

## Microscale Diagnostic Diagenetic Features in Neoproterozoic and Ordovician Units, Tandilia Basin, Argentina: A Review

<sup>1</sup>Patricia E. Zalba, <sup>2</sup>Martín Morosi, <sup>3</sup>Marcelo Manassero and <sup>4</sup>María S. Conconi

<sup>1</sup>Comisión de Investigaciones Científicas,

Provincia de Buenos Aires-Centro de Tecnología de Recursos Minerales y Cerámica, Argentina

Adjunct Research Fellow, School of Geosciences, Monash University, Melbourne, Australia

<sup>2</sup>Comisión de Investigaciones Científicas Provincia de Buenos Aires-Centro de Tecnología de Recursos Minerales y Cerámica, Facultad de Ciencias Naturales y Museo de La Plata, Argentina

<sup>3</sup>CONICET-Centro de Investigaciones Geológicas,

Facultad de Ciencias Naturales y Museo de La Plata, Argentina

<sup>4</sup>Comisión de Investigaciones Científicas Provincia de Buenos Aires-Centro de Tecnología de Recursos Minerales y Cerámica, Facultad de Ingeniería de La Plata, Argentina

---

**Abstract:** This review is the result of many years of research on stratigraphical correlation, sedimentology and mineralogy of one of the oldest sedimentary basins of Argentina that experimented numerous diagenetic changes along the evolution of its geological history: Tandilia. Previous and new data are presented and supported with photographs that illustrate different aspects of microscale diagnostic features of diagenesis recorded in weathered crystalline basement rocks and the overlying sedimentary succession represented by the Neoproterozoic Villa Mónica, Olavarría, Cerro Largo and Las Aguilas formations and the Late Ordovician Balcarce Formation. The study gathers optical and scanning electron microscopy data supported by X-ray diffraction analysis. The finding of Microbially Induced Sedimentary Structures (MISS) in siliciclastic and mixed facies helped to unveil hidden biosignatures, fundamental to understanding the origin of life on Earth.

**Key words:** Diagenesis, texture, diagnostic features, MISS, Neoproterozoic, Ordovician

---

### INTRODUCTION

Diagenesis comprises a broad spectrum of physical, chemical and biological post-depositional processes by which original sedimentary assemblages and their interstitial pore waters react in an attempt to reach textural and geochemical equilibrium with their environment (Curtis, 1977; Burley *et al.*, 1985). These processes are dynamic and evolve throughout the history of the basin according to local variation in temperature, pressure and chemistry where syndepositional processes, burial and uplift are main stages and which, in many cases, may be characterized by typical diagnostic features imprinted in the sediments. Nevertheless, in ancient deposits, several superimposed diagenetic processes and also weathering and erosion, may partially or completely erase original fabric characteristics and consequently obliterate diagnostic features. In the case of the oldest Neoproterozoic sedimentary unit of the Tandilia Basin (Fig. 1), the Villa Mónica Formation, these kind of

problems diffculted its petrological classification for more than 40 years (Zalba *et al.*, 2010).

The Neoproterozoic Villa Mónica, Olavarría, Cerro Largo and Las Aguilas formations (Fig. 2) were selected to make a review of significant diagnostic diagenetic features detected. Also, few examples of diagenetic processes have been taken from the Ordovician Balcarce Formation at the Chillar area. Yet, some structures are shown for the first time because of recent findings of reliable evidence for the interpretation of their origin.

Textural studies were carried out on clays, well-preserved and weathered stromatolitic dolostones, minor quartzarenites, ooid grainstones and crystalline basement rocks.

On the basis of previous contributions, this review, gives a summary of diagnostic diagenetic features and veiled biosignatures found in siliciclastic and mixed facies.

In the case of the Villa Mónica Formation, for example, rare microbial structures found some years ago at San Manuel area were only interpreted after having

---

**Corresponding Author:** Patricia E. Zalba, Comisión de Investigaciones Científicas, Provincia de Buenos Aires-Centro de Tecnología de Recursos Minerales y Cerámica, Argentina. Adjunct Research Fellow, School of Geosciences, Monash University, Melbourne, Australia  
Tel: 00542214248725, +54221154084592

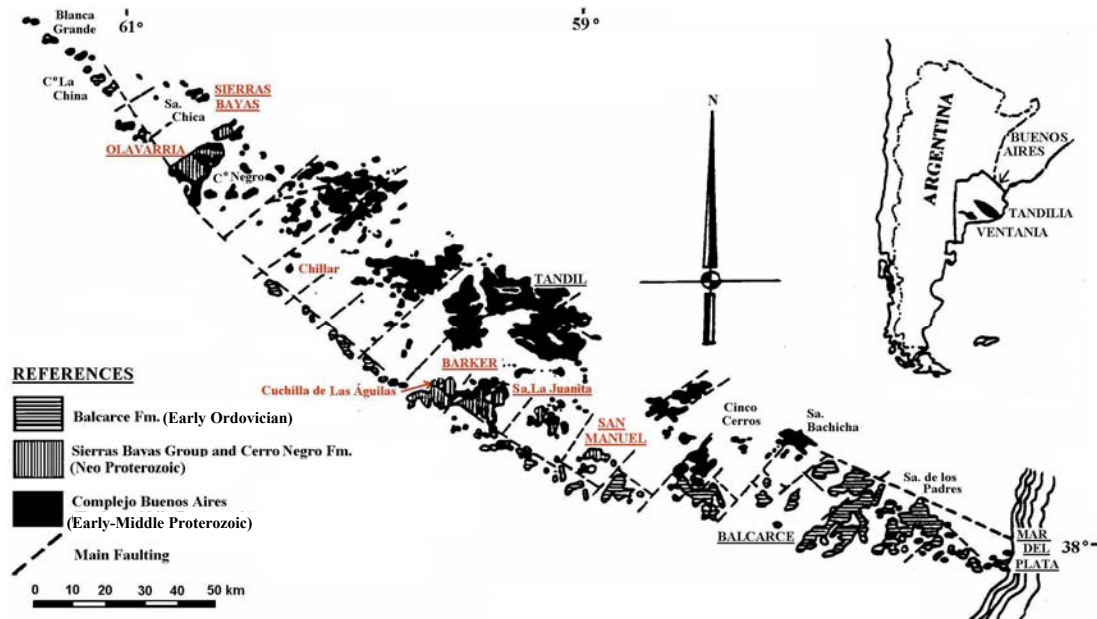


Fig. 1: Geologic map of the Tandilia Basin, Buenos Aires, Argentina (Iñiguez *et al.*, 1989). Study localities in red

Area	Sierras Bayas	Barker	Sedimentary Cycles
Age			
Early Ordovician		Balcarce Fm. (quartzite)	Batan
			La Providencia
Neo Proterozoic	Cerro Negro Fm. (claystone, marl and limestone)	Cerro Negro Fm. (claystone, marl and limestone)	Villa Fortabat
	Loma Negra Fm. (limestone)	Loma Negra Fm. (limestone)	Diamante
	Sierras Bayas Group	Sierras Bayas Group	Malegni
	Olavarría Fm. (claystone)	Las Águilas Fm. (?) (breccia, claystone and quartzite)	Tofolletti
	Cerro Largo Fm. (quartzite)	Cerro Largo Fm. (quartzite)	
	Villa Mónica Fm. (dolomite, claystone and quartzite)	Villa Mónica Fm. (dolomite, claystone and quartzite)	
Palco Proterozoic	Complejo Buenos Aires (granitoids)		

Fig. 2: Stratigraphic units and sedimentary cycles of the Tandilia Basin (Iñiguez *et al.*, 1989; Andreis *et al.*, 1996; Poiré and Spalletti, 2005)

compared them with others more complete and better-preserved recently identified in other localities of Tandilia. When we noticed that some structures in the mixed facies of the Villa Mónica Formation were biogenerated (Zalba *et al.*, 2010) we continued with new petrographical observations in the Neoproterozoic Villa Mónica, Olavarría and Las Águilas formations, searching for biosignatures and also for more data to understand the controversial origin of minerals like pyrophyllite, alunite

and halloysite, which we consider of diagenetic origin (Zalba *et al.*, 2007).

In this contribution we follow the classification of the diagenetic processes through the classical scheme of early diagenesis (eogenesis), burial diagenesis (mesodiagenesis) and uplift-related diagenesis (telodiagenesis) according to the scheme developed at first for limestone diagenesis by Choquette and Pray (1970) and later generalized for clastic diagenesis.

## GEOLOGICAL SETTING

The Tandilia Basin, also known as the Sierras de Tandilia or Sierras Septentrionales de Buenos Aires, runs in a NW-SE direction along 300 km in the Province of Buenos Aires, between 36° 30' to 38° 05' S latitude and 58° to 62° W longitude, with a maximum width of 60 km in the Tandil area, becoming narrower at both extremes: Olavarría and Mar del Plata (Fig. 1). The sedimentary successions of this basin represent the western end of a bigger basin that extends to Namibia, Africa (Nama Group) and was preserved after the continental break during the Mesozoic (Dalla Salda and Iñíguez, 1979).

The Tandilia Basin is the first mining area of the Buenos Aires Province, with numerous mining localities. Barker, Sierras Bayas and San Manuel, represent important ones, with limestones and clays as the principal mining commodities. It is a non-continuous succession of hills emerging from the extended plains of the pampa, with heights varying between 50 and 490 m over the sea level. Besides, it is necessary to emphasize the great quality of the clay deposits, which have preserved the necessary physicochemical characteristics for their industrial application.

The sedimentary succession has been studied since the 19<sup>th</sup> century from the geological, sedimentological, geochemical, petrological, mineralogical, structural, geochronological, paleontological, environmental and economical points of view. A compilation of the pioneers, the classical and the more recent studies may be consulted in Teruggi and Kilmurray (1980), Zalba *et al.* (1988, 2007, 2010), Iñíguez *et al.* (1989), Poiré and Spalletti (2005).

The Crystalline Basement rocks of the Sierras de Tandilia are covered by apparently tabular sedimentary siliciclastic, biochemical and bioconstructed successions included in different lithostratigraphic units which represent one of the oldest sedimentary deposits known in Argentina, of Neoproterozoic and Early Ordovician ages.

Studies in the Barker locality (Fig. 1) contributed to the understanding and correlation of the different deposits which outcrop between Olavarría and Mar del Plata areas, the two extremes of the Tandilia Basin. From the seventies to the eighties, the first detailed studies were performed at Cuchilla de Las Aguilas and Sierra La Juanita, to the west of Barker (Fig. 1), which permitted the recognition of new lithostratigraphic units: the Las Aguilas Formation (Zalba, 1979); the Cerro Negro Formation (Zalba, 1981), first described for the Olavarría (Sierras Bayas) area (Iñíguez and Zalba, 1974) and the creation of the Sierras Bayas and Balcarce formations

(Dalla Salda and Iñíguez, 1979). Poiré (1987) defined the Cerro Largo Formation at Olavarría, which later was also detected in the Barker area (Fig. 2). The Las Aguilas Formation has been correlated with the Cerro Negro Formation and recently, with the Olavarría Formation (Poiré and Spalletti, 2005) but we consider that its stratigraphic position is not definitive yet.

Iñíguez *et al.* (1989); Poiré (1993); Andreis *et al.* (1996) and Poiré and Spalletti (2005), are some of the authors who interpreted that different sedimentary cycles, separated by regionally extended unconformities, were created by sea-level changes.

According to Zalba *et al.* (2007) 'The sedimentary sequences of Tandilia have probably not exceeded 2-3 km of burial. This statement is based on the comparatively simple authigenic mineralogy of these successions (Iñíguez and Zalba, 1974; Iñíguez *et al.*, 1989; Zalba, 1982), also revealed on several world examples of onshore basin-margin sequences (Hebridean Basins, Morton, 1987; Yorkshire Basin, Hemingway and Riddler 1982; Dorset Basin, Scotchman, 1991a, b), which, according to these authors, experienced a 2.5 km of burial. Furthermore, the abundance of compaction features like straight-line and suture boundaries and especially the presence of triple junctions in sandstones (Ahmad and Bhat, 2006) observed in the quartzarenites of the Sierras Bayas Group and of the Balcarce Formation (Iñíguez *et al.*, 1996) support this, assumption'.

At present there are still many geological problems to solve but, according to recent studies (Zalba *et al.*, 2007; 2010) detailed petrographical work and the interpretation of paragenetic sequences have proved to be of the most importance in the better understanding of many processes which have occurred in these ancient rocks.

## DIAGENETIC PROCESSES AND DIAGNOSTIC FEATURES REVEALED BY TEXTURAL ANALYSES

Diagnostic features related to different regimes of diagenesis: syndiagenesis, eodiagenesis, mesodiagenesis (burial) and telodiagenesis were recognized in stromatolitic dolostones, ooid grainstones, shales, marls and quartzarenites of the Tandilia Basin, where continuous diagenetic processes developed throughout its evolution.

Cementation is the process which describes precipitation of authigenic minerals in available pore space causing the lithification of the sediment. The most ubiquitous mineral cement found in most rocks is silica, but there are also many others (carbonates; sulfates; phosphates; ferric, manganese and magnesium oxides; ferric hydroxides, gypsum, etc.), which are widespread in sedimentary deposits.

In the case of the studied Neoproterozoic and Ordovician lithostratigraphic units of the Tandilia Basin the main mineral cements are silica in its varieties trydimite, quartz and chalcedony; carbonates (calcite, dolomite); clay minerals (illite-smectite, kaolinite, halloysite); pyrite; hematite; goethite and APS minerals: alunite; svanvergite-Ce-florencite, according to Zalba *et al.* (2007, 2010). All these cements were formed in different regimes of diagenesis and, sometimes, are found superimposed in the same sample.

Precipitation of calcite from blue-green and red algal and bacterial activity is a well known cementation process and it is considered to be syndiagenetic (Larsen and Chilingar, 1979). It acts as a powerful preservation agent when very tiny and delicate fossil remains are involved. A summary of the main authors who studied this phenomenon can be checked in Noffke (2007).

A related process is recrystallization, which comprises a change in crystal size or shape resulting from thermodynamic instability like reprecipitation of finely grained calcite by coarse grained calcite cement (Hendry *et al.*, 1996) when kinetic barriers are exceeded to allow the reaction to proceed, taking into account that both recrystallization and neomorphism always require the presence of an aqueous medium (Worden and Burley, 2003). This process is different from replacement of a mineral by other which occupies the place of the formerly formed; no matter if it is authigenic or detrital and where dissolution-precipitation process takes place like in carbonate cements replacing detrital quartz (Hesse, 1987). The definition of replacement given by Worden and Burley (2003) is 'growth of a chemically different authigenic mineral within the body of a pre-existing mineral'.

Recrystallization from microsparite to macrosparite occurs during syndiagenesis, together with dolomitization. It is assumed that dolomitization in the Villa Monica Formation was complete (Zalba *et al.*, 2010) and took place at shallow depth and low temperature (less than 70°C), according to Girard and Deynoux (1991) and Chafetz and Zhang (1998). In Fig. 3a, a delicate domal structure due to microbial activity has been preserved in fresh domal stromatolitic dolostones. Figure 3b depicts a dolomicrite cement recrystallized to dolosparite in well-preserved stromatolitic dolostones. Alizarin-red staining shows that all the micro and macrosparite have been transformed into dolomite. Precipitation of calcite (red) in fractures also cuts the dolomitized stromatolitic rocks and is a telodiagenetic process, separated by millions of years from the dolomitization one.

Figure 3c and d show a completely silicified stromatolitic dolostones. Note well-preserved

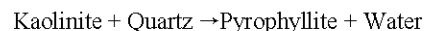
rhombohedra at the center of the photograph. These euhedral crystals of completely silicified dolomite, suggest that dolomitization preceded precipitation of silica as a postdepositional process and has occurred as an early diagenetic process.

Figure 3e shows trydimite crystals included in quartz and surrounded by chalcedony in fresh stromatolitic dolostones. The silica has precipitated as opal-A due to organic activity and later recrystallized to opal-CT (trydimite was also identified by X-ray diffraction) and then to quartz forming megacrystals up to 20 cm long which precipitated in cavities and voids (Zalba *et al.*, 2010). Chalcedony represents the last pulse of silica precipitation. Figure 3f is a detail of Fig. 3e.

Cellular microbial colonies and crinkled, banded lamination (dark) can be seen in dolomite rhombohedra (in brown) where cavities have been filled with quartz (Fig. 3g). We interpreted (Zalba *et al.*, 2010) that cellular/banded stromatolitic structures and crinkled lamination are the kind of deposits derived from bacteria and blue-green algae activity, according to Schieber (1998). Cathodoluminescence analysis performed on the previous sample (Fig. 3h) shows dolomite with microbial colonies included in quartz crystals (in orange) and (Fig. 3i) quartz crystal grown in dolomite cavities. The quartz crystals include dolomite rhombohedra, again suggesting that dolomitization preceded silicification processes.

Pyrophyllite has been found in crystalline basement rocks as well as in overlying sedimentary deposits of different Neoproterozoic units (Villa Mónica and Las Aguilas formations).

Hydrothermally formed pyrophyllite has been found in weathered basement rocks (saprock and saprolite) from San Manuel (Zalba and Andreis, 1998) and Sierra La Juanita (Cerro de La Cruz) areas. Thin sections of these rocks are shown in Fig. 4a and b where quartz (dissolved) and kaolinite have reacted to form pyrophyllite. In the system  $\text{Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$  (Evans and Guggenheim, 1998) pyrophyllite is stable over a narrow temperature range (~250 to ~350°C), at 1 and 2 Kbars pressure (Hemley *et al.*, 1980) with the most frequent reaction producing pyrophyllite during prograde metamorphism being:



Pyrophyllite (Fig. 4c) has also been found in clay deposits of the Las Aguilas Formation, Barker area (Zalba, 1979) and as intraclasts (Fig. 4d) in weathered dolomite deposits which have been totally replaced by illite-smectite (Zalba *et al.*, 2010) in the Villa Mónica

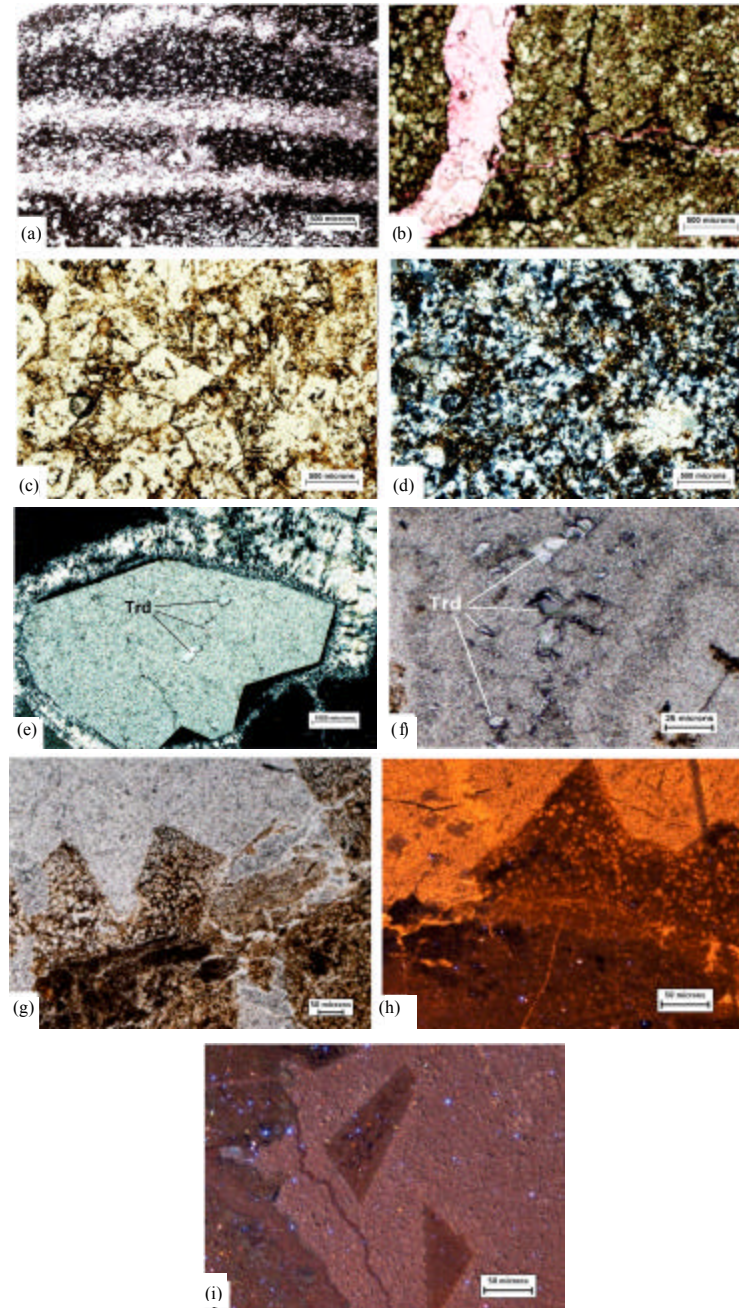


Fig. 3: Cementation (a) Dolomicrite with domal structures due to microbial activity (parallel nicols). (b) Well-preserved stromatolitic dolostones. Alizarin red differentially tinted dolomite and calcite (red) showing calcite only in fractures. La Siempre Verde quarry (parallel nicols). (c) Completely silicified stromatolitic dolostones where silica pseudomorphs after rhombohedral crystals of dolomite are clearly seen (parallel nicols). (d) The same sample, La Placeres quarry (crossed nicols). (e) Quartz crystal (arrow) grown in cavities of dissolved dolomites with trydimite crystals enclosed (crossed nicols). (f) Detail of the previous photograph. Trd: trydimite (crossed nicols). (g) Quartz crystal grown in cavities of stromatolite dolostones. See white dots which represent silicified microbial colonies. La Siempre Verde (parallel nicols). (h) Same sample as in (g) observed under cathodoluminescence. Quartz (brown), silica (orange). (i) Same sample observed under cathodoluminescence. Quartz crystal grown in cavities of stromatolite dolostones which include dolomite rhombohedra (in brown). Villa Mónica Formation, Sierra La Juanita, Barker

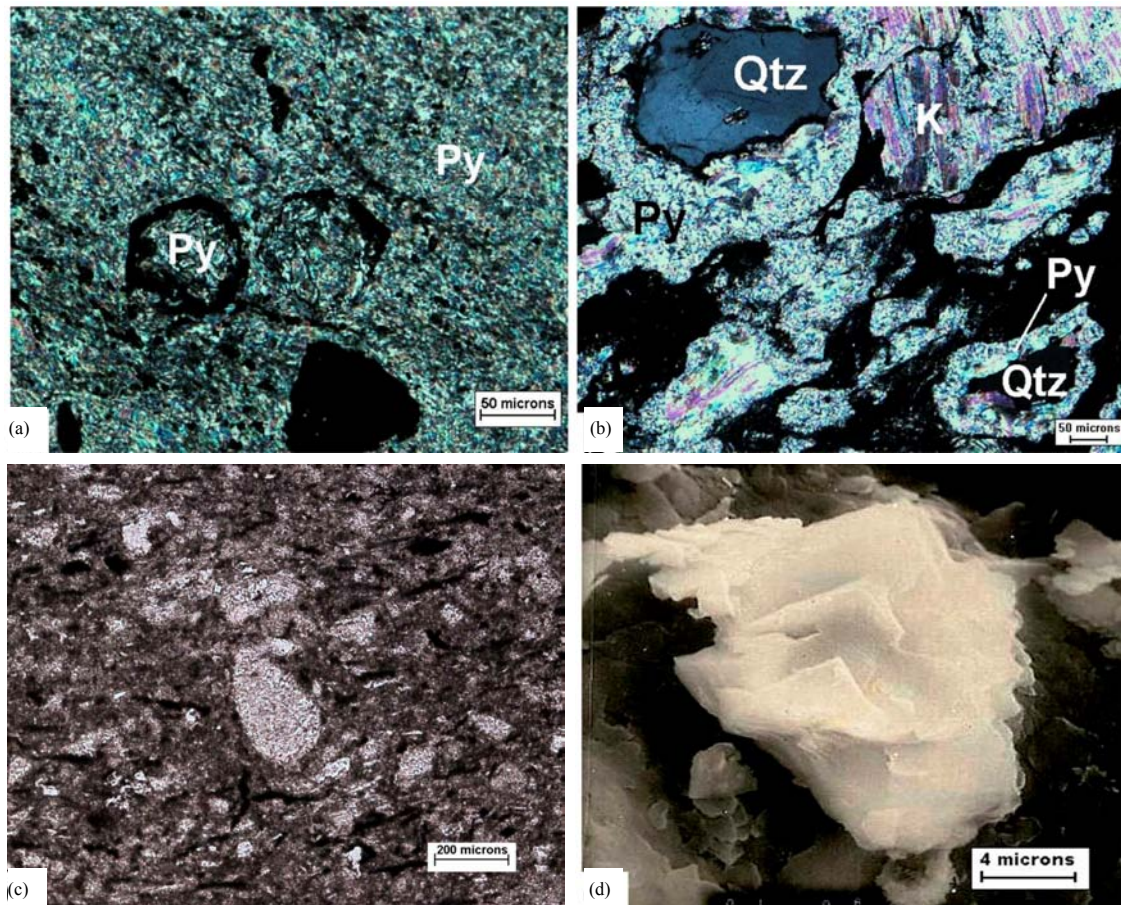


Fig. 4: Hydrothermal and detrital pyrophyllite (a) Masses of hydrothermally formed pyrophyllite (Py) also replacing opaque minerals, saprocks, San Manuel (crossed nicols). (b) Hydrothermally formed pyrophyllite (Py) dissolving quartz (Qtz), associated with kaolinite ghosts (K), saprocks, basement of Cerro de La Cruz, Sierra La Juanita (crossed nicols). (c) Pyrophyllite intraclast (center of the photograph) in clay deposits, Villa Mónica Formation, San Manuel (parallel nicols). (d) SEM. Detrital pyrophyllite in clay deposits of the Las Aguilas Formation, Cuchilla de Las Aguilas, Barker. Note characteristic straight borders

Formation, San Manuel area (Zalba and Garrido, 1984). From field and petrological observations, pyrophyllite in the Las Aguilas Formation, at Barker area and in the Villa Mónica Formation, at San Manuel area, were considered of detrital origin and related to the weathering and erosion of local crystalline basement rocks (Fig. 4a, b). However, the origin of pyrophyllite in the sedimentary deposits has been also attributed to hydrothermal processes (Dristas and Frisciale, 2003), being this subject a long-term matter of discussion.

Pyrophyllite is also found in clasts of silicified basal breccias of the Las Aguilas Formation at Barker area, considered as reworked carbonatic platform sediments. The fabric of these deposits presents abundant silt-to fine sand-sized allochemes (including ooids, oolites of

concentric fabric and intraclasts) but also shows wavy-crinkled lamination attributed to microbial processes and similar to fabrics observed in modern and ancient mounds that Riding (2000) has termed agglutinated stromatolites. The deposits are classified as ooid grainstones.

The oolites may show nucleus of quartz, or show no nucleus (Fig. 5a and b). Detrital quartz (center of Fig. 5b) shows syntaxial overgrowths. Compaction has put oolites in contact but they are slightly deformed (Fig. 5a, b). It is clearly observed that pyrophyllite has grown *in situ* at expense of detrital quartz in fine grained silica cement in the same sample (Fig. 5c). Pyrophyllite has also grown as a selective replacement of oolite nuclei (Fig. 5d). Furthermore, agglutinated mammellar pyrophyllite can be

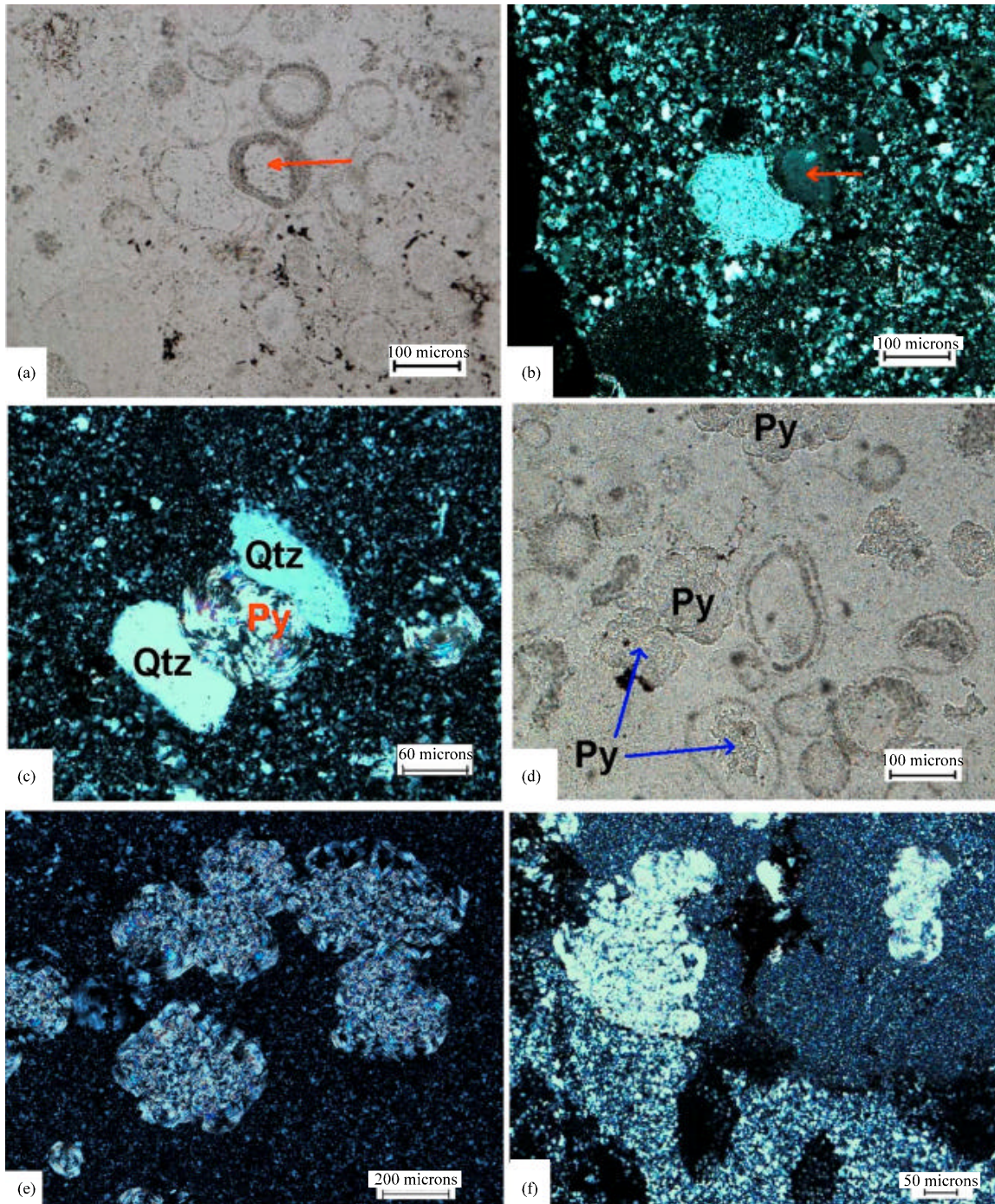


Fig. 5: Ooid grainstone deposits. (a) Oolites with quartz nucleus (arrow). Slight deformation by compaction (parallel nicols). (b) Same photograph with crossed nicols. Quartz nucleus (arrow). Detrital quartz (center of the photograph) with dissolved syntaxial overgrowths in contact with an oolite and with signals of compaction. (c) Diagenetic pyrophyllite (Py) growing at expense of detrital quartz (Qtz). Note dissolution of syntaxial quartz overgrowths (crossed nicols). (d) Pyrophyllite (Py) growing as diagenetic masses and also as nucleus of oolites (arrows) (parallel nicols). (e) Mammellar and agglutinated diagenetic pyrophyllite in the same sample (crossed nicols). (f) Two generations of silica cement in contact. Diagenetic pyrophyllite grows only in the micro silica cement. Las Aguilas Formation, Cuchilla de Las Aguilas, Barker (crossed nicols)

seen in the same deposits (Fig. 5e). It is not well understood the origin of this pyrophyllite but textural relationship with quartz makes a diagenetic origin a reasonable hypothesis.

Chalcedony cement has replaced all previous carbonate cement within the ooid grainstone. It is possible to recognize two different grain sizes of silica cement-textures (Fig. 5f) which could be the result of selective recrystallization or replacement of rocks of different porosity. Irregular masses of presumably diagenetic pyrophyllite have grown only in the fine grained cement.

In conclusion, calcite precipitation from cyanobacteria, precipitation of opal A→opal CT (trydimite)→quartz (silicification) and dolomitization are considered textural diagnostic characteristics of syndiagenesis and eodiagenesis. The presence of pyrophyllite in sediments of different Neoproterozoic units (Villa Mónica and Las Aguilas formations) is consistent with a detrital origin. The material was supplied by the erosion and transportation of hydrothermally formed pyrophyllite in the basement rocks of nearby areas (San Manuel and Sierra La Juanita). If also pyrophyllite has formed diagenetically in ooid grainstones is not well understood, but if so, its formation after compaction (burial) and during telodiagenesis is a reasonable option.

A relatively new concept related to structures found in bioconstructed rocks is the recognition of Microbially Induced Sedimentary Structures-MISS (Noffke *et al.*, 2001), which, according to the original definition of the authors 'do not arise from chemical processes, but from the biotic-physical interaction of microbial mats with the sedimentary dynamics of aquatic environments'. New defined mixed (carbonate-siliciclastic) facies for the Neoproterozoic Villa Mónica Formation show evidence of biosignatures (Zalba *et al.*, 2010) which are described here as MISS.

Microbial mats are well known from stromatolites in carbonates back to 3.5 Ga (Walter, 1994). Many contributions on stromatolites in Proterozoic basins are applied to carbonate environments (Awramik, 1984; Walter *et al.*, 1992) while there are few references to clastic environments (Schieber, 1998; Noffke *et al.*, 2003; Noffke, 2006, 2009). Siliciclastic stromatolites are scarce compared to their carbonate counterparts in the rock record. The paucity of stromatolites in siliciclastic strata may relate to physical conditions and processes within the depositional environment that inhibit stromatolite growths and preservation (Druschke *et al.*, 2009).

MISS (Fig. 6a) are represented by thin sedimentary units (from microns to few millimeters) composed of two biofabrics: (1) A characteristic dark, ferric, wavy, crinkly

microbial mat deposit, with silt to clay-sized detrital grains trapped within (Noffke *et al.*, 1997), interlayered with (2) A micritic, originally carbonate layer (light part of the photograph) with relics of rhomboedral illitic clay subsequent to dolomite enclosed by hematite and where bent micas, signifying detrital origin, are observed. On the one hand, no biogenic structures have remained after carbonate neogenesis in the light part of the unit, presumably because of recrystallization. On the other hand, microbial mat preservation (dark part of the photograph) has been possible due to the precipitation of ferric oxides which did not allow the expansion of diagenetic carbonates, as suggested by Hofmann (1975).

In the siliciclastics of the Carbonate-Siliciclastic facies of the Villa Mónica Formation we can differentiate bioconstructed structures from purely physically deposited siliciclastic beds. In Fig. 6b two different parts can be recognized: Part A) Grain-supported silt to sand-sized sediments interlayered with minor microbial mats with graded structure, showing some grains orientated preferentially with their long axis parallel to the sedimentary surface. Part B) Upwards, the siliciclastic material decreases and a dark, curvy crinkly lamination with detrital material floating within becomes more profuse. These dark deposits represent microbial laminites with great pigmentation (ferric oxides). Within the microbial mats, all the detrital quartz grains are oriented with their long axis parallel to the sedimentary surface. In this framework, these structures are considered part of the MISS, as defined by Noffke *et al.* (2001). The graded structure could be preserved because the microbial laminae have acted as a paste, occupying, trapping, stabilizing the sedimentary surface and preserving it, according to Noffke *et al.* (1997). In the upper intertidal and lower subtidal zone of tidal flats, microbial mats stabilized the sedimentary surface (Krumbein, 1994).

The features of microbial mats shown on vertical thin sections (dark colored, intact and wavy, wrinkled laminae), as stated by Noffke (2007), are important indicative characteristics to distinguish similar wrinkle structures but originated by abiogenic processes. While the laminar morphology of the iron-rich laminites may not preclude an abiologic origin, the concentration of elements such as iron in sedimentary laminae is commonly attributed to microbial metabolism (Flügel, 2004).

Figure 6c is another example of MISS where dark, ferric, crinkly microbial mat laminites with isolated detrital grains within the mats oriented parallel to bedding plane are illustrated. Alternating, graded, well-sorted and well-rounded sandy to silty siliciclastic deposits, with some orientation of their long axis parallel to bedding plane are shown. In Fig. 6d quartz grains float in an illitic

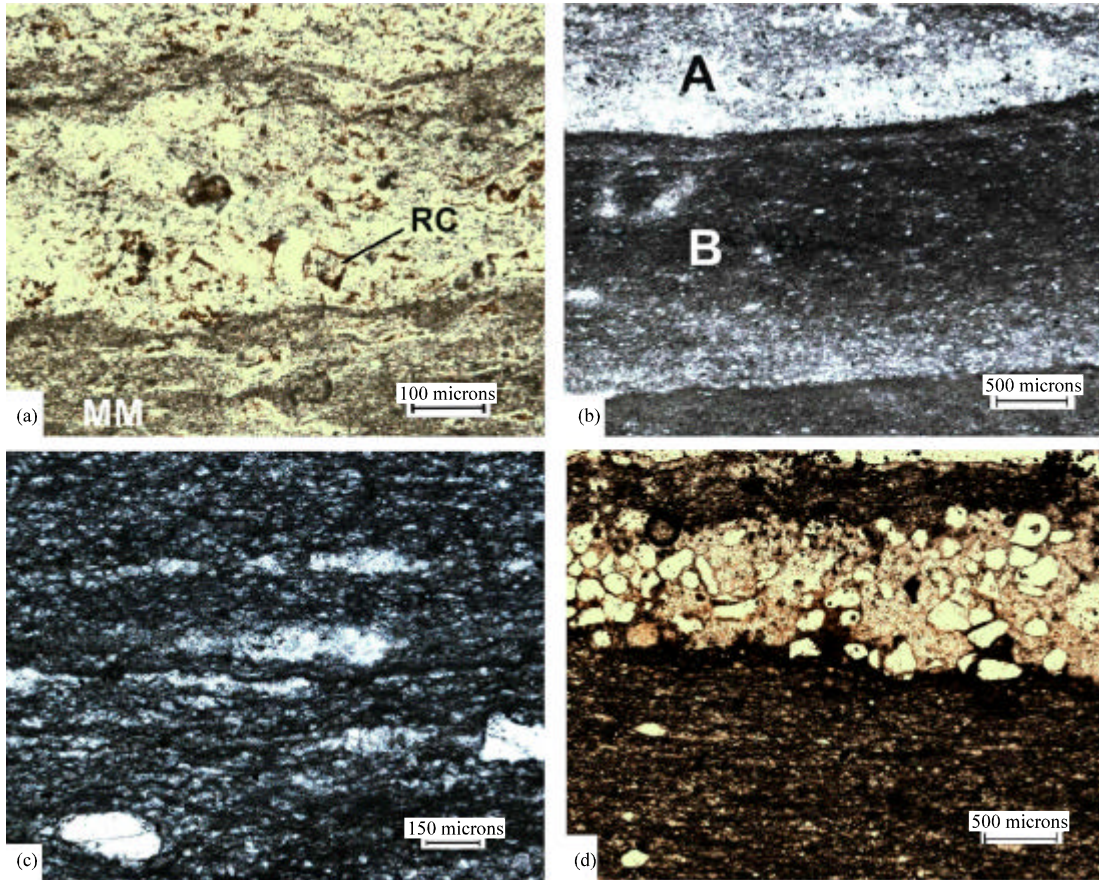


Fig. 6: MISS in Carbonate/Siliciclastic facies. (a) Dark, hematized, wavy crinkly microbial mat laminae (MM) alternating with light parts containing illitized dolomite with ghost rhombohedral crystals (RC) (parallel nicols). (b) Part A) Basal, grain-supported silt to sand-sized sediments with graded structure and minor interlayered microbial mats. Some grains are oriented with their long axis parallel to bedding plane. Part B) Dark, wavy, crinkly microbial laminae with detrital grains ‘floating’ within and all oriented with their long axis parallel to the bedding plane (crossed nicols). (c) Dark, ferric, crinkly microbial mat laminae with isolated detrital grains within the mats oriented parallel to bedding plane (crossed nicols). (d) Tidal deposits. Quartz grains ‘float’ in an illitic epimatrix and alternate with microbial mats (dark part). Detrital quartz grains oriented with their long axis parallel to bedding planes (parallel nicols). Villa Mónica Formation, Don Camilo quarry, Sierra La Juanita, Barker

epimatrix and alternate with microbial mats (dark part) where detrital quartz grains oriented with their long axis parallel to bedding planes are clearly observed.

Figure 7a, b and c are from the same sedimentary deposits (Olavarría Formation, Cruz Pavone quarry, Sierras Bayas) and exemplify very thin microbial mats developed in siliciclastic (illitic) sediments, also recognized as MISS. The curved, dome, dark surfaces are considered to be bedding planes and the geometry of the domes do not superpose with each other upwards, that is why the same colony could not have grown after a renewal of the sediment supply (Fig. 7b). Other examples of MISS have been recently found in tidal deposits of the

Las Aguilas Formation, first described by Zalba (1979) and also in well-preserved and weathered domal stromatolitic dolostones of the Villa Mónica Formation, both at Barker area. These structures are very similar (hematized, dark microbial mats, wrinkle structures, detrital grains with their long axis parallel to bedding planes trapped within the mats, dome structures) to those described previously for the Villa Mónica and Olavarría formations, as can be seen in Fig. 7d. That is why they are considered now as mixed facies and not purely siliciclastic, as they were firstly defined (Zalba, 1979).

The dark, hematized cement showed in Fig. 8a and b has been attributed to microbial mat relics in silicified

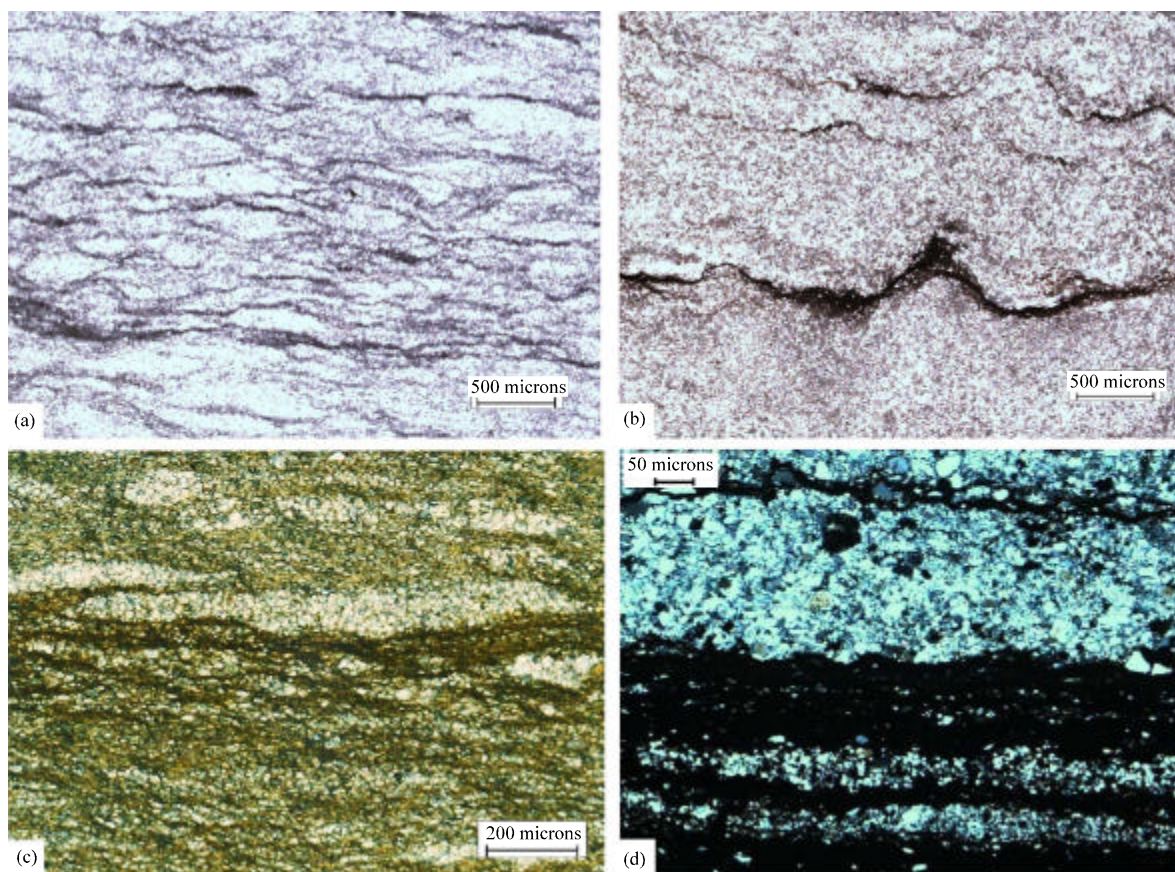


Fig. 7: MISS in Carbonate/Siliciclastic facies (a) Dark, hematized, crinkly lamination as relics of microbial activity (parallel nicols). (b) MISS where domes do not superpose upwards, separated by the renewal of continental input between microbial cycles (parallel nicols). (c) Microbial mats intercalated in siliciclastic facies. Olavarría Formation, Cruz Pavone quarry, Sierras Bayas (crossed nicols). (d) Tidal deposits (alternation of clayey and sandy sediments) with microbial mats (dark, hematized microbial activity relics) alternating with clastic sediments (crossed nicols). Las Aguilas Formation, Cuchilla de Las Aguilas, Barker

oid grainstones, with whole ooids, fractured ooid intraclasts and detrital grains trapped within, interpreted as reworked sediments.

This is the first time that MISS have been identified in different Neoproterozoic units of the Tandilia Basin. The proof that the hematized deposit is microbially induced and not a fracture infilled with hematite, is the textural relationship between the trapped quartz grains and the mat relics (Fig. 8b).

Evidently, a further step on diagenesis caused the fracture of some of the hematized, dark mat relics. The fractures have been infilled with illitic matrix (epimatrix) (Fig. 8c) while in Fig. 8d, microbial mat relics in stromatolitic dolostones are isolated and very difficult to recognize if other diagnostic associated features (e.g., cellular microbial colonies) are not detected or original texture has been totally erased.

Microbial mat formation in bedding planes may support the division of sedimentary units, an important concept supported by Gerdes *et al.* (1991) and which was taken into account for the detection and understanding of microbial mat relics in the named *ferruginous clays* (Manassero, 1986), also known as *Psamopelites* (Poiré and Iñiguez, 1984) of the Villa Mónica Formation at La Placeres and at San Manuel localities (Fig. 8d and e, respectively). That is why based on field work and petrological studies these facies were recently reclassified as mixed (Zalba *et al.*, 2010). The finding of MISS in these deposits corroborates the presence of biosignatures although diagenesis has almost erased any other signal of organic existence and the sediments are at present mainly composed of detrital illite and pyrophyllite and diagenetic interstratified illite-smectite and kaolinite (Zalba and Andreis, 1998).

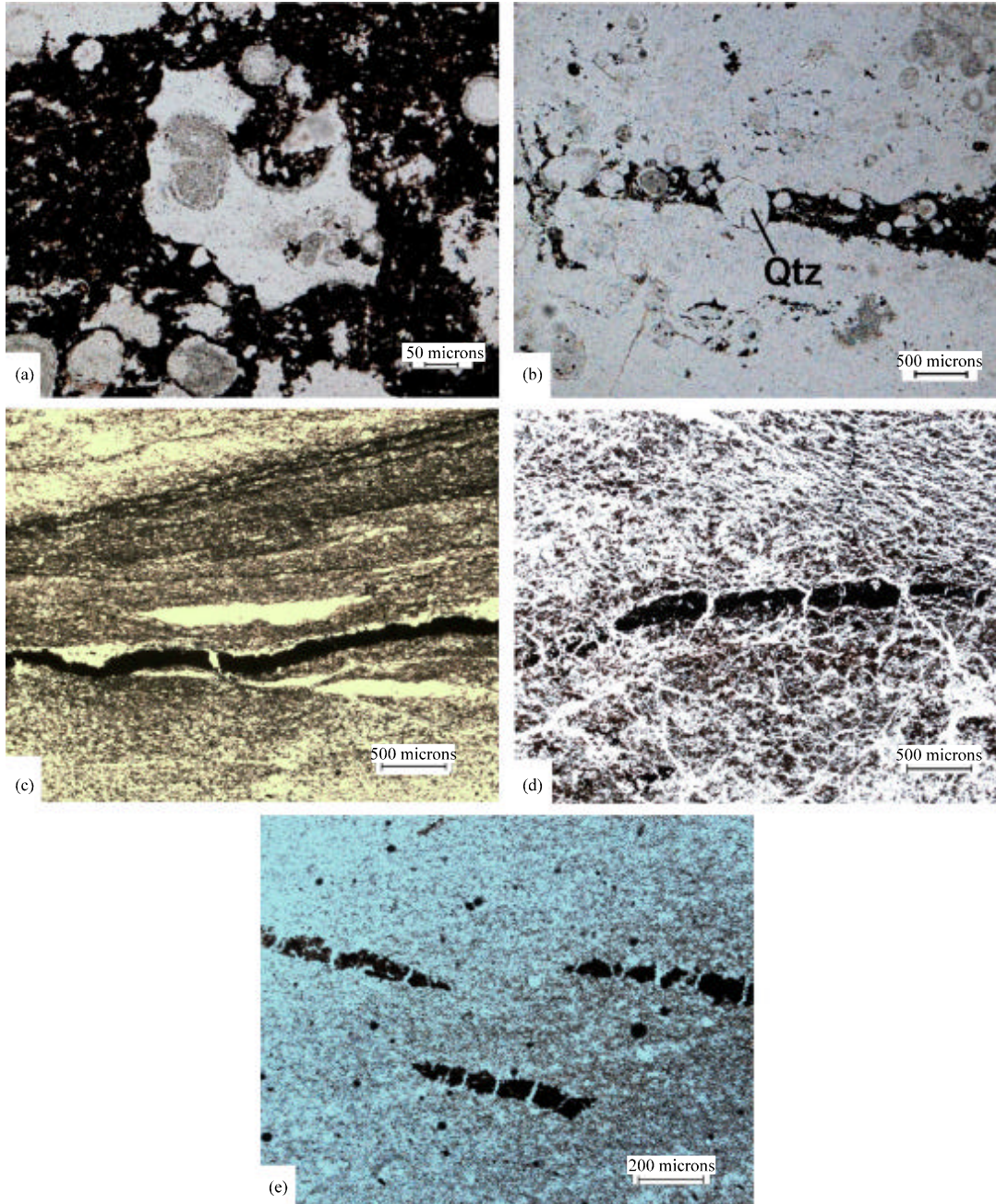


Fig. 8: Relics of MISS (a) Relics of microbial mats (dark) completely hematized with an intraclast (center of the photograph) containing ooids. The mats also contain reworked material (clasts and ooids). (b) The same sample. Microbial mat levels intercalated in ooid grainstone deposits, with quartz grains and ooids trapped within. Las Aguilas Formation, Cuchilla de Las Aguilas, Barker. (c) Dark, hematized microbial mat relics in mixed facies (Carbonate/Siliciclastic). Villa Mónica Formation, La Placeres quarry, Sierra La Juanita, Barker. (d) Fractured MISS where epimatrix has infilled cracks in well-preserved dolostones, Villa Mónica Formation, La Siempre Verde, Sierra La Juanita, Barker. (e) Note the similarity with Fig 8d. Isolated and aligned hematized relics of fractured MISS in weathered stromatolitic dolostones completely replaced by illitic clays. The alignment is interpreted as representing original bedding planes. Villa Mónica Formation, San Manuel. All photographs taken with parallel nicols

MISS are syndiagenetically formed and they have been preserved through silicification and dolomitization (eodiagenesis); mesodiagenesis (e.g., neof ormation and transformation of minerals, compaction) and also through telodiagenetic processes (e.g., compression, fracture, introduction of meteoric fluids, mineral transformation, introduction of illitic matrix, etc.).

The presence of iron minerals and dolomite cements suggests microbial mat mineralization. In modern environments photosynthetic cyanobacteria may produce oxygen at the surface of microbial mats but, directly below the oxic surface layer, anaerobic bacteria degrade mat generated organic matter and may create a localized, strongly reducing environment (Gerdes *et al.*, 2000). These environmental conditions favour the precipitation of calcium and ferroan carbonates and pyrite (Schieber, 2007; Schieber and Riciputi, 2004). Such minerals and also oxidized forms of pyrite (hematite and goethite) can be a valuable indicator of the former presence of microbial mats (Noffke *et al.*, 2006; Schieber, 2007). In the case of the examples shown in Fig. 8d and e, hematization during early burial has enabled the preservation of discontinuous microbial mat relics preserved as lonely witnesses of original bedding planes.

Compaction is the process which takes place during burial and involves from 'simple grain rearrangement during shallow burial as well as the ductile deformation of soft sand grains and intergranular matrix. This is quite different from the process known as chemical compaction, which involves the chemically induced dissolution of grains at intergranular contacts and reprecipitation of the dissolved material on grain surfaces facing open pores' (Worden and Burley, 2003). When a solid organic or inorganic component present in sediments is dissolved by

an aqueous pore solution a cavity or an empty space is created within the host sedimentary deposit (Schmidt and MacDonald, 1979).

Quartz cement can be associated with two different lithofacies: carbonate and siliciclastic. Figure 9a represents quartz cement as syntaxial overgrowths developed in quartzarenites during burial diagenesis, when compaction was not great and large pore space was still available. Figure 9b shows calcite cement filling secondary porosity in dissolved stromatolitic dolostones replacing syntaxial quartz overgrowths, interpreted as a telodiagenetic stage.

Examples of mesodiagenesis can be described in quartzarenites from the Cerro Largo Formation where the presence of triple junctions and sutural, dissolved contacts between grains are interpreted as the effect of deep burial compaction (Fig. 10a). These quartzarenites also show stylolitization. Quartz grains have been disrupted and pulled-apart by the force of the introduction of illitic matrix (arrows in Fig. 10b) in an advanced regime of telodiagenesis. A good example of extensive pressure-solution and sutural contacts between quartz grains due to stylolitization processes is observed in the same deposits (Fig. 10c). Stylolitization has also affected grainstone deposits of the Las Aguilas Formation, where ooids (Fig. 10d) and diagenetically formed pyrophyllite (Fig. 10e) have been fractured and dissolved.

Neomorphism describes the process of replacement and recrystallization of one mineral by a related mineral but involving change in the details of the mineral chemistry, excluding simple pore filling processes (Folk, 1965). The term has widely applied to limestones and dolostones, describing the coarsening of aragonitic

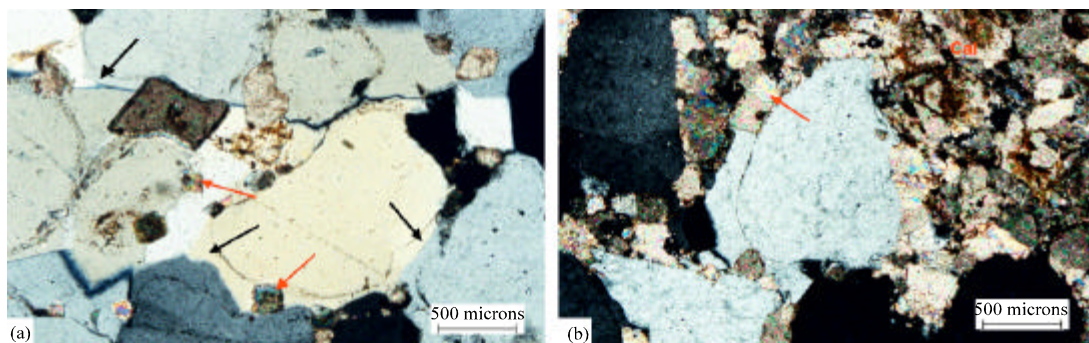


Fig. 9: Compaction and cementation. (a) Quartz cement (red arrows) growing before calcite cement with dissolution of detrital grains. Syntaxial quartz overgrowth (black arrows). Quartzarenites, Cerro Largo Formation, La Placeres quarry Sierra La Juanita, Barker (crossed nicols) and (b) Calcite cement (Cal) filling secondary porosity in dissolved stromatolitic dolostones and replacing syntaxial quartz overgrowths (red arrow). Villa Monica Formation, La Siempre Verde, Sierra La Juanita, Barker (crossed nicols)

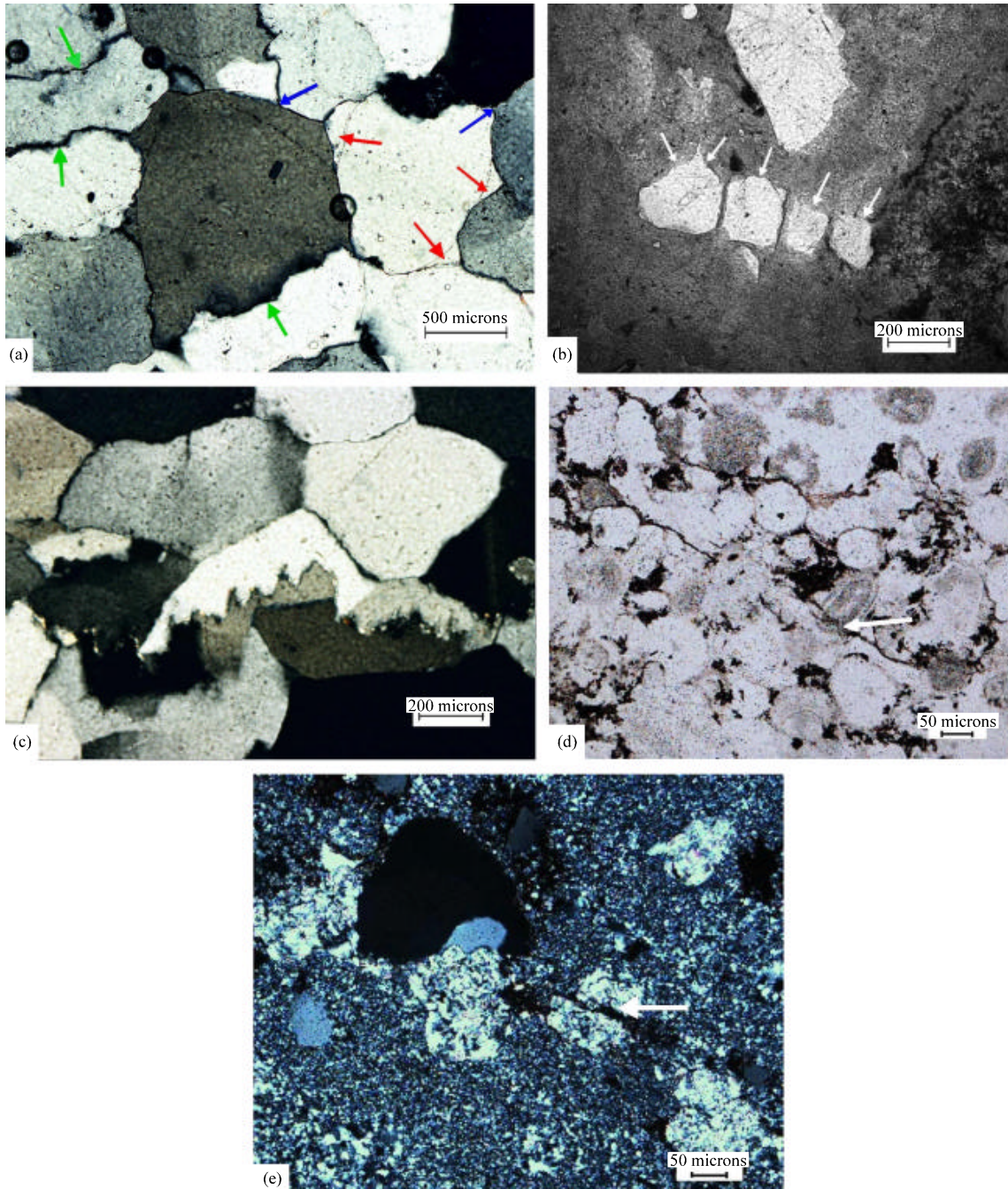


Fig. 10: Burial diagenesis: compaction and stylolitization. (a) Secondary overgrowths (red arrows), triple junction (blue arrows) and sutural contacts (green arrows) between quartz grains (crossed nicols). Quartzarenites, Cerro Largo Formation, Sierra La Juanita, Barker. (b) The photograph represents a further step on burial diagenesis where stylolitization developed in quartzarenites of the Cerro Largo Formation can be seen in two dimensions (arrows). During a telodiagenetic stage, the force of the introduction of clay matrix has broken and pulled-apart the quartz grain (parallel nicols). (c) Other example of stylolitization in the same sample (crossed nicols). (d) Ooid grainstone. Stylolites (arrow) cutting silicified oolites (parallel nicols). (e) Stylolites infilled with hematite cutting diagenetic pyrophyllite (arrow) in silicified ooid grainstones in the same sample (crossed nicols). Las Aguilas Formation, Cuchilla de Las Aguilas, Barker

micrite into calcite microspar and is equally applicable to sandstones. This phenomenon commonly preserves textural evidence (ghost fabrics) of the previous phase (Worden and Burley, 2003).

Neomorphism is an important mesodiagenetic process observed in weathered stromatolitic dolostones, where dolomite has been completely replaced by illite-smectite formed during burial diagenesis with rutile needle inclusions in a sagenite-like structure (Zalba *et al.*, 2010). The illite-smectite has replaced almost completely the dolostones where only relics of hematized microbial mat deposits have remained (dark area of the photograph), with some detrital quartz grains trapped within (Fig. 11a). Also, perpendicular clay coatings of kaolinite surrounding a partially altered detrital plagioclase in quartzarenites of the Villa Mónica Formation have been preserved after mesodiagenesis (Fig. 11b).

Tangential illitic clay coatings (cutans) disposed as detrital, mechanically infiltrated clays (Fig. 12a) around

syntaxial quartz overgrowths in quartzarenites are a typical example of telodiagenesis in the Cerro Largo Formation (Zalba *et al.*, 2010). An example of dedolomitization in the carbonate facies of the Villa Mónica Formation (Zalba *et al.*, 2010) was interpreted as a telodiagenetic process taking into account the fabric geometry and mineral paragenesis which suggest that the rim (Fig. 12b) was formed by marginal dedolomitization (cf. Larsen and Chilingar, 1979).

Ferriargillans (typical cutans, Brewer, 1960, 1976) are found in kaolinitic clays along with smectite and goethite filling fractures which cut weathered stromatolitic dolostones. Further compaction processes caused the development of slickensides (stress cutans). Orientation of the clay laminae in the ferriargillans produces extinction when parallel to the polarizers (Fig. 13a). Kaolinite cutans fill fractures inclined or parallel to the stromatolitic structure, whereas postdating ferric hydroxides (goethite) coat the fracture walls (Fig. 13b).

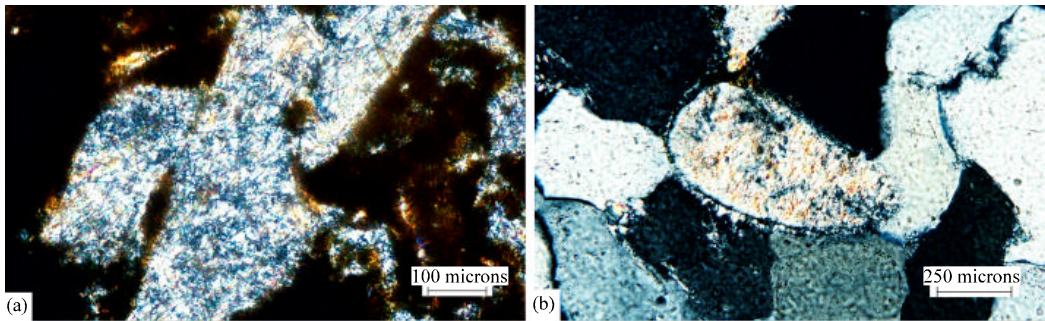


Fig. 11: Neomorphism during mesodiagenesis (a) Neof ormation of rutile needles developed in illite-smectite epimatrix replacing stromatolitic dolostones. La Siempre Verde quarry, Villa Mónica Formation, Sierra La Juanita, Barker (crossed nicols). (b) Perpendicular coatings around detrital, partially altered plagioclase. Same rock shown in previous figure (crossed nicols)

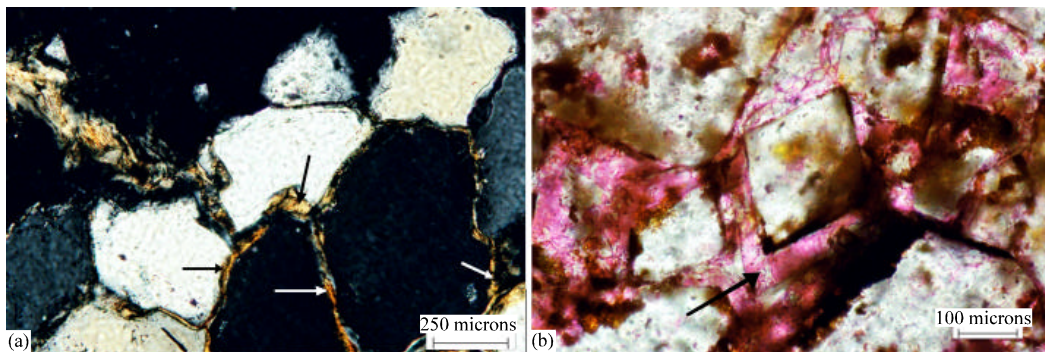


Fig. 12: Neomorphism during telodiagenesis. (a) Tangential clay coatings (arrows) of illitic composition infiltrated (epimatrix) around quartz grains in quartzarenites, Cerro Largo Formation, Sierra La Juanita, Barker (crossed nicols). (b) Epitaxial calcite rims (arrow) on rhombohedral dolomite crystal. Sample stained with Alizarin-red (parallel nicols). Villa Mónica Formation, La Siempre Verde, Sierra La Juanita, Barker

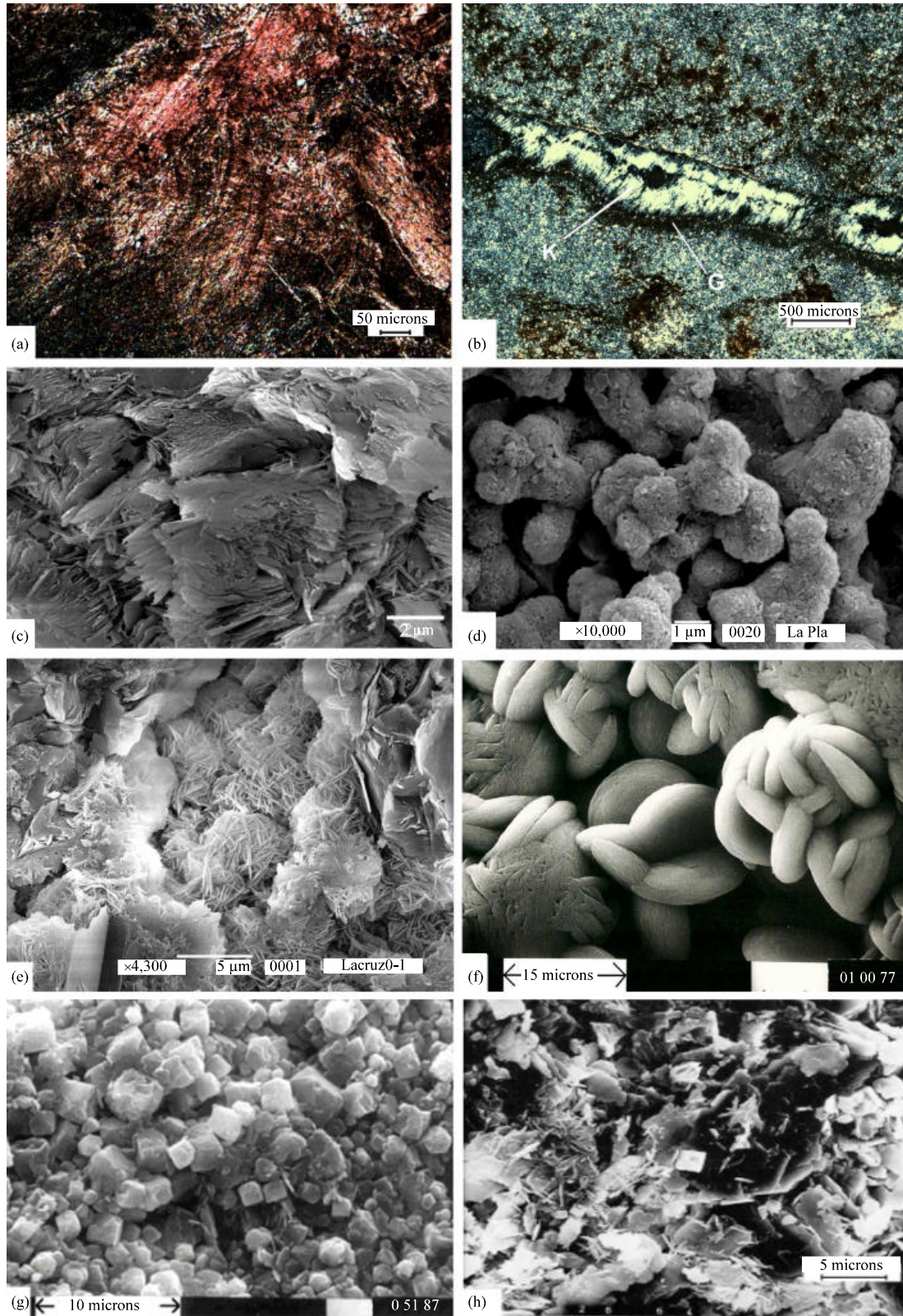


Fig. 13: Continued

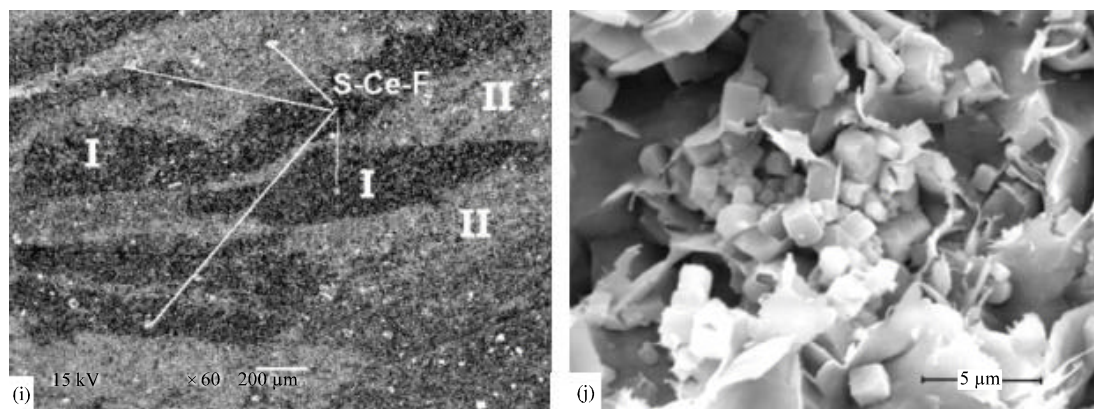


Fig. 13: Neomorphism during telodiagenesis. (a) Slickensides with ferriargilans: cutans (crossed nicols). (b) Kaolinite cutan (K) in fractures surrounded by postdating goethite (crossed nicols). Villa Mónica Formation, La Placeres quarry, Sierra La Juanita, Barker. (c) SEM. Hexagonal, platy kaolinite transforming to halloysite. (d) SEM. Hexagonal, platy kidney-shaped kaolinite aggregates growing in fractures. (e) and (f): SEM. Goethite aggregates growing in fractures and pore space. Villa Monica Formation, San Manuel. (g) SEM. Pseudocubes of alunite. (h) SEM. Kaolinite, halloysite and alunite. (I) Backscattered electron image of APS minerals svanbergite-Ce-florencite (S-Ce-F). (i) High-porosity zones with alunite, halloysite, diaspore and svanbergite-Ce-florencite. (II) Low-porosity zones rich in pyrophyllite, kaolinite, micas, svanbergite-Ce-florencite and heavy metals. Photographs g, h and i correspond to fractures and sedimentary discontinuities. Las Aguilas Formation, Cuchilla de Las Aguilas, Barker. (j) SEM. Fibrous illite-smectite, alunite and kaolinite growing in pore space of quartzarenites of the Balcarce Formation, Chillar

Tubes of halloysite formed at expense of platy, hexagonal kaolinite (Fig. 13c), kidney-shaped kaolinite aggregates (Fig. 13d) and goethite aggregates growing in fractures and cavities (Fig. 13e and f) of Carbonate/Siliciclastic deposits of the Villa Mónica Formation at San Manuel locality are observed by Scanning Electron Microscopy (SEM). All these phase minerals have been interpreted as formed during a telodiagenetic stage according to Zalba *et al.* (2010).

The presence of alunite as pseudocubic crystals (Fig. 13g) associated with kaolinite, halloysite (Fig. 13h) and also diaspore and goethite, have been reported by Zalba (1982) and Zalba *et al.* (1988) and interpreted as formed by the introduction of meteoric fluids through sedimentary discontinuities of clay and heterolithic deposits of the Las Aguilas Formation (Zalba *et al.*, 2007). Moreover, SEM images obtained by the authors in backscattering mode and microprobe analyses allowed the identification of disseminated crystals of Aluminum Phosphate Sulfate (APS) in a clay matrix (Fig. 13i) which fall in the compositional field of a solid solution between svanbergite ( $\text{SrAl}_3(\text{PO}_4, \text{SO}_4)(\text{OH})_6$ ) and Ce-florencite ( $\text{CeAl}_3(\text{PO}_4)_2(\text{OH})_6$ ), two APS minerals of the beudantite and the crandallite groups, respectively, according to Gaboreau *et al.* (2005). These SEM images indicate that APS minerals have preferentially crystallized in the more porous sediment.

Most of the time, it is not possible to determine the absolute time of formation of diagenetic minerals. In some cases, we can define the order of formation of the minerals present in the host sediments (paragenetic sequence). Observation of the phenomenon must be followed by interpretation, which is related to the knowledge of the consequences which brings to the fabric a determined process (e.g. compaction, authigenesis, etc.). In the case of the origin of APS minerals, associated with kaolinite, halloysite, diaspore and goethite in the Neoproterozoic Las Aguilas Formation, K-Ar data of alunite provided an age of  $254 \pm 7$  Ma (middle Permian) which sets boundary on the age of the diagenetic processes that led to the formation of all these paragenetic minerals (Zalba *et al.*, 2007).

Recently, SEM observations made on the quartzarenites of the Balcarce Formation (Early Ordovician) sampled at Chillar locality (Fig. 1) proved that also these paragenetic minerals are present in porous spaces and cavities of these rocks (Fig. 13j).

All these telodiagenetic features described for different sedimentary Neoproterozoic and Ordovician units all along the Tandilia Basin show a striking coincidence in time with the deformation of the Ventania Basin, located 150 km SW of the study area. The time of formation of alunite is coherent with the Permian age proposed by Von Gosen and Buggisch (1989) and

Varela *et al.* (1985) for the main deformation and folding stage of the Ventania System, relating it with the uplift, erosion and telodiagenetic stage that occurred in the Tandilia Basin (Zalba *et al.*, 2007).

#### ACKNOWLEDGMENTS

The authors would like to thank the Comisión de Investigaciones Científicas Provincia de Buenos Aires and the Centro de Tecnología de Recursos Minerales y Cerámica for financial support. We are grateful to all our collaborators of previous pieces of research on the subject on which we based this review.

#### REFERENCES

- Ahmad, A.H.M. and G.M. Bhat, 2006. Petrofacies, provenance and diagenesis of the dhosa sandstone member (Chari Formation) at Ler, Kachchh sub-basin, Western India. *J. Asian Earth Sci.*, 27: 857-872.
- Andreis, R.R., P.E. Zalba, A.M. Iñiguez Rodríguez and M. Morosi, 1996. Stratigraphy and paleoenvironmental evolution of the upper succession Cerro Largo Formation, Sierras Bayas (Buenos Aires, Argentina). *Proceedings of the 6th Argentina Meeting of Sedimentology, (AMS'96)*, Bahía Blanca, Province of Buenos Aires, pp: 293-298.
- Awramik, S.M., 1984. Ancient Stromatolites and Microbial Mats. In: *Microbial Mats: Stromatolites*, Cohen, Y., R.W. Castenholz and H.O. Halvorson (Eds.). A.R. Liss Publisher, New York, pp: 1-22.
- Brewer, R., 1960. Cutans: Their definition, recognition and interpretation. *Eur. J. Soil Sci.*, 11: 280-292.
- Brewer, R., 1976. *Fabric and Mineral Analysis of Soils*. R.E. Krieger Publishing Co., Huntington, New York, pp: 480.
- Burley, S.D., J.D. Kantorowicz and B. Waugh, 1985. Clastic Diagenesis. In: *Sedimentology: Recent and Applied Aspects*, Brenchley, P.J. and Williams, B.P. (Eds.). Geological Society of London, London, pp: 189-226.
- Chafetz, H.S. and J. Zhang, 1998. Authigenic euhedral megaquartz crystals in a Quaternary dolomite. *J. Sedimentary Res.*, 68: 994-1000.
- Choquette, P.W. and L.C. Pray, 1970. Geologic nomenclature and classification of porosity in sedimentary carbonates. *AAPG Bull.*, 54: 207-250.
- Curtis, C.D., 1977. Sedimentary geochemistry: Environments and processes dominated by involvement of an aqueous phase. *Phil. Trans. R. Soc. Lond.*, 286: 353-372.
- Dalla Salda, L. and A.M. Iñiguez, 1979. La Tinta, Precambrian and Paleozoic of Buenos Aires. *Proceedings of the 7th Argentine Geological Congress, (AGC'79)*, Neuquen, pp: 109-117.
- Dristas, J.A. and M.C. Frisicale, 2003. Two types of hydrothermal clay deposits in the south-east area of Tandilia. Buenos Aires Province, Argentina. *Proceedings of the 12th International Clay Conference, (ICC'01)*, Elsevier, Bahía Blanca, Argentina, pp: 85-92.
- Druschke, P., G. Jiang, T.B. Anderson and A.D. Hanson, 2009. Stromatolites in the late Ordovician Eureka quartzite: Implications for microbial growth and preservation in siliciclastic settings. *Sedimentology*, 56: 1275-1291.
- Evans, B.W. and S. Guggenheim, 1988. Talc, pyrophyllite and related minerals. *Rev. Mineral. Geochem.*, 19: 225-294.
- Flügel, E., 2004. *Microfacies of Carbonate Rocks, Analysis, Interpretation and Application*. Springer-Verlag, Berlin, pp: 976.
- Folk, R.L., 1965. *Petrology of Sedimentary Rocks*. Cambridge University Press, Cambridge, pp: 170.
- Gaboreau, S., D. Beaufort, Ph. Vieillard, P. Patrier and P. Bruneton, 2005. Aluminum phosphates sulphates minerals associated with Proterozoic unconformity-type uranium deposits in the East Alligator Rivers Uranium Field, Northern Territory, Australia. *Can. Mineralogist*, 43: 795-809.
- Gerdes, G., W.E. Krumbein and H.E. Reineck, 1991. Biolaminations-Ecological Versus Depositional Dynamics. In: *Cycles and Events in Stratigraphy*, Einsele, G., W. Ricken and A. Seilacher (Eds.). Springer-Verlag, Berlin, pp: 592-607.
- Gerdes, G., T. Klenke and N. Noffke, 2000. Microbial signatures in peritidal siliciclastic sediments: A catalogue. *Sedimentology*, 47: 279-308.
- Girard, J.P. and M. Deynoux, 1991. Oxygen isotope study of diagenetic quartz overgrowths from the Upper Proterozoic Quartzites of Western Mali, Taoudeni basin: Implications for conditions of quartz cementation. *J. Sedimentary Petrol.*, 61: 406-418.
- Hemingway, J.E. and J. Riddler, 1982. Basin inversion in the North Yorkshire: *Transactions of the Institute of Mining and Metallurgy, Section B. Applied Earth Sci.*, 91: 175-186.
- Hemley, J.J., J.W. Montoya, J.W. Marinenko and R.W. Luce, 1980. Equilibria in the system  $Al_2O_3$ - $SiO_2$ - $H_2O$  and some general implications for alteration/mineralization processes. *Econ. Geol.*, 75: 210-228.

- Hendry, J.P., N.H. Trewin and A.E. Fallack, 1996. Low-Mg-Calcite marine cement in Cretaceous turbidites: Origin, spatial distribution and relationship to sea-water chemistry. *Sedimentology*, 43: 877-900.
- Hesse, R., 1987. Selective and reversible carbonate-silica replacements in lower Cretaceous carbonate-bearing turbidites of the Eastern Alps. *Sedimentology*, 34: 1055-1077.
- Hofmann, H.J., 1975. Stratiform Precambrian stromatolites, Belcher islands, Canada: Relations between silicified microfossils and microstructure. *Am. J. Sci.*, 275: 1121-1132.
- Iñiguez, A., M. Manassero, D.G. Poiré and J. Maggi, 1996. Genesis and provenance of quartzarenites of Olavarría, Provincia de Buenos Aires, Argentina. Proceedings of the 6th Argentina Meeting of Sedimentology (AMS'96), Bahía Blanca, Province of Buenos Aires, Argentine, pp: 61-66.
- Iñiguez, A.M., A. del Valle, D.G. Poiré, L. Spalletti and P.E. Zalba, 1989. Precambrian/Lower Paleozoic Basin of Tandilia, Province of Buenos Aires. In: *Argentine Sedimentary Basins*, Chebli, G. and L. Spalletti (Eds.). National University of Tucumán, Geological Correlation Superior Institute, Series of Geological Correlation, Argentina, pp: 245-263.
- Iñiguez, A.M. and P.E. Zalba, 1974. Geology of refractory clay deposits of the Province of Buenos Aires, Argentine. *Rev. Argentine Geol. Assoc.*, 29: 304-310.
- Krumbein, W.E., 1994. *Biostabilization of Sediments*. BIS-Verlag, Oldenburg, pp: 256.
- Larsen, G. and G.V. Chilingar, 1979. *Diagenesis in Sediments and Sedimentary Rocks*. Developments in Sedimentology 25. Elsevier, Amsterdam, pp: 579.
- Manassero, M.J., 1986. Stratigraphy and structure at the eastern sector of the Barker locality, Province of Buenos Aires. *Rev. Argentine Geol. Assoc.*, 41: 375-384.
- Morton, N., 1987. Jurassic subsidence history in the Hebrides, N. W. Scotland. *Marine Petroleum Geol.*, 4: 226-242.
- Noffke, N., G. Gerdes, T. Klenke and W.E. Krumbein, 1997. A microscopy sedimentary succession of graded sand and microbial mats in modern siliciclastic tidal flats. *Sedimentary Geol.*, 10: 1-6.
- Noffke, N., G. Gerdes, T. Klenke and W.E. Krumbein, 2001. Microbially induced sedimentary structures - a new category within the classification of primary structures. *J. Sedimentary Res.*, 71: 649-656.
- Noffke, N., R. Hazen and N. Nhlenko, 2003. Earth's earliest microbial mats in a siliciclastic marine environment (Mozaan Group, 2.9 Ga, South Africa). *Geology*, 31: 673-676.
- Noffke, N., 2006. Spatial and temporal distribution of microbially induced sedimentary structures: A case study from siliciclastic storm deposits of 2.9 Ga old Witwatersrand Supergroup, South Africa. *Precambrian Res.*, 146: 35-44.
- Noffke, N., K.A. Eriksson, R.M. Hazen and E.L. Simpson, 2006. A new window into early Archean life: Microbial mats in Earth's oldest siliciclastic tidal deposits (3.2 Ga Moodies Group, South Africa). *Geology*, 34: 253-256.
- Noffke, N., 2007. Microbially induced sedimentary structures in Archean sandstones: A new window into early life. *Gondwana Res.*, 11: 336-342.
- Noffke, N., 2009. The criteria for biogenicity of Microbially Induced Sedimentary Structures (MISS) in Archean, sandy deposits. *Earth Sci. Rev. Microb. Mats Earth Fossil Record Life Geobiol.*, 96: 173-180.
- Poiré, D.G. and L. Spalletti, 2005. The Precambrian-Lower Paleozoic Sedimentary Cover of the Tandilia System. In: *Geology and Mineral Resources of the Province of Buenos Aires*, De Barrio, R.E., H.O. Etcheverry, M.F. Caballé and E. Llambias (Eds.). University of La Plata, Argentina, pp: 51-68.
- Poiré, D.G. and A.M. Iñiguez, 1984. Psamopelites member of the Sierras Bayas Formation, Olavarría, Province of Buenos Aires. *Rev. Argentine Geol. Assoc.*, 39: 276-283.
- Poiré, D.G., 1987. Mineralogy and sedimentology of the Sierras Bayas Formation in the septentrional nucleus of the homonymous hills, Olavarría, Province of Buenos Aires. Doctoral Thesis, Faculty of Natural Sciences and Museum of La Plata, La Plata University, pp: 271.
- Poiré, D.G., 1993. Stratigraphy of Precambrian sedimentary Olavarría, Sierras Bayas, Province of Buenos Aires, Argentina. Proceedings of the 12th Argentine Geological Congress and 2nd Congress of Oil Exploration, (AGCCHE'93), Mendoza, pp: 92-98.
- Riding, R., 2000. Microbial carbonates: The geological record of calcified bacterial-algal mats and biofilms. *Sedimentology*, 47: 179-214.
- Schieber, J., 1998. Possible indicators of microbial mat deposits in shales and sandstone: Examples from the Mid-Proterozoic Belt Supergroup, Montana, USA. *Sedimentary Geol.*, 120: 105-124.
- Schieber, J. and L. Riciputi, 2004. Pyrite and marcasite coated grains in the Ordovician Winnipeg Formation, Canada: An intertwined record of surface conditions, stratigraphic condensation, geochemical reworking and microbial activity. *J. Sed. Res.*, 75: 907-920.
- Schieber, J., 2007. Oxidation of detrital pyrite as a cause for marcasite formation in marine lag deposits from the Devonian in the eastern US. *Deep-Sea Res.*, 54: 1312-1326.

- Schmidt, V. and D.A. McDonald, 1979. Texture and recognition of secondary porosity in sandstones. *SEPM Special Publ.*, 26: 205-225.
- Scotchman, I.C., 1991a. Kerogen facies and maturity of the Kimmeridge Clay Formation of Southern and Eastern England. *Marine Petroleum Geol.*, 8: 278-295.
- Scotchman, I.C., 1991b. The geochemistry of concretions from the Kimmeridge Clay Formation of southern and eastern England. *Sedimentology*, 38: 79-106.
- Teruggi, M.E. and J. Kilmurray, 1980. Sierras Septentrionales of the Buenos Aires Province. National Academy of Sciences, Cordoba, pp: 919-956.
- Varela, R., L. Dalla Salda and C. Cingolani, 1985. Structure and geological composition of the Colorada, Cortapie and Chasico hills, Sierras Australes of Buenos Aires. *Rev. Argentine Geol. Assoc.*, 40: 254-261.
- Von Gosen, W. and W. Buggisch, 1989. Tectonic evolution of the Sierras Australes fold and thrust belt, Buenos Aires Province, Argentina: An outline. *Zentralblatt Für Geologie Und Paläontol. Teil, 1*: 947-958.
- Walter, M.R., J. Bauld, D.J. Des Marais and J.W. Schopf, 1992. A General Comparison of Microbial Mats and Microbial Stromatolites: Bridging the gap between the modern and the Fossil. In: *The Proterozoic Biosphere: An Interdisciplinary Study*, Schopf, J.W. and C. Klein (Eds.), Cambridge University Press, New York, pp: 335-338.
- Walter, M.R., 1994. Stromatolites: The Main Geological Source of Information on the Evolution of the Early Benthos. In: *Early Life on Earth Nobel Symposium*, Bebgstone, S. (Ed.). Columbia University Press, New York, pp: 270-286.
- Worden R.H. and S.D. Burley, 2003. Sandstone Diagenesis: the Evolution of Sand to Stone. In: *Sandstone Diagenesis: Recent and Ancient*, Burley, S.D. and R.H. Worden (Eds.). Reprint Series of the International Association of Sedimentologists, Blackwell Publishing Ltd., New York, pp: 3-44.
- Zalba, P.E., 1979. Clay deposits of Las Aguilas Formation, Barker, Buenos Aires Province, Argentina. *Clay and Clay Minerals*, 27: 433-439.
- Zalba, P.E., 1981. New level of claystones in the Loma Negra limestone quarry. *Rev. Argentine Geol. Assoc.*, 37: 99-102.
- Zalba, P.E., 1982. Scan electron micrographs of clay deposits of Buenos Aires Province, Argentina. *Proceedings of the International Clay Conference, (ICC'82), Developments in Sedimentology*, Elsevier, Bologna-Pavia, Italy, Amsterdam, pp: 513-528.
- Zalba, P.E. and L.B. Garrido, 1984. Study of clay deposits of El Ferrugo and Constante 10, Province of Buenos Aires. *Geology, mineralogy and textural, genetic and technological classification of clays. Proceedings of the 9th Argentine Geological Congress, (AGC'84), Bariloche*, pp: 441-445.
- Zalba, P.E., R.R. Andreis and A.M. Iñiguez, 1988. Las Aguilas Formation, Sierras Septentrionales de Buenos Aires, new stratigraphic proposal. *Rev. Argentine Geol. Assoc.*, 43: 198-209.
- Zalba, P.E. and R.R. Andreis, 1998. Saprolitized crystalline basement and overlying sedimentary sequence in San Manuel, Loberia, Sierras Septentrionales of Buenos Aires, Argentine. *Proceedings of the 7th Meeting of Sedimentology, Salta, (MSS'98), Argentine*, pp: 143-153.
- Zalba, P.E., M.J. Manassero, E. Laverret, D. Beaufort, A. Meunier, M. Morosi and L. Segovia, 2007. Middle Permian Telodiagenetic processes in Neoproterozoic sequences, Tandilia System Argentina. *J. Sedimentary Res.*, 77: 525-538.
- Zalba, P.E., M. Manassero, M.E. Morosi and M.S. Conconi, 2010. Preservation of biogenerated mixed facies: A case study from the Neoproterozoic Villa Mónica Formation, Sierra La Juanita, Tandilia, Argentina. *J. Applied Sci.*, 10: 363-379.