microbial mats commonly trap micritic sediments, sand and coarse grains, and form complex structures (Riding, 2000, 2011). These deposits are overlain by weathered microbial mats and siliciclastics (carbonate-siliciclastic facies), that also show loose, dispersed individual or random aggregates of pyramidal quartz megacrystals of different sizes. Very thin, greenish, laminated and graded clay bed intercalations (0.10 meters to some millimeters) are observed. The deposits show folding and localized brecciation effects. Fractures, showing sizes of 2 to 20 cm, are oriented in all directions and also cut the weathered microbial mat and siliciclastic deposits at all levels. In some cases they are filled with red clays (Zalba *et al.* 2010).

La Placeres quarry. At this site (Fig. 1, Section B and Fig 3), located 12 km west of the Estancia La Siempre Verde quarry, the well preserved dolostones represented by columnar and domal head stromatolite deposits with quartz megacrystals in dissolution cavities (carbonate facies) are only seen at the base of the outcrop and have shown to be completely silicified.

Above these facies, the section continues

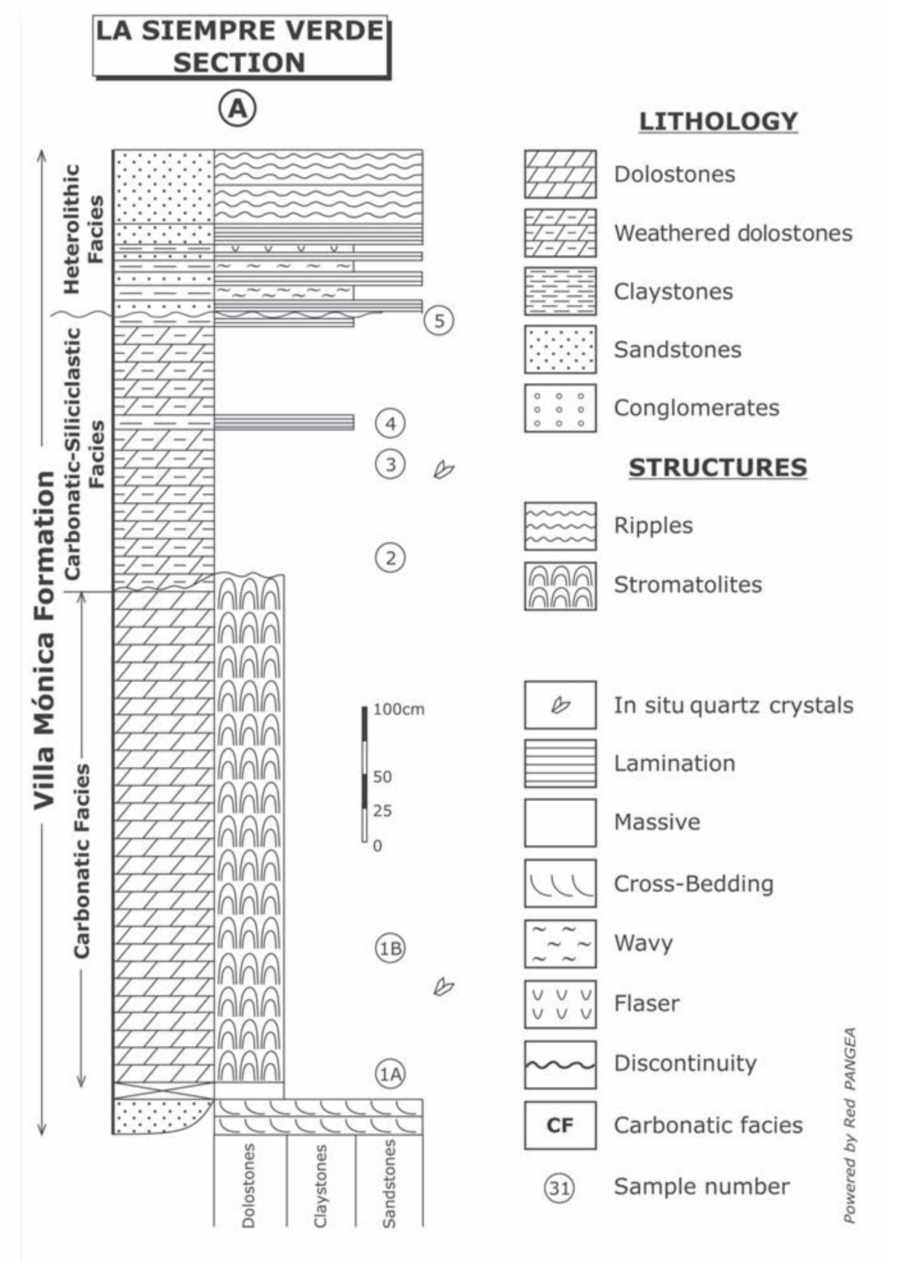

Figure 2: Estancia La Siempre Verde Section, lithology, sedimentary structures and references for Figs. 2, 3 and 4.

with up to 4 meters of weathered, brownish to yellowish calcareous mat deposits (carbonate-siliciclastic facies) with centimetric quartzite sandy intercalations (channelized bodies) and smaller, loose, pyramidal quartz megacrystals. The first mention of the presence of loose and unoriented quartz crystals within a clay matrix in these deposits was by Manassero (1986). Well-developed greenish, laminated and folded clay intercalations as in Estancia La Siempre Verde, 0.5 to 0.10 m thick, are described. All the sediments of the carbonate-siliciclastic facies are cut by fractures and cracks (2 to 20 cm wide) oriented in all directions and filled with reddish clays. Overlying this facies a thickening and coarsening upward heterolithic facies are developed.

Don Camilo quarry: this is the best developed and thicker (8 m) stratigraphic section studied where folding and fracturing are well represented (Fig. 1, Section C and Fig 4). The basal carbonate facies are not exposed and the siliciclastics show a major participation in the carbonate-siliciclastic facies than in the previous sites. The heterolithic facies is a thickening and coarsening upward sequence, represented by 2 m of alternating folded, lenticular, laminated and rippled quartzites (5 to 20 cm thick) and clay to silt-sized sediments (2 to 8 cm thick) that overlie the weathered carbonate-siliciclastic facies. Also, the complex network fracture system, infilled with reddish clays cutting different levels of these weathered rocks, is clearly observed in this area. For mineralogy and origin of these reddish clays see Zalba *et al.* (2010a-b).

Lithofacies

Neoproterozoic shallow carbonates associated with siliciclastics, with very seldom preserved sedimentary structures, are described in order to interpret the paleoenvironmental conditions of deposition.

1-Carbonate lithofacies (Figs. 5 and 6): Dominantly composed of fine grained stromatolites (laminated benthic microbial deposits, Fig. 5a) with distinct and continuous lamination, typical of most Precambrian stromatolites, with average head diameter of 10 cm, generally tubular (Druschke, *et al.* 2009, Kah *et al.* 2009, Riding, 2011) simple in shape, devoid of branching and inclination. Carbonate and clastic cycles are common (Figs. 5b and c) where the columnar boundstones are replaced to the top by a thin, coarse to medium quartz sandstones probably derived from coastal areas (Southgate, 1989; Osleger, 1991, Kah *et al.* 2009) (Figs. 6a and b). Intercolumnar areas are narrow (Fig. 6c) and filled with small quartz pebbles and coarse quartz grains (intercolumnar grit). The average synoptic thickness of the stromatolites is 30 cm, and they are constituted by calcimicrite and calcisparite debris. Shallow subtidal (above fair weather wave-base) environments are characterized by these relatively high-relief domal and columnar stromatolites associated with intraclastic and/or fine-grained detrital material (Kah *et al.* 2009). The stromatolite subtidal assemblage described by Iñíguez *et al.* (1989); Poiré (1989, 1993); Andreis *et al.* (1996); Gómez Peral *et al.* (2003); Poiré y Spalletti (2005), Gaucher *et al.* (2005) for the stratotype area of Sierras Bayas, located 100 km NW of the study area show greater diversity and it is composed by: *Colonella, Conophyton resotti, Conophyton, Cryptozoon, Gongylina, Gymnosolem, Inzeria, Jacuphyton, Jurusonia nisvensis, Katavia, Kotuikania, Kussiella, Minjaria, Parmites, Parmites cf. Cocrescens* and *Stratifera*. These stromatolites show a great diversity in shapes and microstructures and the models for their growth implicate changes in sedimentation rates or environment (Reading, 1996, Riding, 2000). In general terms, the greater the height of the elongated columns below the wave base the deeper the subtidal growing conditions. In our case, the synoptic relief of aproximately 30 cm suggests shallow subtidal to lower intertidal conditions.

The stromatolite bodies have good preservation and show well developed dissolution secondary porosity, accordingly to Zalba *et al.* (2010a) was subsequently filled by quartz micro and megacrystals (Figs. 5d and 6d) during early diagenetic stages.

2- Carbonate mixed siliciclastic lithofacies: The carbonates of these facies (Fig. 7) consist of stromatolites, with laminar structures typical of microbial features (mat deposits) like domal built-up, and ferric oxides and hydroxides stained contact features intercalated with fine-grained sandstones and shales (Dunham, 1962; Embry y Klovan, 1971, Schieber, 1998) averaging 5 to 10 cm in thickness (Fig. 7a-b). They usually occur above the largest stromatolite bodies. The cryptoalgal lamination (Prat y James, 1986, Schieber, 1998) attributed to blue-green algae, is composed of dolomicrite partially replaced by illitic clay Zalba *et al.* 2010a). Thin siliciclastic deposits re intercalated among them mainly composed of green silt to clay-sized sediments showing lamination (Fig. 7c).

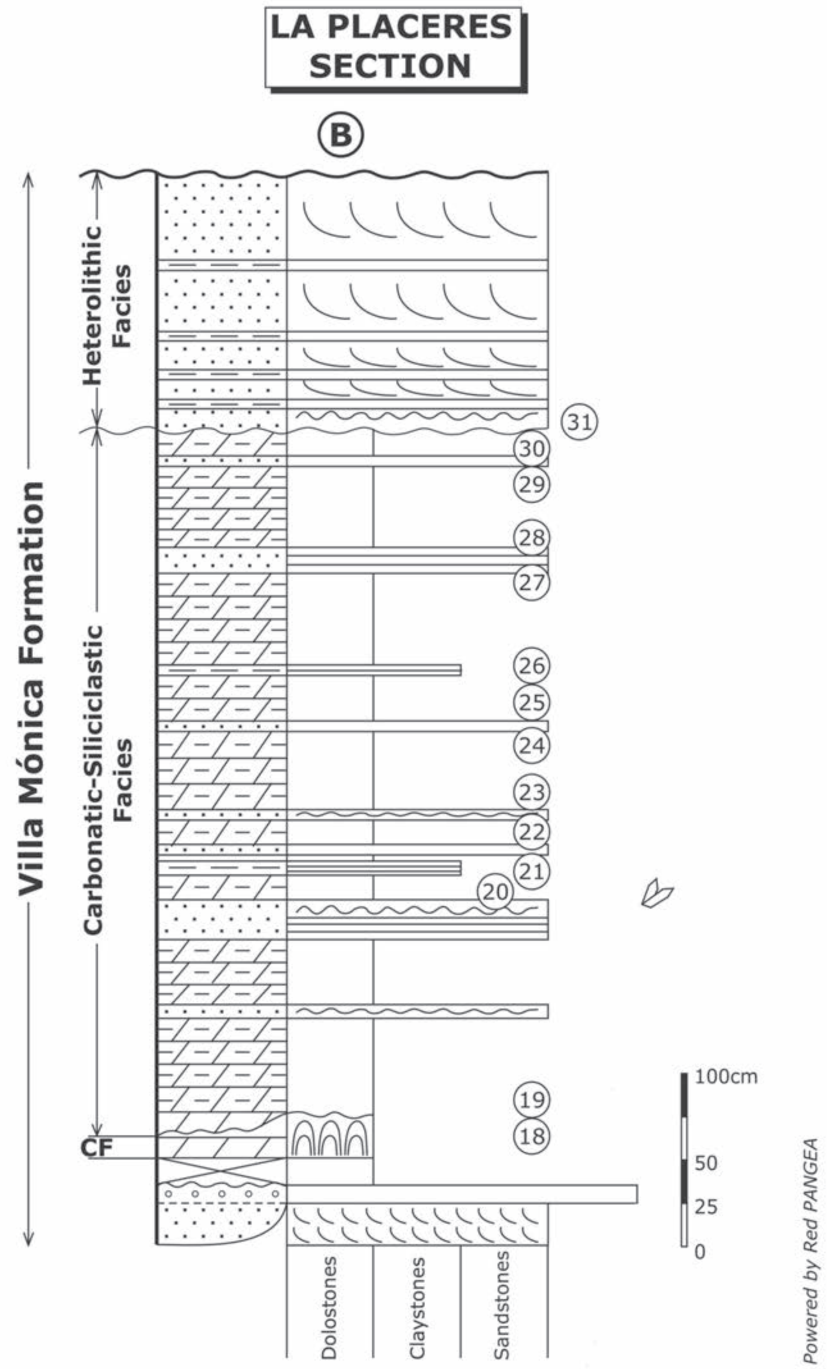

Figure 3: Estancia La Placeres Section, lithology and sedimentary structures. See references in Fig. 2.

The laminar mat layers are composed by silt to clay sized sediments and are interpreted here as having being deposited in low energy intertidal environments. From thin sections, the sedimentary structures strongly suggest biogenic influence and are recognized as microbially induced sedimentary structures MISS defined by Noffke *et al.* (2001) which, according to the authors do not arise from chemical processes, but from the biotic-physical interaction of microbial mats with the sedimentary dynamics of aquatic environments. In this case, the ´MISS` are repre-

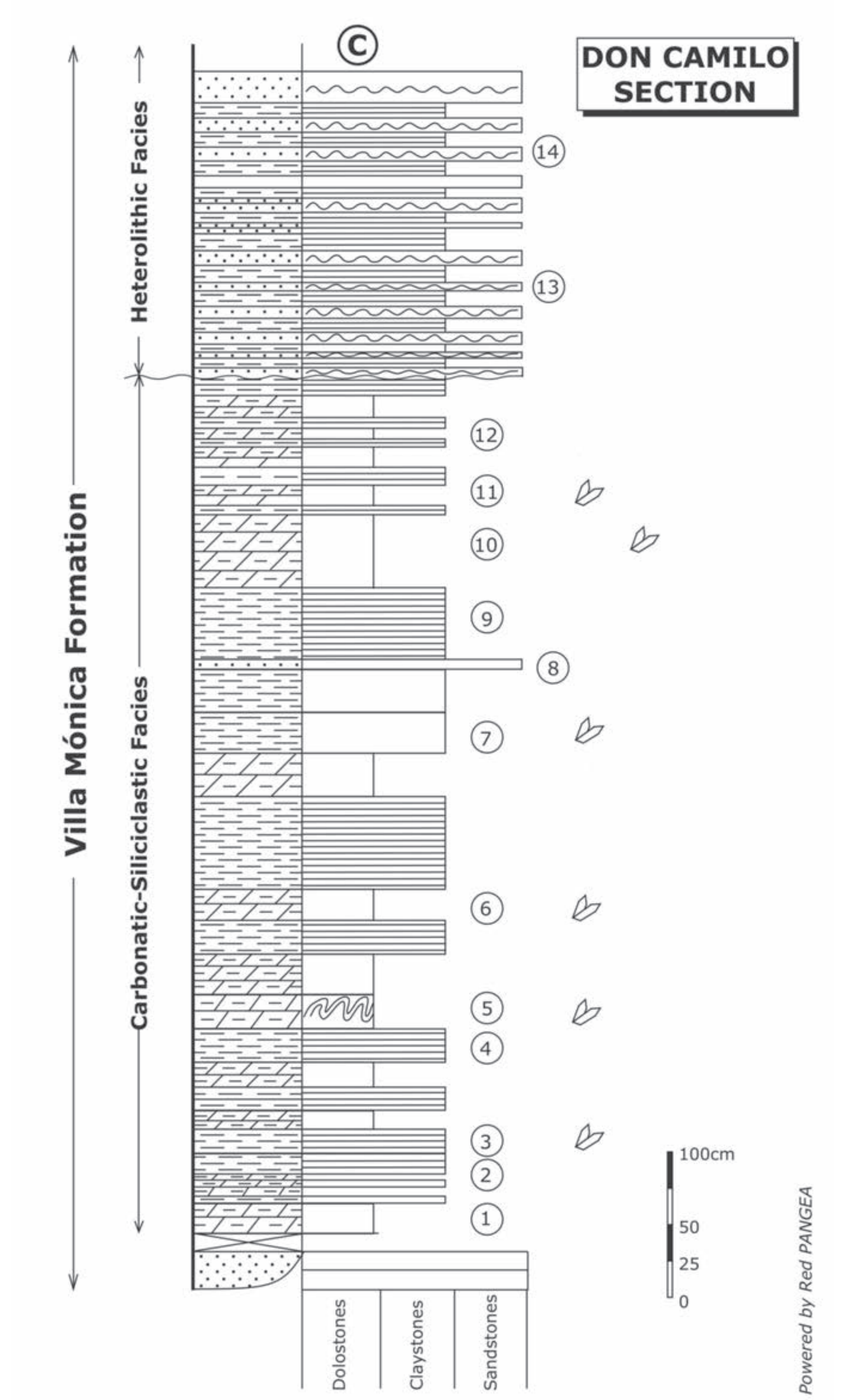

Figure 4: Estancia Don Camilo Section, lithology and sedimentary structures. See references in Fig. 2.

sented by sedimentary units of variable thickness (from microns to few millimeters) composed of two biofabrics: 1) A characteristic dark, ferric, wavy, crinckly microbial mat deposit, with silt to clay-sized detrital grains trapped within, interlayered with a 2) A carbonate layer (light area of the photograph) with relics of rhomboedra illitic clay replacing dolomite and surrounded by hematite, and where flexured micas are observed (Fig. 8a), suggesting detrital origin. On the one hand, no biogenic structures have remained after carbonate neogenesis in the light area of the unit, presumably because of the force of carbonate crystallization. On the other hand, microbial mat preservation (dark area of the photograph) has been possible on account of precipitation of ferric oxides which prevented the development of diagenetic carbonates (Hofmann, 1975).

These facies are interpreted as crypto microbial laminites based on the presence of very thin wavy-crinkly laminae, which may be locally domed with peloidal microtextures, alternating with other species of microbial mats where carbonate crystallization destroyed the biostructures (Fig. 8a).

The siliciclastics of the carbonate mixed-siliciclastic lithofacies are represented by scarce, lenticular sand, and silt to clay-sized sediments. Within the fines, it is important to differentiate two types:

1) Purely physically deposited siliciclastic beds, composed of silt and illitic clay with graded structure (Fig. 8b) due to differential settling from suspension after flooding events (Reineck y Singh, 1986), associated with tides and even storms (Reineck and Gerdes, 1996).

2) Siliciclastic-microbial mat units: (Fig. 8c) They are composed of two parts: A) Grain-supported silt to sand-sized sediments interlayered with thin microbial mats, and showing graded structure, with some grains orientated preferentially with their long axis parallel to the sedimentary surface. B) The siliciclastic material decreases and a dark, wavy crinckly lamination with detrital material floating within becomes more abundant. These dark deposits represent microbial laminae with pigmentation (ferric oxides). Within the microbial mats, all the detrital grains are oriented with their long axis parallel to the sedimentary surface. In this context, these structures are considered part of the 'MISS' (Noffke *et al.*

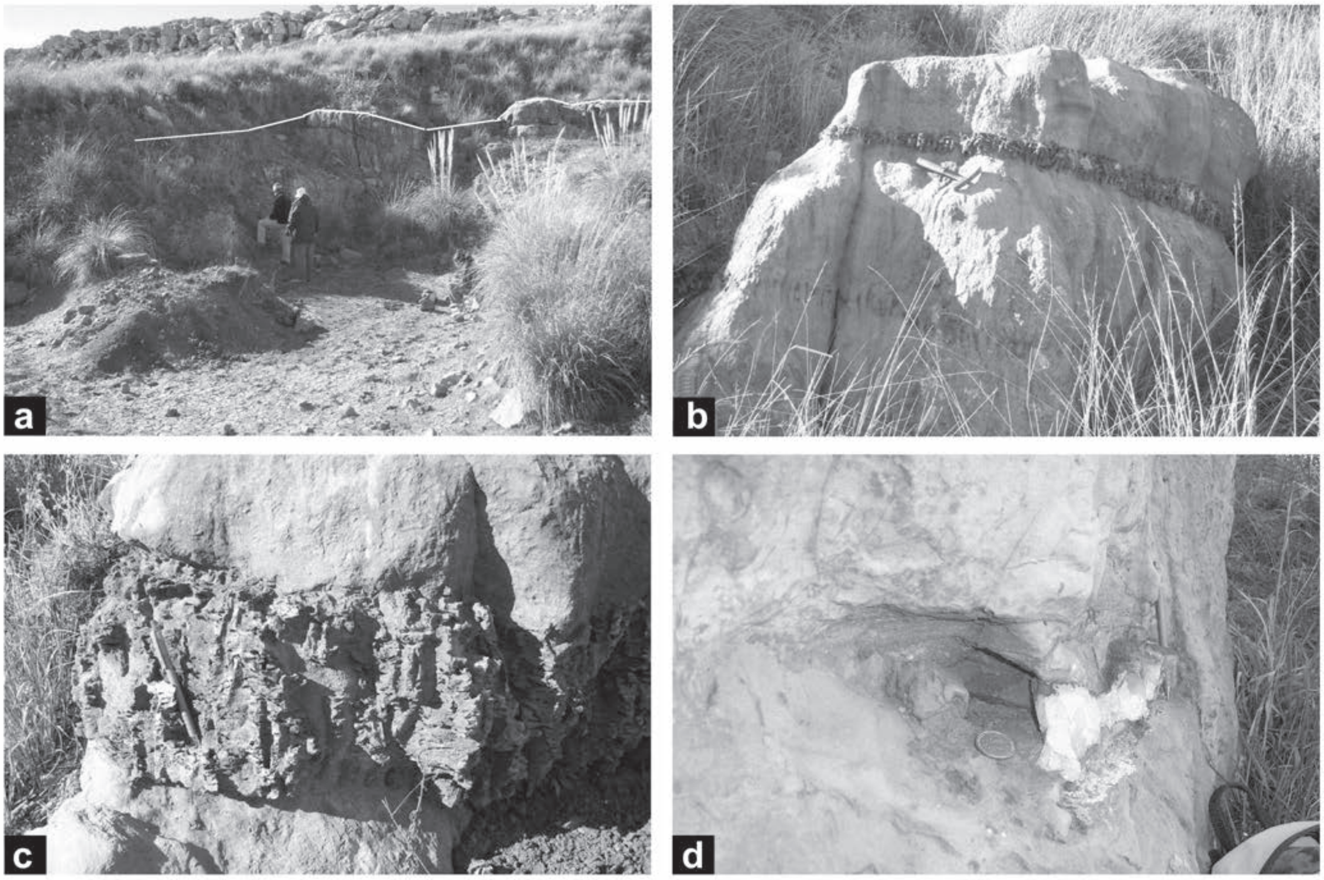

Figure 5: Low energy subtidal to lower intertidal lithofacies. a) General view of stromatolite bodies. b) Shallowing upward cycles with sandy beds to the top. c) Detail of top of cycle. d) Megaquartz crystal in cavities of dolostones.

2001, 2003, Nofkke, 2009).

The graded structure has been preserved and the microbial laminae occupied, trapped and, at the same time, stabilized the sedimentary surface. In the upper intertidal and lower subtidal zone of tidal flats, microbial mats are developed and stabilize the sedimentary surface (Krumbein *et al.* 1994). Each microbial mat essentially represents a plane of low-rate deposition, as stated by Noffke *et al.* (1997). During its development, grains still fall down and become glued together by the microbial mat described by Shinn (1983) as 'trapping'. As they grow upwards, the mats gradually incorporate the grains, a feature described as 'binding' by Dunham (1962). Microbial mat formation in bedding planes may support the separation of sedimentary units (Gerdes *et al.* 1991).

The characteristics of microbial mats appreciated on vertical thin sections (dark coloured, undisturbed, and wavy, wrinkled laminae), as sustained by Noffke (2007), are important diagnostic characteristics to differentiate similar wrinkle structures but originated by abiogenic processes in an autocyclic tidal flat.

3. *Heterolithic deposits* (Fig. 9a, b, c and d). These rocks predominate towards the top of the unit and were named 'Psamopelites' by Poiré e Iñíguez (1984) and assigned to the overlying Cerro Largo Formation. They contain abundant traction structures, such as symmetrical wave ripples suggesting deposition up to the breaker zone.

From thin section observations it is clear that this coarsening and thickening upward arrangement also depicts microbial mat development but with a drastic diminution of its activity towards the top of the unit with respect to siliciclastic episodes. The microbial mats in these facies are represented by dome-shaped, dark, ferric crinkly laminae with isolated, detrital grains within the mats oriented parallel to the sedimentary surface (Fig. 10a, dark areas of the photograph).

The microbial mats alternate with siliciclastics, well-sorted, well rounded-shaped quartzose deposits (light area of the photograph) which show graded structure, some orientation of the long axis parallel to bedding, and the grains 'floating' in an illitic epimatrix. Fractured sedimentary micro dikes are considered to represent structures developed by compaction in response to different rheological properties of ancient microbial mats and grain-supported sand beds subjected to deformation. Note illitic epimatrix and tangential coatings in the quartz grains (Fig. 10b).

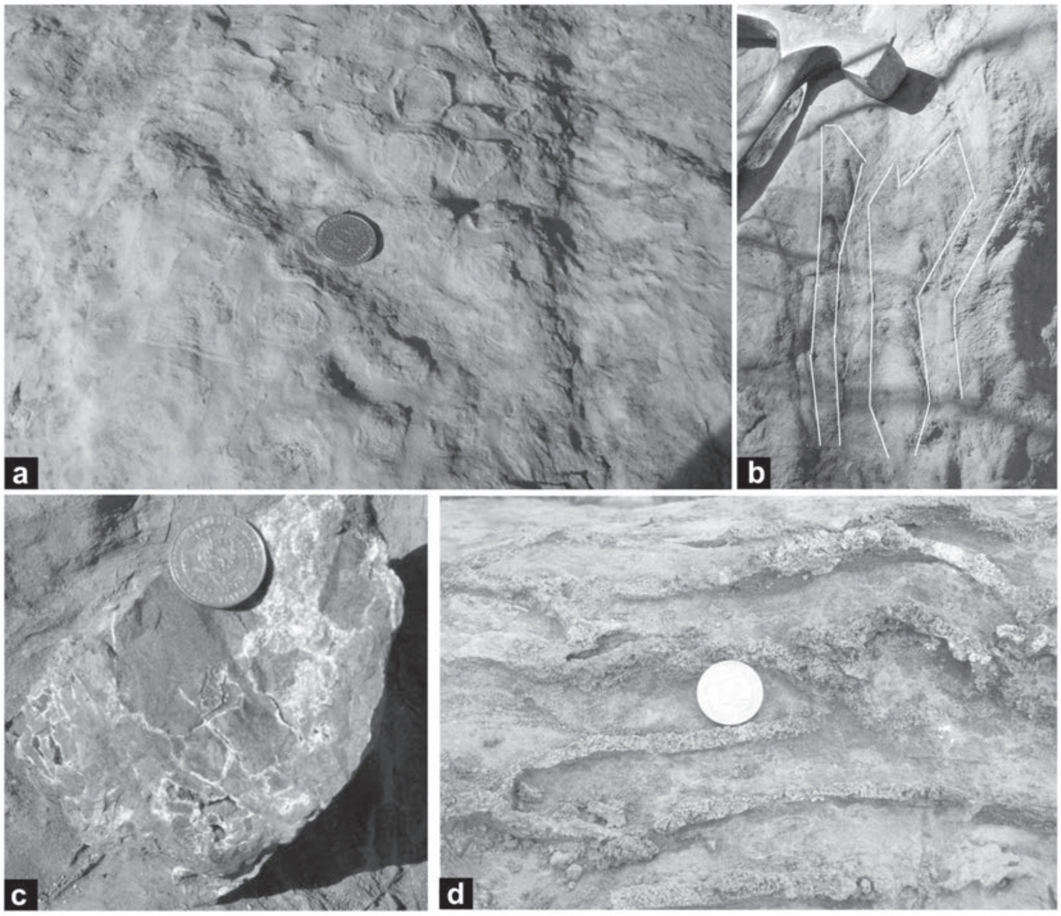

Figure 6: Low energy subtidal to lower intertidal lithofacies. a) Plain view of algal head dolostones b) View of the section of the previous slide. c) Microquartz crystal filling fractures and interparticle porosity. d) Intercolumnar quartz grit and plain view of algal head dolostones.

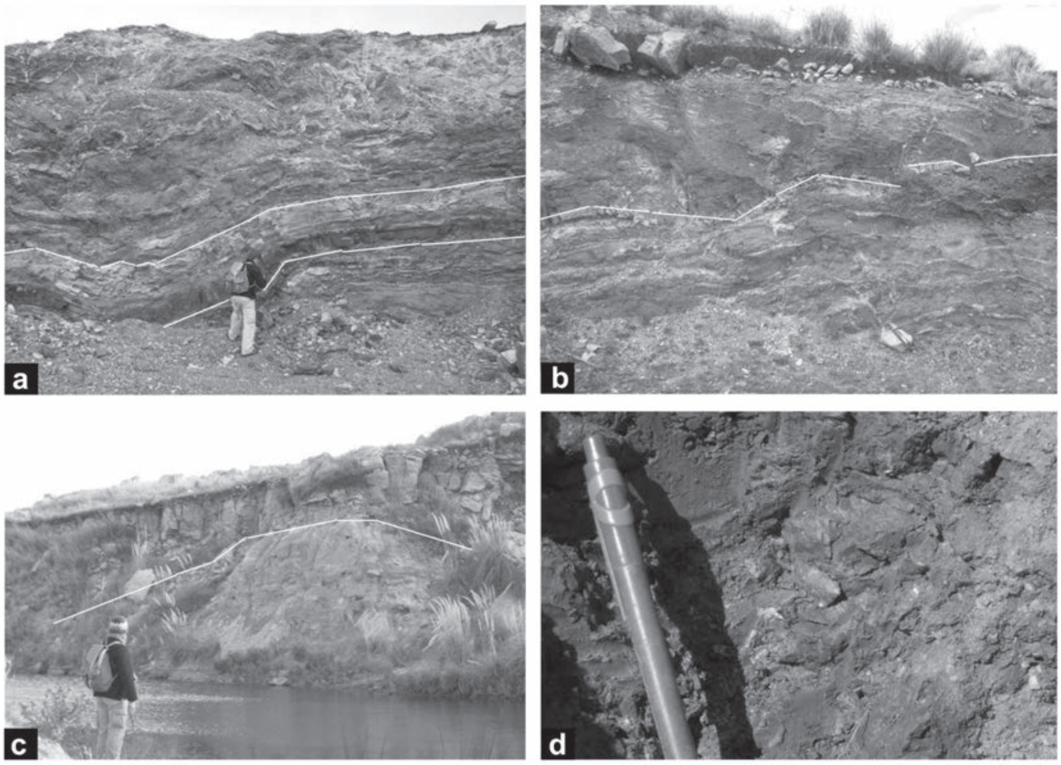

Figure 7: Low energy intertidal lithofacies. a) General view of Don Camilo quarry. b) Close up of previous slide and fine bedding features. c) General view of La Placers Quarry, d) Detail of loose quartz crystals in fine altered carbonate laminar mat associated with siliciclastics.

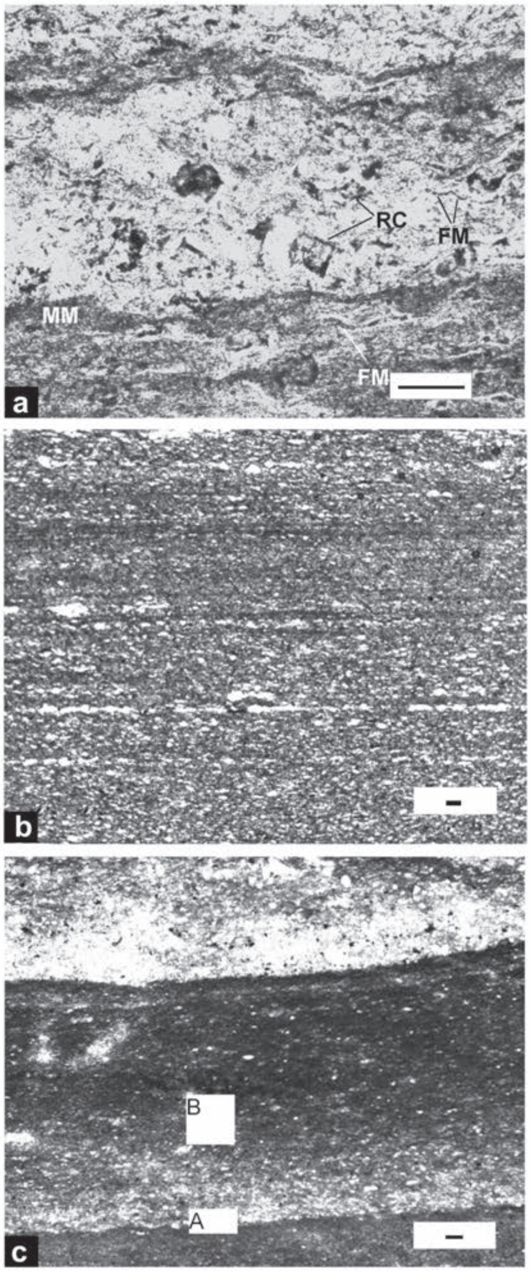

Figure 8: Thin sections of mixed-siliciclastic lithofacies. Bar scale 100 microns. a) Low energy intertidal mixed facies: ´MISS`. Dark, hematized, wavy crinkly microbial mat laminae (MM) alternating with light parts containing illitized dolomite with ghost rhomboedral crystals (RC). Abundant flexured detrital micas (FM) are seen in both dark and light portions of the ´MISS`; b) High Energy intertidal heterolithic lithofacies: Purely physically deposited siliciclastic beds. Silt to clay-sized sediments with graded structure; c) ´MISS` composed of two parts: A) A basal, grain-supported silt to sand-sized sediment with graded structure and minor interlayered microbial mats. Some grains are oriented with their long axis parallel to the bedding plane. B) Dark, wavy, crinkly microbial laminae with detrital grains ´floating` within and all oriented with their long axis parallel to the bedding plane.

Paleoenvironmental conditions

The carbonate facies are located to the base of this unit and include five meters of dolopackestone/wackestone described in the La Siempre Verde Section (Fig 2). This carbonate platform is composed of abundant stromatolites of dominant columnar and domal shapes and sizes up to 30 cm high (Fig 5 and 6) similar to the ones described by Jiang *et al*.. (2003) for a tidal Proterozoic carbonate platform within a passive margin setting in Asia. The columnar stromatolites are commonly linked with peloids, ooids and intraclasts present in lows between stromatolite heads. The relatively high relief limits interference and generates these simple shapes like columns and domes we see in the study area, on the other side, low relief permits sediment to interfere with accretion and generates branching (Riding, 2011). These facies are interpreted to have accumulated in a relatively undisturbed shallow subtidal to lower intertidal environment.

In the carbonate-siliciclastic deposits the grain-supported intervals of the siliciclastic/microbial mat units indicate the initial deposition of coarse grains from suspension in a relatively upper flow regime. When flow velocity decreases the grain size decreases gradually to finer sediments. The origin of grading in intertidal flats has been attributed to deposition in the last phase of heavy floods (Reineck y Singh, 1986). As stated by Noffke *et al.* (1997), and also sustained by Kah *et al.* (2009) in modern environments the orientation of the grains within the mats with their long axis parallel to the bedding plane points out to an energetically suitable position following gravity forces, made possibly by the friction reduction of the soft organic matter. According to these authors the particles in the grain-supported part of the sedimentary unit (siliciclastic-microbial mats) do not show predominant orientation of their long axis parallel to the bedding plane, since the compact fabric may not allow for their arrangement according to gravity.

We agree with Noffke *et al.* (1997) in that build-up of these types of successive sedimentary units is a response to alternate depositional and non-or-low-rate depositional events. No reworking of the surface of each unit is perceived, since microbial mats prevent erosion during periods of increased flows. Otherwise, the units would lose their appearance and would have been amalgamated. A specific character of the occurrence of microbial mats is the arrangement of detrital quartz grains within the organic layers and the presence of separation surfaces between sedimentary units, whose preservation is precisely attributed to microbial activity and which result in bedding planes in consolidated rocks after burial.

Many authors coincide in that the recognition of microbial mats in ancient terrigenous sediments is a difficult task, due to the fact that mat morphology is obliterated first by depositional processes or bioturbation and later by compactional processes (Schieber, 1998). The interpre-

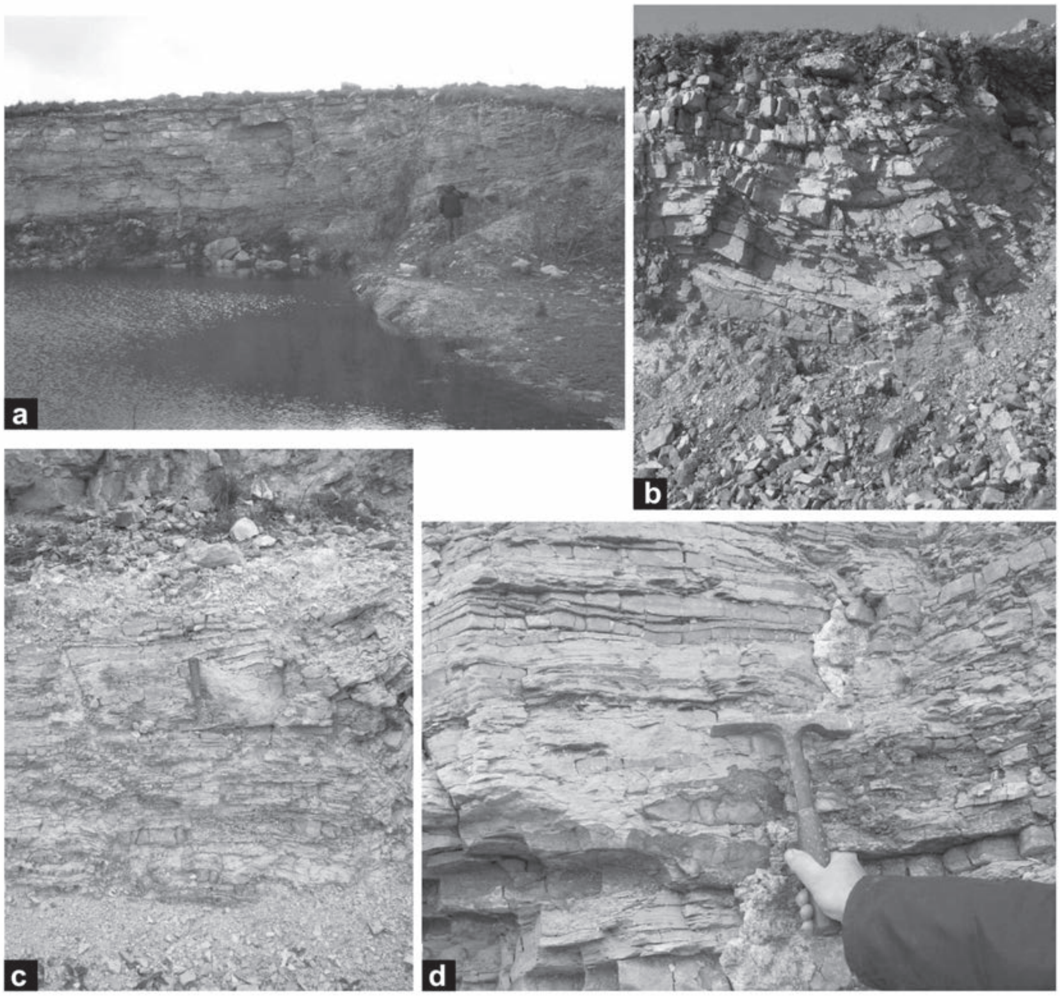

Figure 9: High energy intertidal heterolithic lithofacies. a) General view of Don Camilo Quarry. b) Close up of previous slide, c) Detail of symetrical wave sedimentary structures. d) Quartz dominated heterolithic lithofacies.

tation of fine-grained Precambrian stromatolites is a challenge, as we do not know if they are agglutinated or precipitated and which microbes are involved, and also many morphotypes of these Proterozoic bodies have no modern analogues. They occur in a variety of modern tropical environments, from humid shores where they pass laterally towards freshwater marsh or to evaporite sabkhas (Riding, 2000).

The potential of preservation is also controlled more by the presence of these microbial communities than by physical factors, because sediment surfaces colonized by microbes are less erodable. Features like wrinkle structures (Fig. 9) as well as erosional marks and microbial sand chips are formed by tractional currents in intertidal and supratidal zones (Bouougri y Porada, 2002).

Considering the balance between the proportions of sediments and the development of microbial laminae it is possible to infer that the detrital short-lived continental input was not strong enough to eliminate the microbial colonies, but allowed them to grow in thin cycles.

The fact that concavities and convexities of microbial mats do not superpose upwards in the sequence would mean that the growth of the microbial mats would have to be interrupted by external periodically controlled events (environmental) occurring in tidal flats such as seasonal episodes (Hofmann, 1975). When buried by sand, the bacteria quickly migrated upward towards the new sedimentary surface, where they established new mat fabrics (Noffke, 2007). The microbial mats usually develop under translucent quartz that conducts light into deeper portions of the biofilms in sites with moderate hydraulic reworking. These biofilms must be able to tolerate the physical sediment dynamics caused by waves and currents (Noffke, 2009).

The recognition of a mixed origin for the carbonate-siliciclastic and heterolithic lithofacies by Zalba *et al.* (2010 a,b), considering a microbial control versus pure detrital processes in the sedimentary record was decisive in the right assessment of the paleoenvironmental conditions. The association of mud-silt-sand tidal deposits with flaser and lenticular bedding with wrinkle and 'MISS' has been studied in detail (Noffke, 2009).

The traditional model of peritidal carbonate sedimentation on continental shelves and epeiric seas (Iñíguez *et al.* 1989, Cingolani, 2011), regardless of age, is a shoreline model based on modern analo-

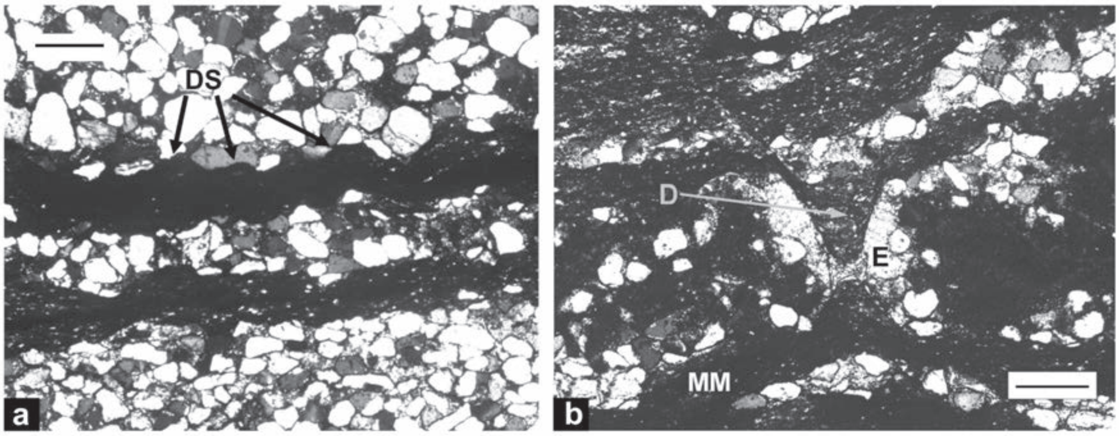

Figure 10: Thin sections of the high energy intertidal heterolithic lithofacies. Bar scale 500 microns. a) ´MISS`. Dome-shaped elevations (DS) in dark, ferric, crinkly microbial mat laminae with isolated detrital grains within the mats oriented parallel to bedding plane. The geometry of the microbial mats does not superpose upwards. Alternating, graded, well-sorted and well- rounded sand to silt-sized siliciclastic deposits, with some orientation of their long axis parallel to bedding plane. The grains ´float´ in an illitic epimatrix. b) Deformed ´MISS`. Sedimentary micro dyque (D) between fractures. Microbial mat deposits (MM). (E): illitic epimatrix. Quartz grains show tangential coatings.

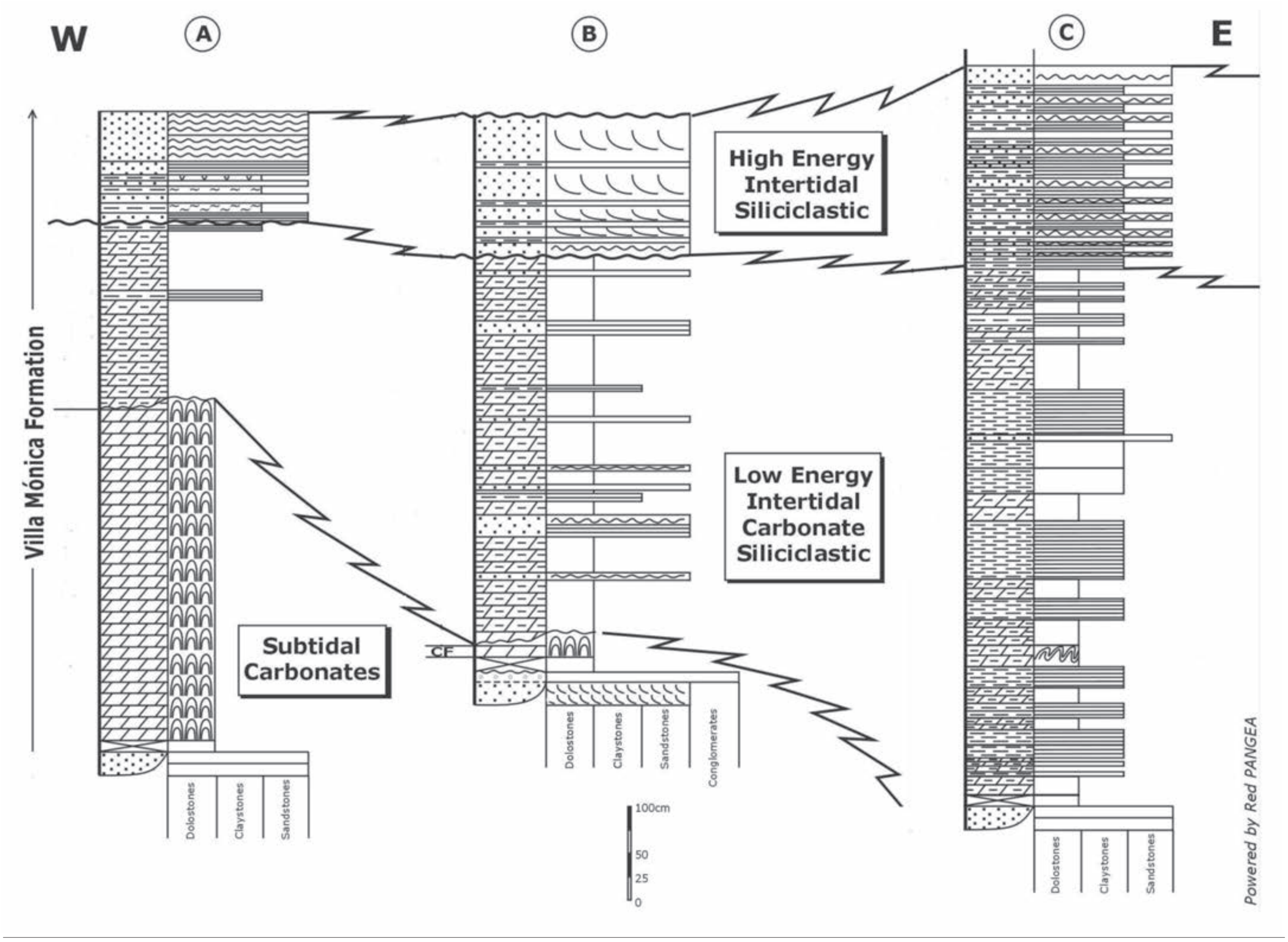

Figure 11: Section correlation along an E-W transect. The deepest lithofacies are well exposed to the west, and the shallow lithofacies are thicker towards the east..

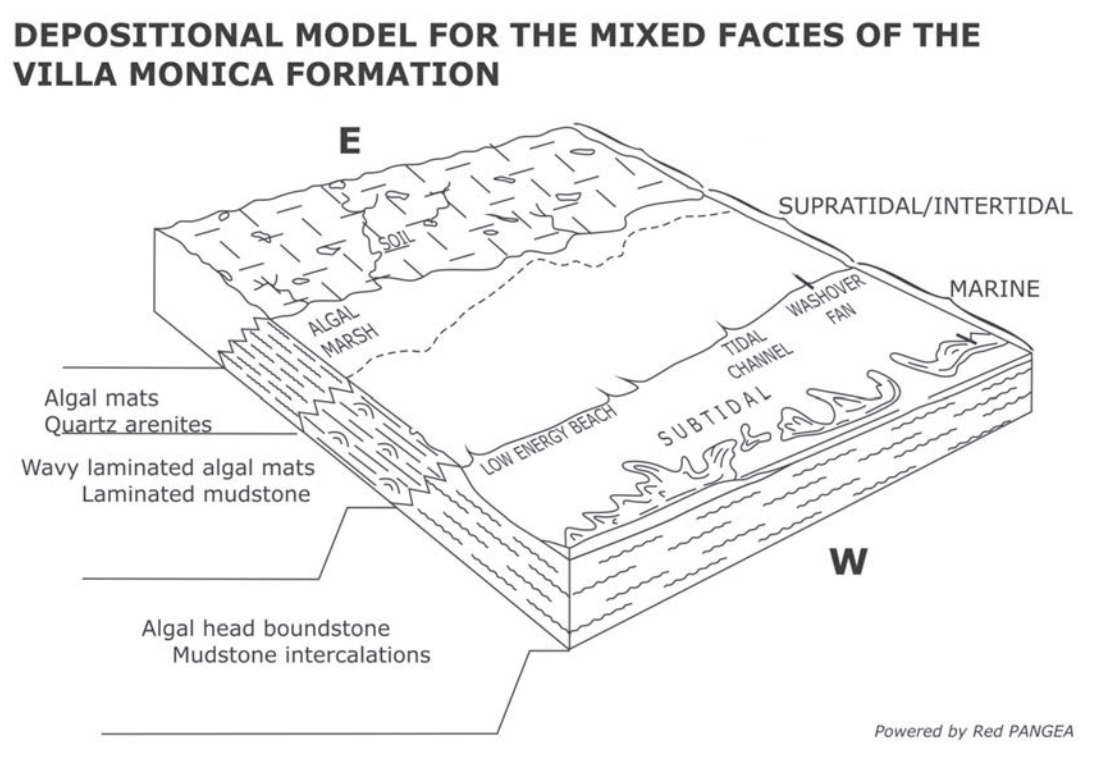

Figure 12: Peritidal block diagram model. Quartz arenites and mudstones are dominant to the east (heterolithic facies), while wavy laminated algal mats and mudstones (carbonate-siliciclastic facies) predominate in middle areas. Towards the west and to the deeper areas of the platform, algal head boundstones are developed (carbonate facies).

gues of coastal tidal flats in various tropical areas. According to this concept, peritidal sediments are considered to fringe the land surface or the lee sides of reefs or grainstone shoals, or as in this case large, shallow epeiric seas (Andreis *et al.* 1996) form laterally continuous regionally broad belts many tens or even hundreds of kilometers in width (Pratt y James, 1986).

All the lithofacies described here (Fig. 10) are interpreted then as representing a prograding carbonate sequence dominated by tidal processes. The sea was opened to the west during Precambrian times and the coast line had an N-S trend which is coherent with regional sandstone paleocurrents data provided by previous authors (Andreis, 2003). It is important to underline that due to the pericratonic location of these epeiric seas described above, these peritidal carbonates could have been exposed geographically and experimented important facies changes due to small sea level fluctuations. Although the interpretation is based on limited data, a simple depositional model proposed here is to consider the algal head boundstones as typical shallow subtidal to lower intertidal.

The carbonate succession bearing laminated mat deposits are correlated with low energy intertidal lithofacies, whereas the heterolithic intervals with minor microbial mat intercalations, is interpreted as a high energy intertidal lithofacies. The location of them in the succession is also coherent with the fact that microbially induced sedimentary structures may correlate with turning points of regression-transgression (Noffke, 2009) or marine flooding surfaces, representing a period of sediment starvation and non-deposition following a transgression. (Mata y Bottjer, 2009).

In Fig. 11, a section correlated along an E-W transect is displayed. The deepest facies are well exposed to the west, and the shallowest facies are thicker towards the east. The spatial facies distribution is presented in Fig. 12. Microbial mats and quartz arenites are dominant to the east, while wavy laminated microbial mats and mudstones predominate in middle areas. Towards deeper areas of the platform, algal head boundstones and mudstones are more abundant. These lithofacies show basal boundaries defined by a relatively abrupt shift from ramp to coastal facies, where tidal influence is well represented by sedimentary structures and biologically influenced mineralization like flat laminated microbial ecosystems associated to quartz grains (Noffke, 2009). Studying modern MISS, Noffke (2007) previously explained how this mineralization takes place: 'In modern environments, microbial mats decompose and mineralize the organic matter of the filaments of cyanobacteria and trichomes. The resulting chemical compounds eventually react with ions from the surrounding seawater, and initial, amorphous gels are formed. Later those gels crystallize to form e.g., aragonite, tenorite (the precursor of pyrite), or other minerals such as iron oxides and iron hydroxides. That is those minerals replaced the organic matter of the filaments and trichomes.

CONCLUSIONS

In the Sierra La Juanita, the Villa Mónica Formation studied units are mainly composed of well-preserved boundstones with columnar stromatolites, and of microbial mats associated with siliciclastics, like illitic clays and quartzose sandstones. The mixed-siliciclastic facies, considered by previous authors as exclusively siliciclastic and named *ferruginous clays*), were deposited in intertidal environments. The micro-units described as siliciclastic-microbial mat units constitute a unique character, only appreciated on thin sections, of terrigenous translucent quartz grains capable of retaining bacteria filaments in a photosynthetic environment and being stabilized by their cyclic activity.

Towards the top of the Villa Mónica Formation, thin sedimentary cycles were formed in a littoral environment, where detrital illitic clays were derived from the erosion of basement rocks. All these subenvironments were developed in a Neoproterozoic shallow epeiric sea with intense blue-green algae production and where prograding peritidal carbonate precipitation took place with minor intercalated siliciclastic events where terrigenous input was dominant. This succession is capped by high energy coastal siliciclastic sediments represented by quartzose sands.

The concluding interpretation is a simple depositional facies belt with a N-S coastal line where the algal head boundstones and mudstones located to the west are part of the subtidal lithofacies. To the East, the mixed-siliciclastic succession bearing laminated microbial deposits are correlated with low energy intertidal deposits whereas the heterolithic deposits are disposed also to the most eastern areas, and are interpreted as high energy intertidal facies with quartzose sandy input. This actual evidence of the presence of 'MISS' was decisive in the evaluation of the paleoenvironmental conditions and also confirmed the rightness of considering the heterolithic facies as part of the Villa Mónica Formation.

ACKNOLEDGEMENTS

The authors want to express their deep gratitude to Maisa Tunik, Fernando Gómez, Pablo Pazos and to an unknown reviewer for careful reading, critical review and very valuable suggestions that improved this contribution

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Recibido: 14 de julio, 2011.
Aceptado: 7 de febrero, 2012.