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Acritarchs of Las Ventanas Formation (Ediacaran, Uruguay): Implications for the timing of coeval rifting and glacial events in western Gondwana

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Abstract

Acritarchs and other organic-walled microfossils occurring in siltstones of the Las Ventanas Formation (Quebrada de Viera and El Perdido members) are systematically described and illustrated. The assemblage includes the following species: *Leiosphaeridia tenuissima*, *Leiosphaeridia minutissima*, *Lophosphaeridium* sp., *Soldadophycus bossii*, *Soldadophycus major*, *Soldadophycus* sp. and *Vendotaenia antiqua*. The microflora is characterized by low diversity (six species), dominance of *L. tenuissima*, absence of acanthomorphic acritarchs, and relatively large size of sphaeromorphs, reaching 400 μm in diameter. A number of species are shared with acritarch assemblages preserved in the overlying Arroyo del Soldado Group. Differences between assemblages include the occurrence of abundant *Bavlinella faveolata* and small size of spheroids in the Arroyo del Soldado Group. The assemblage occurring in Las Ventanas Formation is assigned to the Ediacaran Leiosphere Palynoflora, which spans the interval between the base of the Ediacaran (end of the Marinoan Glaciation, 635 Ma) and the termination of the Gaskiers Glaciation (582 Ma). An early Ediacaran age between 615 and 579 Ma is also supported by available radiometric ages. An extensional setting for Las Ventanas basin is suggested on the basis of the bimodal, synsedimentary volcanism, strong palaeorelief, great thickness of alluvial fan conglomerates and the evolution from continental to open marine environments. Diamictites occurring in the Quebrada de Viera Member are described for the first time, including associated dropstones which suggest a glacial origin. If confirmed, this would be one more example of the association between rifting and glaciation in the Neoproterozoic, coeval with a low-diversity, high-abundance acritarch microflora. A causal relationship between these tectonic, climatic and biologic events is discussed.
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Keywords: Neoproterozoic; Rifting; Ediacaran; Acritarchs; Uruguay

1. Introduction

The Las Ventanas Formation, erected and mapped by Midot (1984), is composed of a thick, fining- and thinning-upward volcanosedimentary sequence covering an area in excess of 120 km^2 of the southern Nico Perez Terrane (Bossi and Campal, 1992; Bossi and Gaucher, 2004). Polymictic orthoconglomerates predominate, passing into sandstones and siltstones up section. The structure in its type area corresponds to a broad syncline (Cerro Las Ventanas Syncline) with an axis oriented S20W.

Bossi and Navarro (1991) consider the Las Ventanas Formation to represent the volcanosedimentary record of an extensional event associated with the former Lavalleja Group, which was then considered to be of Neoproterozoic age. Masquelin and Sánchez Bettucci (1993) correlate outcrops of Las Ventanas Formation with the predominantly conglomeratic Playa Hermosa Formation, which they consider Neoproterozoic or Cambrian in age. Sánchez Bettucci and Ramos (1999) assign Las Ventanas Formation to the Ordovician, on the basis of occasional syenite clasts occurring in the conglomerates, which the authors supposed to be Cambrian in age.

The discussion about the tectonic and palaeoclimatic significance of the unit has been hindered by the lack of reliable age constraints. The discovery of well preserved acritarchs, vendotaenids and wrinkle structures in fine-grained

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siliciclastic rocks (pelites) of the Las Ventanas Formation by Blanco (2004) and Blanco and Gaucher (2004) allowed the age of this unit to be constrained for the first time. Here we describe the organic-walled microfossils from Las Ventanas Formation, and discuss their biostratigraphic significance, as well as their tectonic and palaeoclimatic implications.

2. Lithostratigraphy and depositional environments

The Las Ventanas Formation is subdivided into the following members, from base to top (Blanco and Gaucher, 2005; (Fig. 2)):

(a) La Rinconada Member, made up of basic volcanics, mainly basalts, volcanoclastic breccias and subordinate basic tuffs, reaching 500 m in thickness. It is overlain with erosional unconformity by:

(b) The Quebrada de Viera Member, which is composed of polymictic, mostly clast-supported conglomerates, grading to conglomerate-sandstone intercalations up section. Diamictites occur only at the base of the unit (see below). Maximum thickness reaches 3.800 m. Lithoclast composition shows provenance from a mixed volcanic (basic and acid) and granitic source area. Up to 37% basalt clasts in certain conglomerate levels suggest little chemical weathering and/or a steep palaeorelief (Füchtbauer, 1988). Cross bedding and normal grading are common sedimentary features of the conglomerates. Sandstones are texturally and mineralogically immature arkoses, often showing hummocky cross-stratification at the top of this member (Blanco and Gaucher, 2005). Whereas basalt clasts are more common at the base, rhyolitic clasts and intercalated rhyolitic tuffs occur at the top.

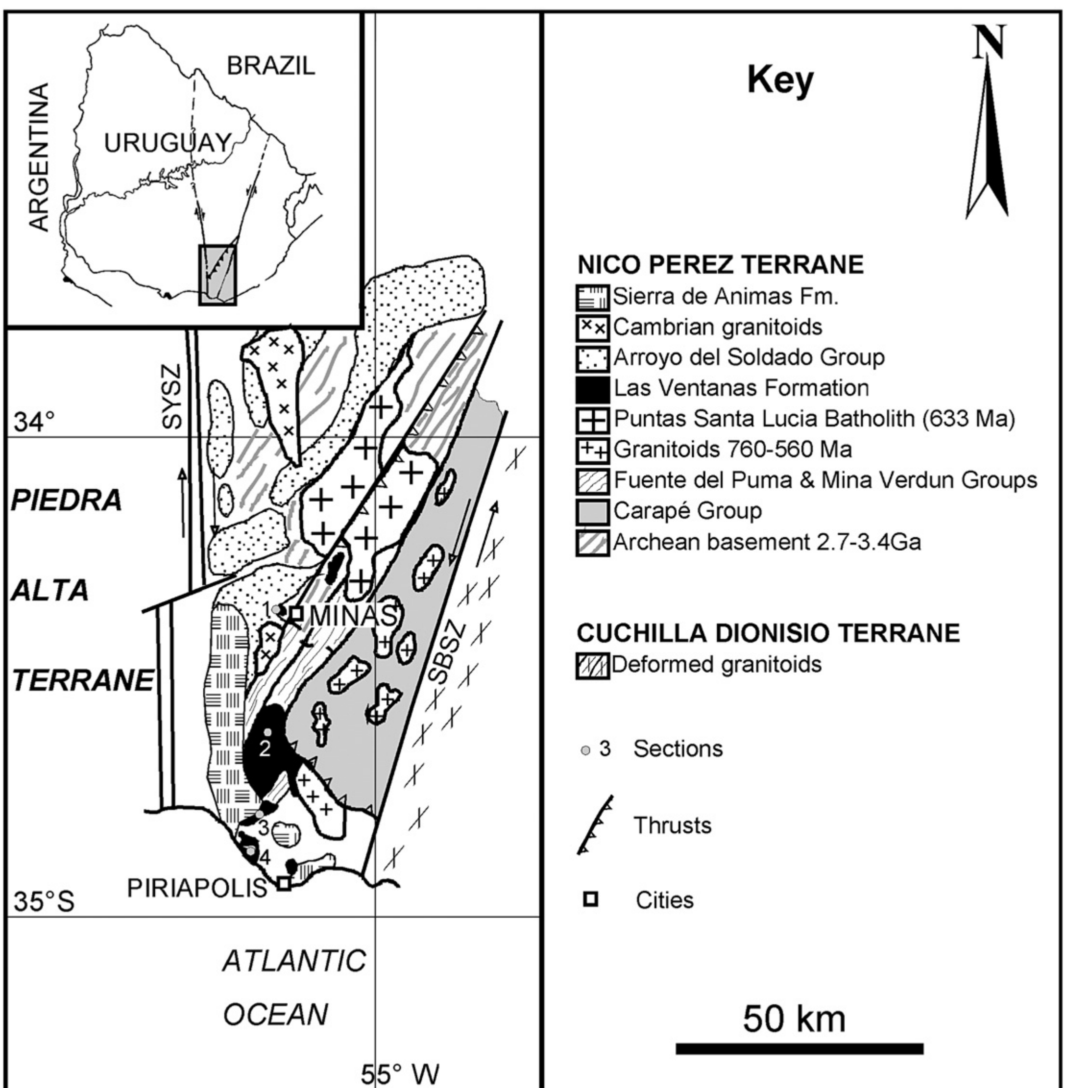

Fig. 1. Geological map of the southern Nico Pérez Terrane, showing outcrop area of the Las Ventanas Formation. SYSZ: Sarandí del Yí Shear Zone, SBSZ: Sierra Ballena Shear Zone. Sections: 1: CUCPSA Mine; 2: site LAN 63; 3: Cañada Azucarera (LA 31); 4: Cerro de los Burros (PIR 22).

(c) El Perdido Member concordantly overlies the Quebrada de Viera Member and is characterized by laminated siltstones and shales up to 600 m in thickness, showing reddish colours at the base and green and grey colours at the top (Blanco and Gaucher, 2005). Abundant pyrite at the top of this member indicates dysoxic or anoxic conditions.

Conglomerates of the Las Ventanas Formation represent alluvial fan and fan delta deposits (Pecoits et al., 2004; Blanco and Gaucher, 2005), on the basis of (Einsele, 2000): (1) predominance of unchannelized, conglomerate deposits; (2) occurrence of both stream deposits (predominant) and sedimentary gravity flows; (3) great thickness of conglomerates; and (4) intercalation of conglomerates with marine siltstones and sandstones at the top of the Quebrada de Viera Member.

Thus, the Las Ventanas Formation represents a deepening-upward sequence, recording evolution from an alluvial fan-dominated environment to shallow marine conditions with occasional storms. Sedimentary structures, thickness of conglomerate deposits, abundance of unstable lithoclasts and immaturity of sandstones point to a steep palaeorelief. Bimodal volcanism evolves from mainly basic (basalts) at the base to mainly acid (rhyolitic) at the top.

An extensional geotectonic setting, possibly a rift, was postulated by Blanco and Gaucher (2005) for the Las Ventanas Formation. In favour of this hypothesis are the bimodal, synsedimentary volcanism, strong palaeorelief, great thickness of alluvial fan conglomerates and the evolution from continental to open marine environments. A number of magmatic units occurring in the Nico Pérez Terrane may be associated with this extensional event, including the Nico Pérez Dyke Swarm (581±13 Ma, K–Ar: Rivalenti et al., 1995), the Pan de Azúcar Pluton (579±1.5 Ma, Ar/Ar: Oyhantçabal et al., 2006; Fig. 1), and the Puntas del Santa Lucía Batholith (633±10 Ma, U–Pb SHRIMP: Hartmann et al., 2002; Fig. 1). Whereas the Las Ventanas Formation is probably younger than the Puntas del Santa Lucía Batholith (Bossi et al., 1998) and older than the Pan de Azúcar Pluton (Blanco and Gaucher, 2005), the contact with dykes of the Nico Pérez Dyke Swarm is not exposed. Mafic dykes cross-cutting conglomerates of Las Ventanas Formation in the vicinity of Minas (point 1, Fig. 1) yielded K–Ar ages between 485±13 Ma and 109±3 Ma, which are interpreted by González et al. (2004) as minimum ages of the dykes. If we assume that these dykes belong to the Nico Pérez Dyke Swarm, then the Las Ventanas Formation also predates this unit.

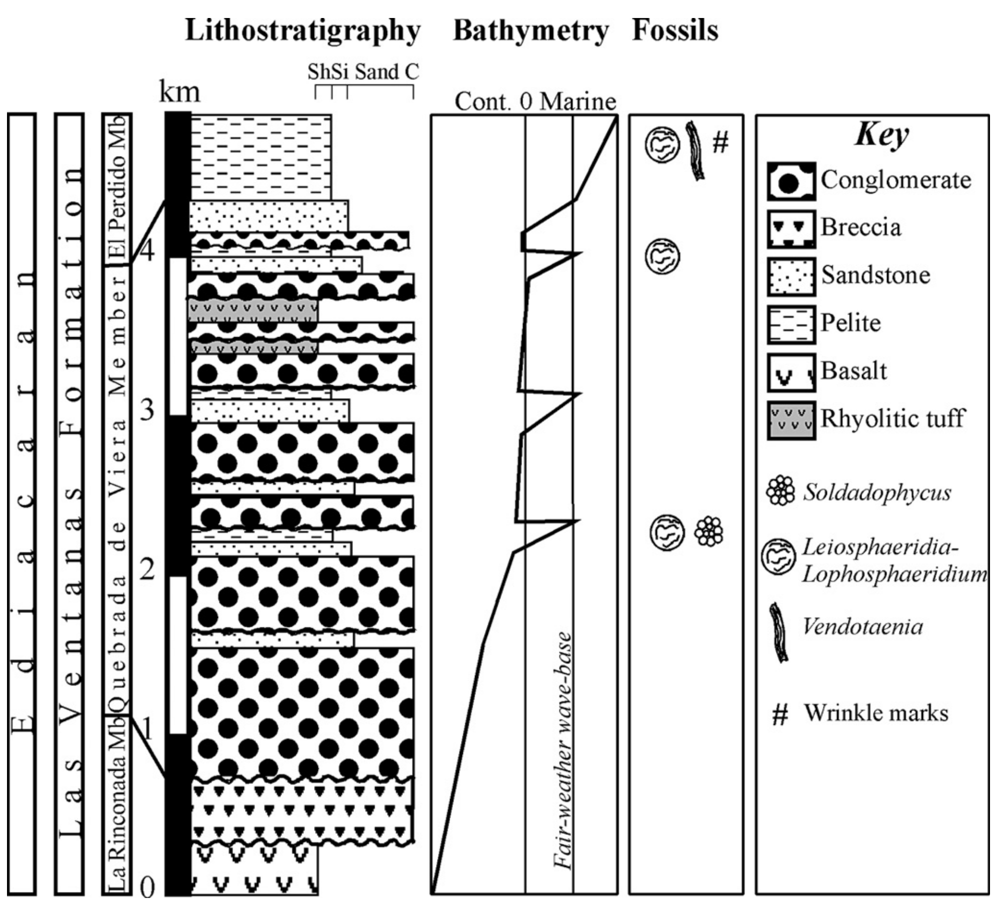

Fig. 2. Idealized stratigraphic column of Las Ventanas Formation, showing acritarch-bearing levels and volcanic horizons. Note transition from continental into marine environments and bimodal volcanism. K–Ar age of basalts of La Rinconada Member according to Sanchez Bettucci and Linares (1996). ASG: Arroyo del Soldado Group (overlying Las Ventanas Formation).

3. Age constraints

The Las Ventanas Formation is intruded by syenites of the Sierra de Animas Formation, which yielded an Rb–Sr age of 520 ± 5 Ma (Bossi et al., 1993), and also by the Pan de Azúcar Pluton (559 ± 28 Ma, Rb–Sr: Preciozzi et al., 1993; 579 ± 1.5 Ma, Ar/Ar: Oyhantçabal et al., 2006). K–Ar ages of 572 ± 7 Ma were obtained for synkinematic muscovites crystallized along the Puntas del Pan de Azúcar Thrust (Cingolani, in Bossi and Campal, 1992), which probably reflect thermal overprinting by the Pan de Azúcar Pluton. Basalts of the La Rinconada Member (lower Las Ventanas Formation) yielded K–Ar ages of 615 ± 30 Ma (Sanchez Bettucci and Linares, 1996), providing a maximum age constraint for deposition of the overlying conglomerates. Therefore an early Ediacaran age is supported by the available radiometric ages.

A number of organic-walled microfossils were mentioned for the first time by Blanco (2004), Blanco and Gaucher (2004) and Blanco and Gaucher (2005) from Las Ventanas Formation, namely: *Leiosphaeridia tenuissima*, *L. minutissima*, *Lophosphaeridium* sp., *Soldadophycusbossii*, *S. major*, *Soldadophycus* sp. and *Vendotaenia* sp. The assemblage is characterized by its low diversity, local abundance and large size (up to 400 μm) of *Leiosphaeridia*. Wrinkle structures (Hagadorn and Bottjer, 1999) occur in siltstones of the upper El Perdido Member (Blanco, 2004). Based on the microfossils and the available datings, Blanco and Gaucher (2005) assign Las Ventanas Formation to the Ediacaran (ca. 600 Ma). On the basis of their microfossil assemblages, Blanco and Gaucher (2005) postulate that the Las Ventanas Formation immediately predates the Arroyo del Soldado Group, which represents a thick shelf succession deposited in the late Ediacaran to Early Cambrian, between 575 and 535 Ma (Gaucher, 2000; Gaucher et al., 2003, 2004a).

4. Materials and methods

Eighteen palynological macerations of pelites from the Las Ventanas Formation were prepared at the Micropalaeontology Laboratory of the Facultad de Ciencias (Montevideo). Following crushing and digestion of samples (ca. 150 g) with concentrated HCl, 72% HF was applied for 24 h to the silicate/organic residues. After neutralization, hot, concentrated HCl was used to dissolve fluorides. Remaining organic residues were recovered by means of a 5 μm sieve, stored in glass flasks and mounted with glycerin–gelatine on standard glass slides. Throughout the preparation, gravity settling was used instead of centrifugation, to avoid destruction of fragile, large acritarchs. Microfossils were examined under a Leica DM LP polarizing microscope, using transmitted, reflected, and combined reflected–transmitted light (in the latter cases with oil immersion objectives). This permitted observation of opaque structures, as well as differentiation between fossil microstructures and minerals and modern contaminants. This method, developed by Pflug and Reitz (1992, and references therein), allows comparison of the reflectivity and transparency of microfossils. Modern contaminants are non-reflective, regardless of their transparency and colour, because they have not undergone carbonisation. Moreover, the epi-illumination method allows identification of opaque mineral structures that resemble microfossils (e.g. pyrite framboids). All the structures described here are clearly reflective, compressed (compaction) and organic in nature.

5. Systematic palaeontology

5.1. Repository

All palynological slides, containing specimens described here, are kept in the Precambrian collection of the Departamento de Paleontología, Facultad de Ciencias (Montevideo, Uruguay). The position of specimens in the slides is clearly marked on corresponding duplicates.

Incertae sedis

Group **Acritarcha** Evitt (1963)

Genus *Leiosphaeridia* Eisenack (1958), emend. Downie and Sarjeant (1963), emend. Turner (1984)
Type species: *Leiosphaeridia baltica* Eisenack (1958)

Leiosphaeridia minutissima Naumova (1949), emend. Jankauskas et al. (1989) Fig. 3A

1992 *Leiosphaeridia minutissima* Butterfield and Chandler:

Figs. 3A–3I

1994 *Leiosphaeridia minutissima* Hofmann and Jackson:

Figs. 15.9–15.15, 15.16

1996 *Leiosphaeridia minutissima* Hofmann and Jackson:

Figs. 12A–C

2000 *Leiosphaeridia minutissima* Gaucher: p. 66

Material. Ten well-preserved specimens and vesicle-fragments in palynological macerations of pelites of the Quebrada de Viera and El Perdido members (LA 31 and LAN 63, Fig. 1).

Description. Thin-walled, psilate, originally spheroidal vesicles with common, mainly concentric folds. Diameter ranging from 32 to 70 μm (mean = 50 μm; standard deviation, S.D. = 19 μm; N = 4).

Remarks. We apply here the criteria established by Jankauskas et al. (1989) for the classification of leiospherids. *L. minutissima* occurs as a subordinate component of the microbiota of Las Ventanas Formation. Regarding the palaeobiological significance of the taxon, it is clear that it encompasses a variety of disparate organisms.

Leiosphaeridia tenuissima Eisenack (1958)
Fig. 3 B–I

1958 *Leiosphaeridia tenuissima* Eisenack: pl. 1.2–1.3

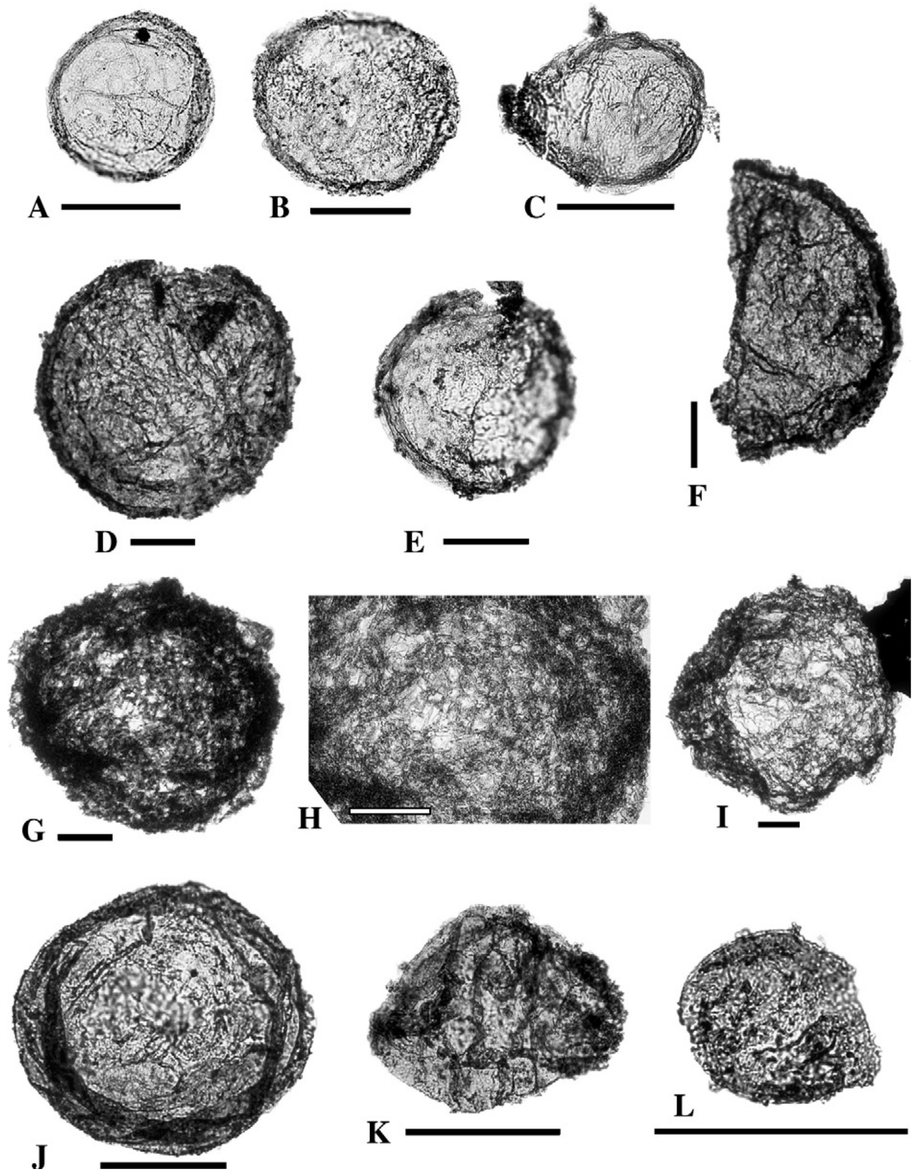

Fig. 3. Sphaeromorphs of Las Ventanas Formation recovered from shales and siltstones by means of standard palynological maceration. (A) *Leiosphaeridia minutissima* Naumova, emend. Jankauskas et al. (1989), specimen 030927/13A′-4. El Perdido Member (point LAN 63). (B) *Leiosphaeridia tenuissima* Eisenack (1958), specimen 030411/4C-11, Quebrada de Viera Member (point LA 31). (C) *L. tenuissima*, specimen 030927/13C-1, El Perdido Member (point LAN 63). (D) *L. tenuissima*, specimen 030927/13B-2, El Perdido Member (point LAN 63). (E) *L. tenuissima*, specimen 030411/4–12, Quebrada de Viera Member (point LA 31). (F) *L. tenuissima*, large specimen (diameter: 230 µm) 030411/4–10, Quebrada de Viera Member (point LA 31). (G) *L. tenuissima* with micro-wrinkled surface texture and 280 µm in diameter, specimen 030927/13A′-1. El Perdido Member (point LAN 63). (H) Detail of surface texture of previous specimen. (I) *L. tenuissima* with micro-wrinkled surface texture and 250 µm in diameter, specimen 030927/13A′-5. El Perdido Member (point LAN 63). (J) *Lophosphaeridium* sp., with prominent concentric folds and small verrucae, specimen 030927/13B′-1, El Perdido Member (point LAN 63). (K) *Lophosphaeridium* sp., specimen 030927/13B-4, El Perdido Member (point LAN 63). (L) *Lophosphaeridium* sp., specimen 030411/4B-12, Quebrada de Viera Member (point LA 31). Note verrucated surface texture. All scale bars represent 50 µm.

1994 *Leiosphaeridia tenuissima* Butterfield et al.: Fig. 16I
1994 *Leiosphaeridia tenuissima* Hofmann and Jackson: Figs. 12E
1998 *Leiosphaeridia tenuissima* Gaucher et al.: Fig. 4.6
2000 *Leiosphaeridia tenuissima* Gaucher: pl. 11.5
2003 *Leiosphaeridia tenuissima* Gaucher and Germs
2004c *Leiosphaeridia tenuissima* Gaucher et al.: Fig. 4D
2005a *Leiosphaeridia tenuissima* Gaucher et al.: Fig. 8g–h

Material. Twenty-two well-preserved specimens and dozens of fragments in macerations of siltstones of the Quebrada de Viera and El Perdido members in all fossiliferous samples (sites LA 31, LAN 63 and PIR 22; Fig. 1).

Description. Thin-walled, psilate, originally spheroidal vesicles with common folds. Two different patterns of folding of the walls were observed in the vesicles: (a) simple, psilate sphaeromorphs with mainly concentric folds (Fig. 3B–F); and (b) vesicles with a microplicate wall, expressed as a network of very numerous parallel and intersecting wrinkles (Fig. 3G–I).

Diameter ranging between 82 and 400 μm (mean = 174 μm; S.D. = 85 μm; N = 22). Some individuals show corrosion of the vesicle wall (Fig. 3B, E).

Remarks. *L. tenuissima* is the dominant species of the assemblage preserved in Las Ventanas Formation, occurring in all fossiliferous samples spanning stratigraphically more than 2500 m and in higher numbers than the other microfossils. Specimens are characterized by large diameters up to 400 μm. Differences in folding pattern of vesicle walls suggest that organisms with two different wall structures are included here under *L. tenuissima*: one with a thin but still competent wall, the other with a very thin, pliable membrane. The latter, similar to the outer wall structure reported for the genus *Plicatosphaeridium* (Butterfield, 2005), gives a microplicate pattern upon compaction. Because *Plicatosphaeridium* has a bi-layered wall, unlike microplicate sphaeromorphs from Las Ventanas Formation, we include these vesicles under *L. tenuissima*. Current research aims at establishing the viability of separating microplicate *Leiosphaeridia* into a different species, characterized by extremely thin vesicle walls. The same wall structure has been observed recently in specimens from the Sierras Bayas Group of Argentina (Gaucher et al., 2005b).

It is worth noting that *L. tenuissima* from Las Ventanas Formation is characterized by larger vesicle diameter than specimens occurring in the Arroyo del Soldado Group. In the latter unit, largest reported specimens are 125 μm in diameter. A tendency from larger to smaller leiospherids in the late Neoproterozoic has been noted by Butterfield (1997), and corroborated in the Sierras Bayas Group by Gaucher et al. (2005b).

Genus *Lophosphaeridium* Timofeev (1959), ex Downie (1963), emend. Lister (1970)

Lophosphaeridium sp.
Fig. 3J–L

Material. Three well-preserved specimens in palynological macerations of siltstones of the Quebrada de Viera and El Perdido members (sites LA-31 and LAN 63).

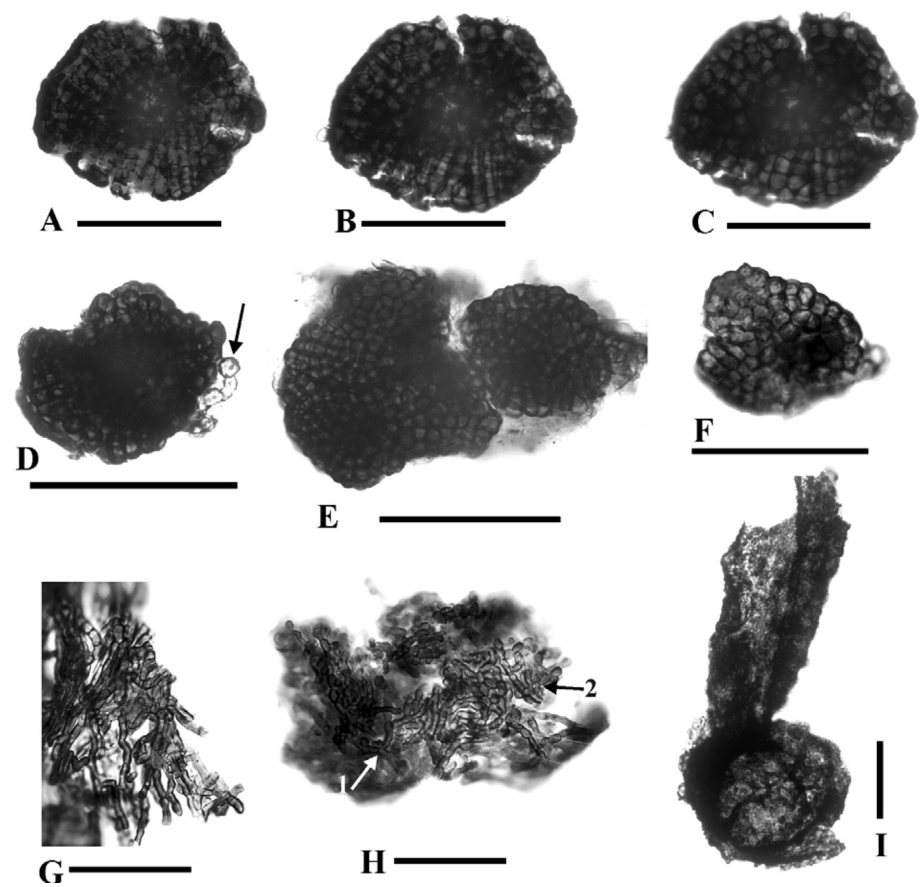

Fig. 4. *Soldadophycus* Gaucher et al. (1996) and acritarch with membranous projection from palynological macerations of pelites, Las Ventanas Formation (Quebrada de Viera Member, point LA 31). (A–C) *Soldadophycus* sp. saucer-shaped colony with radial arrangement of spheroids, specimen 030411/4–30. (A) uppermost focus-level, (B) middle focus-level, (C) lowest focus-level. (D) *Soldadophycus bossii* Gaucher et al. (1996), saucer-shaped colony showing cylindrical cells projecting from the colony (arrowed). Specimen 030411/4B-14. (E) *S. bossii*, two attached, saucer-shaped colonies with concentric arrangement of spheroids. Specimen 030411/4C-12. (F) *S. bossii*, saucer-shaped colony with concentric arrangement of spheroids. Specimen 030411/4-3a. (G) *S. bossii*, filament mat showing septate, branched filaments. Specimen 030411/4–14. (H) *S. bossii*, filament mat showing branching (arrowed, 1) and transition from filamentous to spheroidal cells (arrowed, 2). Specimen 030411/4–28. (I) Sphaeromorphic acritarch (*Lophosphaeridium*?) with membranous extension (disrupted attached vesicle?). Specimen 030411/4B-3. All scale bars represent 50 μm.

Description. Rather robust-walled vesicles with verrucate, plicated surface. Verrucae up to 1 μm in diameter. Concentric folds are prominent in one specimen (Fig. 3J). Diameter of specimens observed: 40, 84 and 123 μm.

Remarks. These sphaeromorphs are left in open nomenclature because of the small number of specimens observed.

Genus *Soldadophycus* Gaucher et al. (1996)

Type species. *Soldadophycus bossii* Gaucher et al. (1996)

Soldadophycus bossii Gaucher et al. (1996)
Fig. 4D–H

1989 Tipo B Palacios, pl.V; Figs. 1–4
1996 *Soldadophycus bossii* Gaucher et al.: Figs. 6.1–6.5; Fig. 6.7
1998 *Soldadophycus bossii* Gaucher et al.: Figs. 4.7–4.8
2000 *Soldadophycus bossii* Gaucher: pls. 14–15; 17.4
2003 *Soldadophycus bossii* Gaucher et al., Figs. 5B; 6A–B
2003 *Soldadophycus bossii* Gaucher and Germs, Figs. 7.1–7.4
2004c *Soldadophycus bossii* Gaucher et al., Figs. 4B, C, E
2005a *Soldadophycus bossii* Gaucher et al., Figs. 7a–b; 9a–b, d–f

Material. Dozens of colonies and colony-fragments in palynological macerations of siltstones, Quebrada de Viera Member (site LA-31, Fig. 1).

Description. *S. bossii* is characterized by the co-occurrence of psilate, originally spheroidal cells and septate, branched filaments (Gaucher et al., 1996). Different colony types made up solely of spheroidal cells, solely of filaments or of both were recognized by Gaucher (2000).

The material from Las Ventanas Formation includes all colony-types (or fragments thereof) described by Gaucher (2000) for the Arroyo del Soldado Group. Especially abundant are saucer-shaped colonies, pseudoparenchymatous aggregates and filament mats. Typical transitions from spheroids to filaments and vice versa is observed in many specimens (e.g. Fig. 4D and H). Diameter of spheroidal cells ranges between 3 and 5.5 μm and width of filaments varies between 2 and 4 μm. Diameter of saucer-shaped colonies ranging from 22 to 68 μm (mean = 51 μm, S.D. = 17 μm, N = 8). Fragments of flat, pseudoparenchymatous colonies reach 300 μm in maximum dimension. These values are typical for the species (Gaucher, 2000).

Remarks. This species occurs only in one sample from the Quebrada de Viera Member, in which it is a major component of the microbiota there, along with *L. tenuissima*. It closely resembles *S. bossii* from the type material of the overlying Arroyo del Soldado Group. Similar morphologies have been reported for *Wengania* Zhang (1989), a red alga from the Doushantuo Formation (Yuan et al., 2002; Xiao et al., 2004). Thalli of this genus are composed of spheroidal to cuboidal cells 2 to 12 μm in diameter. *Wengania minuta* cells range between 3 and 8 μm in diameter (Xiao, 2004), which is similar to *S. bossii* (Gaucher, 2000). *Wengania* is further characterized by spherical thalli (Xiao et al., 2004), which have also been reported for *Soldadophycus*. However, whereas spherical thalli in *Wengania* range between 44 and 750 μm in diameter, spheroidal colonies in *S. bossii* are significantly smaller (17–33 μm: Gaucher, 2000). Moreover, cells are arranged radially in *Wengania* thalli (Xiao et al., 2004) rather than concentrically as in spheroids of *S. bossii* (Gaucher, 2000; Gaucher et al., 2004c; Fig. 4D–F). Finally, *S. bossii* includes colonies predominantly composed of cylindrical, filamentous cells (Fig. 4G–H), which are unknown for *Wengania*. Thus, despite some strong morphological similarities, *Soldadophycus* and *Wengania* seem to comprise distinctively different genera. Future studies will investigate further the relationships between these genera, and the possible affinities of *Soldadophycus* with the Rhodophyta.

Soldadophycus major Gaucher (2000)

2000 *Soldadophycus major* Gaucher: pls. 16.1–6; 17.6
2004c *Soldadophycus major* Gaucher et al.: Fig. 4F–G
2005a *Soldadophycus major* Gaucher et al.: Fig. 8a–e

Material. Five well-preserved colonies and colony-fragments in palynological macerations of siltstones of the Quebrada de Viera Member (site LA-31, Fig. 1).

Description. Colonial, compressed spheroids characterized by hyaline, psilate, pliable walls, ranging between 5 and 9 μm in diameter. Filaments occur in one colony. Colony-types occurring in the Las Ventanas Formation include saucer-shaped and flat, irregular colonies. One saucer shaped-colony measures 102 μm in diameter.

Remarks. The material described here clearly belongs to *Soldadophycus major* Gaucher (2000), because of the similarity to the type material from the Arroyo del Soldado Group in colony habits and size.

S. major occurs in only one sample and is a subordinate component of the microflora preserved in Las Ventanas Formation.

Soldadophycus sp.
Fig. 4A–C

Material. A single well-preserved specimen from siltstones of the Quebrada de Viera Member (site LA-31, Fig. 1).

Description. Flat, discoidal colony 82 μm in diameter, composed of a few hundred psilate, compressed spheroids and originally cylindrical cells, which are arranged in rows radiating from the center. Diameter of spheroids ranging between 3.8 and 8.2 μm (mean = 6.1 μm, S.D. = 1.2 μm, N = 23) and diameter of cylindrical cells between 2.7 and 4.8 μm (mean = 3.6 μm, S.D. = 0.7 μm, N = 13). Length to diameter of originally cylindrical cells varies between 1.3 and 2.3. Some radial cell rows show increasing diameter toward the edge of the colony.

Remarks. The transition between spheroidal and filamentous cells, and the discoidal shape of the colony fit within the generic description of *Soldadophycus*. The colony has an overall shape that strongly resembles *S. bossii*, except for the radial arrangement of cells and the co-occurrence of spheroidal and cylindrical (filamentous) cells in a discoidal colony. Moreover, mean diameter of spheroids is considerably larger than in *S. bossii* (4.3 μm; Gaucher, 2000), though diameter of spheroids range

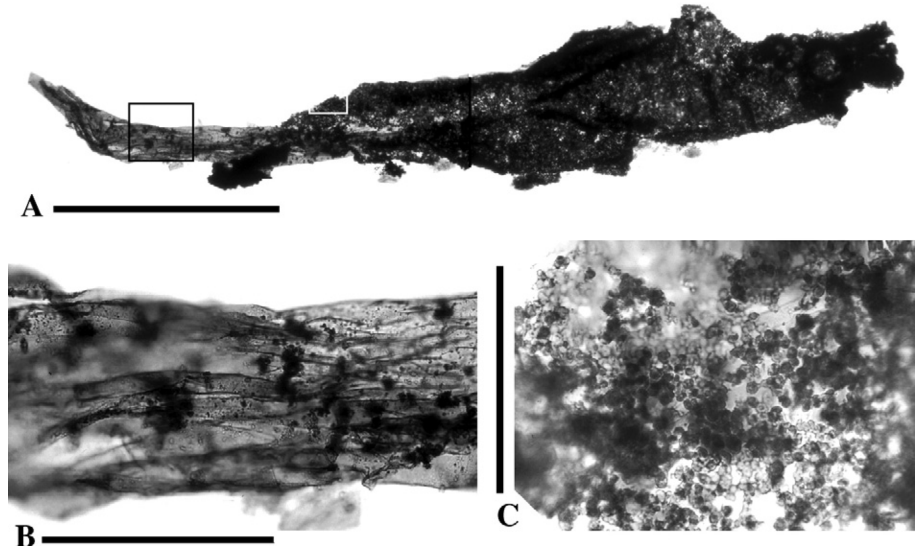

Fig. 5. *Vendotaenia antiqua* Gnilovskaya (1971) from palynological macerations of siltstones from Las Ventanas Formation (El Perdido Member), point LAN 63. (A) General overview of ribbonlike thallus, specimen 030927/13-3. (B) Detail of same specimen (black rectangle), showing typical longitudinal folds. (C) Detail of the same specimen (white rectangle), showing spheroidal cells ca. 3 µm in diameter covering the thallus surface. Scale bar in (A) equals 0.5 mm, in (B) 100 µm, and in (C) 50 µm.

between 2 and 8 µm for both species. Discoidal colonies were also reported for *S. major*, but both spheroid diameter (4–13 µm, mean = 8.1 µm: Gaucher, 2000) and colony diameter (134–190 µm: Gaucher, 2000) are larger than in the colony described here. The material described here under *Soldadophycus* sp. also resembles *Wengania* Zhang (1989), especially *Wengania globosa*, with regard to radial arrangement of cells in the colony, cell size and shape. However, *W. globosa* thalli are usually much larger (up to 750 µm: Xiao et al., 2004), and spherical rather than discoidal as in our material. As with *S. bossii*, the remarkable resemblance to *Wengania* suggests that these organisms may be related at a higher taxonomic level.

Therefore, two possibilities are envisaged: (a) that the fossil represents a previously unknown stage in the life cycle of *S. bossii*; or (b) that it represents a different species of the genus. Until more material is found, with which to clarify the specific assignment, we shall leave it in open nomenclature.

Order Vendotaeniales Gnilovskaya (1986)
Family Vendotaeniaceae Gnilovskaya (1986)
Genus *Vendotaenia* Gnilovskaya (1971)
Type species. *Vendotaenia antiqua* Gnilovskaya (1971)

Vendotaenia antiqua Gnilovskaya (1971)
Fig. 5A–C

1971 *Vendotaenia antiqua* Gnilovskaya: pl. XI.6–8
1979 *Tyrasotaenia podolica* Gnilovskaya
1985 *Vendotaenia antiqua* Gnilovskaya: pls. 30.1–5; 31.1–6; 32.1–4; 33.1–3; 36.2
1985 *Tyrasotaenia podolica* Gnilovskaya: pl. 34.1–4
1994 *Vendotaenia antiqua* Steiner: Fig. 41k, l; Fig. 45a–c; Fig. 47
2003 *Vendotaenia antiqua* Gaucher et al.: Fig. 5A

Material. A single, well-preserved specimen recovered by means of palynological maceration from siltstone of El Perdido Member (site LAN 63, Fig. 1).

Description. A fragment of a compressed, ribbonlike thallus 2 mm in length and 0.35 mm in maximum width, with typical longitudinal–fibrous structure due to compaction folds. The thallus is partially covered or composed of hundreds of originally spheroidal cells 3 µm in diameter (Fig. 5C).

Remarks. The fragmentary material recovered in this work from Las Ventanas Formation closely resembles the microstructure of *Vendotaenia antiqua* (Gnilovskaya, 1985: pls. 32.3, 33.5, 34.3–4; Vidal, 1989: Fig. 1C, E). The width of the thallus falls within the size range known for the species (0.25–3.5 mm: Gnilovskaya, 1985; 0.14–4.1 mm: Steiner, 1994). In the diagnosis of *V. antiqua*, Gnilovskaya (1985) mentions the occurrence of cells 3–5 µm in diameter, which match those occurring in the material described here. *V. antiqua* has been interpreted as the abandoned sheaths of sulfide-oxidizing organotrophic bacteria related to the Beggiatoaceae (Vidal, 1989) or as a multicellular eukaryotic alga (Gnilovskaya, 1985).

6. Discussion

6.1. Biostratigraphy

The acritarch assemblage recovered from Las Ventanas Formation is characterized by: (a) low diversity (six species); (b) dominance of *L. tenuissima* (both in number of specimens and stratigraphic distribution) with abundant *S. bossii* in one sample, (c) absence of acanthomorphic acritarchs, and (d) relatively large size of sphaeromorphs, reaching 400 µm in diameter.

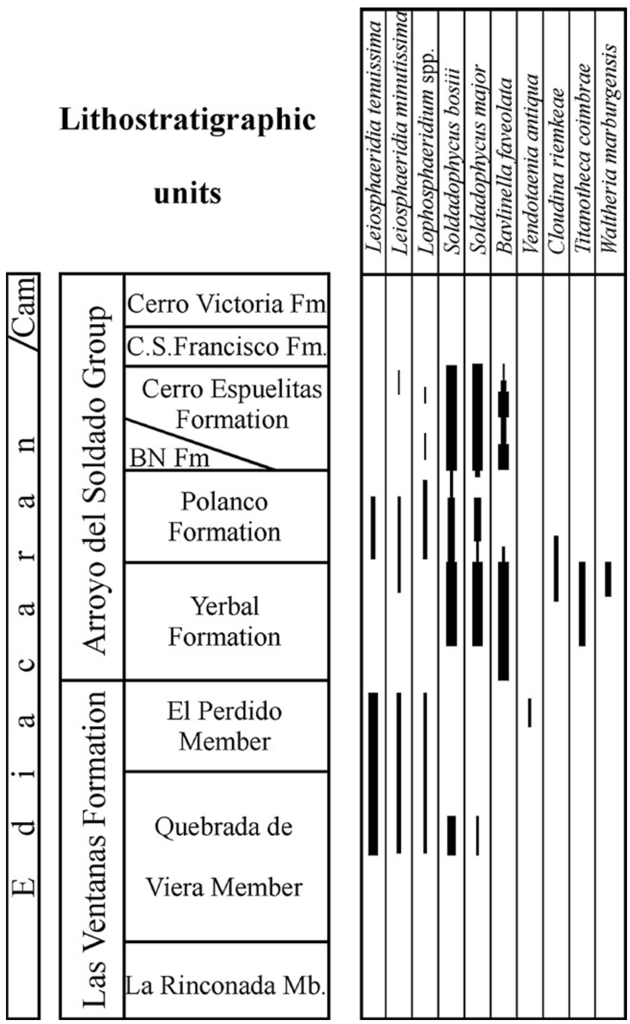

Fig. 6. Biostratigraphy of the Arroyo del Soldado Group and Las Ventanas Formation, showing ranges of most significant taxa. Sources: Gaucher and Sprechmann (1999), Gaucher (2000), Gaucher et al. (2003, 2004a,c) and this work. BN Fm: Barriga Negra Formation. CS: Cerros San Francisco Formation. Lithostratigraphic units are not represented proportionally to their actual thicknesses.

On the basis of low diversity and dominance of sphaeromorphs, the acritarch assemblage of the Las Ventanas Formation can be assigned either to the Ediacaran Leiosphere Palynoflora of Grey et al. (2003, the "Varanger assemblage" of Vidal and Moczydlowska-Vidal, 1997; Knoll, 2000) or the younger Kotlin–Rovno assemblage of Vidal and Moczydlowska-Vidal (1997). The palynoflora occurring in the overlying lower and middle Arroyo del Soldado Group has been correlated with the Kotlin–Rovno assemblage (spanning the 570 to 542 Ma interval; Gaucher, 2000), which is further supported by C and Sr chemostratigraphy (Gaucher et al., 2004a,b). Moreover, Ar–Ar ages of 579±1.5 Ma recently obtained by Oyhantçabal et al. (2006) for the intrusive Pan de Azúcar pluton (Fig. 1) show that Las Ventanas Formation is older than the Kotlin–Rovno assemblage. Thus, the acritarch assemblage preserved in Las Ventanas Formation is better assigned to the Ediacaran Leiosphere Palynoflora (Grey et al., 2003; Grey, 2005). This implies that the unit was deposited between the end of the Marinoan glacial event (635±0.6 Ma: Condon et al., 2005) and the appearance of the Ediacaran Complex Acanthomorph Palynoflora (Grey et al., 2003; Grey, 2005), probably coincident with the end of the Gaskiers glacial event (582±0.4 Ma: Bowring, in MacGabhann, 2005; Bowring et al., 2003). It is interesting to note that *Wengania* from the Doushantuo Formation of China, which bears remarkable similarities to *Soldadophycus*, occurs in phosphorites that yielded Pb–Pb ages of 599±4 Ma and 574±8 Ma (Barfod et al., 2002).

Differences between the assemblages recovered from Las Ventanas Formation and the Arroyo del Soldado Group include (Fig. 6): (a) occurrence of *Bavlinella faveolata* as a dominant species in the Arroyo del Soldado Group (Gaucher, 2000); (b) absence of leiospherids larger than 125 μm in this unit (Gaucher, 2000); (c) dominance of *Leiosphaeridia* in Las Ventanas Formation, unlike the Arroyo del Soldado Group, which is mostly dominated by *Soldadophycus* and *Bavlinella*. The assemblage preserved in the Polanco Formation (*Leiosphaeridia–Lophosphaeridium* assemblage: Gaucher, 2000) resembles the leiospherid assemblage of Las Ventanas Formation, but differs substantially in overall diversity and size of sphaeromorphs. From Las Ventanas Formation into the overlying Arroyo del Soldado Group, a tendency toward smaller sphaeromorphs upwards is observed: from 400 μm in the Las Ventanas Formation to 125 μm in the Polanco Formation of the Arroyo del Soldado Group. This trend has been reported in other shallow-water, marine Ediacaran successions elsewhere (Butterfield, 1997; Gaucher et al., 2005b). Leiospherids occurring in lower Ediacaran successions of Australia (Ediacaran Leiosphere Palynoflora) reach 240 μm in diameter (Grey, 2005).

Pecoits et al. (2004) mention, but neither describe nor illustrate, *B. faveolata* in siltstones of the Las Ventanas Formation. They do figure a microstructure from the San Carlos Formation, which they assign to *B. faveolata*. The figured structure, however, does not show any of the features characteristic of the species (e.g. microspheres or faveolate surface texture) and should be regarded – at best – as a microdubiofossil.

Finally, it is worth noting that the Ediacaran Complex Acanthomorph Palynoflora (ECAP) apparently does not occur either in the Arroyo del Soldado Group or the Las Ventanas Formation. If the Las Ventanas Formation corresponds to the Ediacaran Leiosphere Palynoflora, and the lower-middle Arroyo del Soldado Group to the Kotlin–Rovno assemblage, then the ECAP should occur between both units. Non-deposition, as suggested by the extensional magmatic activity around 579 Ma (Oyhantçabal et al., 2006), or unfavourable sedimentary environments for the ECAP or its preservation may explain the absence of this assemblage.

6.2. Tectonic and climatic events

An extensional geotectonic setting, possibly a rift, was postulated by Blanco and Gaucher (2005) for Las Ventanas Formation. In favour of this hypothesis are the bimodal, synsedimentary volcanism, strong palaeorelief, great thickness of alluvial fan conglomerates and the evolution from continental

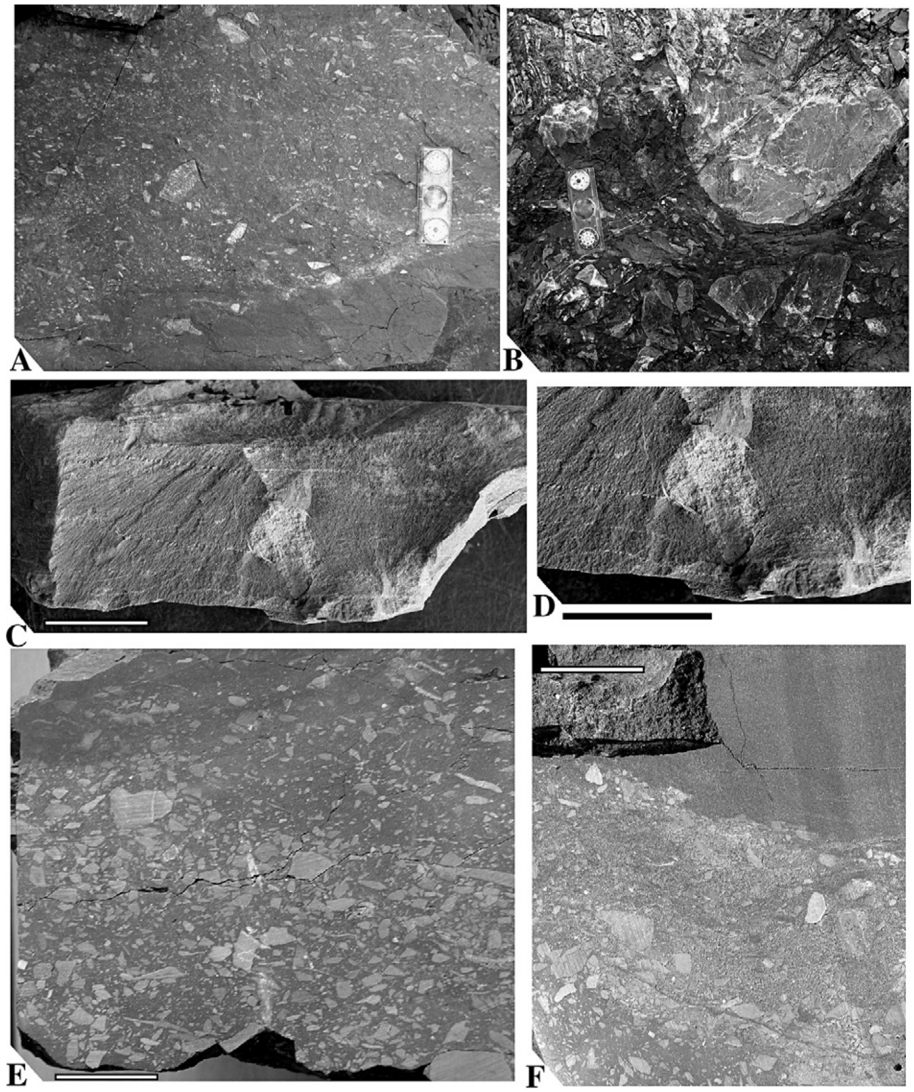

Fig. 7. Diamictites of the lowermost Las Ventanas Formation exposed in the vicinity of Minas (point 1, Fig. 1). (A) Red siltstone overlain by diamictite with angular clasts of underlying limestone, metapelite and granite, embedded in a ferruginous siltstone matrix. Scale is 8 cm long. (B) Monomict diamictite made up of stromatolitic limestone clasts and a ferruginous siltstone matrix filling palaeokarst. Scale: 8 cm long. (C) Dropstone in laminated, ferruginous siltstone. (D) Detail of previous photograph. Note deformation of underlying laminae and almost vertical orientation of long axis of clast. (E) Diamictite of angular metapelite and limestone clasts in a ferruginous siltstone matrix. (F) Diamictite with angular metapelite and limestone clasts grading into siltstone (top right). Scale bars in (C) to (F) represent 2 cm.

to open marine environments. The age of this rifting event is constrained by K–Ar ages of basalts of the La Rinconada Member of Las Ventanas Formation (615 ± 30 Ma: Sanchez Bettucci and Linares, 1996) and datings of a number of magmatic units probably associated with this extensional event, including the Nico Pérez Dyke Swarm (581 ± 13 Ma, K–Ar on biotite: Rivalenti et al., 1995), the Pan de Azúcar Pluton (579 ± 1.5 Ma, Ar/Ar: Oyhantçabal et al., 2006) and the Puntas del Santa Lucía Batholith (633 ± 10 Ma, U–Pb SHRIMP: Hartmann et al., 2002; Fig. 1). The opening of the basin between 633 and 581 Ma is well in accordance with the biostratigraphic data presented above.

Pazos et al. (2003) postulate the interaction of extensional faulting and glacial processes for the possibly correlative Playa Hermosa Formation of Uruguay (Masquelin and Sánchez Bettucci, 1993; Blanco and Gaucher, 2005). Conglomerates of Las Ventanas Formation (Quebrada de Viera Member) are mostly orthoconglomerates without signs of glacial influence (Blanco and Gaucher, 2005). Blanco and Gaucher (2005) discuss in detail the possible correlation between Las Ventanas and Playa Hermosa formations.

More recently, a diamictite level has been found in the CUCPSA limestone quarry (point 1, Fig. 1), which is overlain with erosional unconformity by typical orthoconglomerates of the Quebrada de Viera Member (Las Palmas Formation of Poiré et al., 2003). We assign here these diamictites (Fig. 7) to the Quebrada de Viera Member. Basalts and breccias of the La Rinconada Member are not present, and the Quebrada de Viera Member overlies carbonates of the Mina Verdún Group (Poiré et al., 2003) with erosional and also angular unconformity. A late Mesoproterozoic to early Neoproterozoic age for the Mina Verdún Group has been postulated by Gaucher et al. (2005c), on

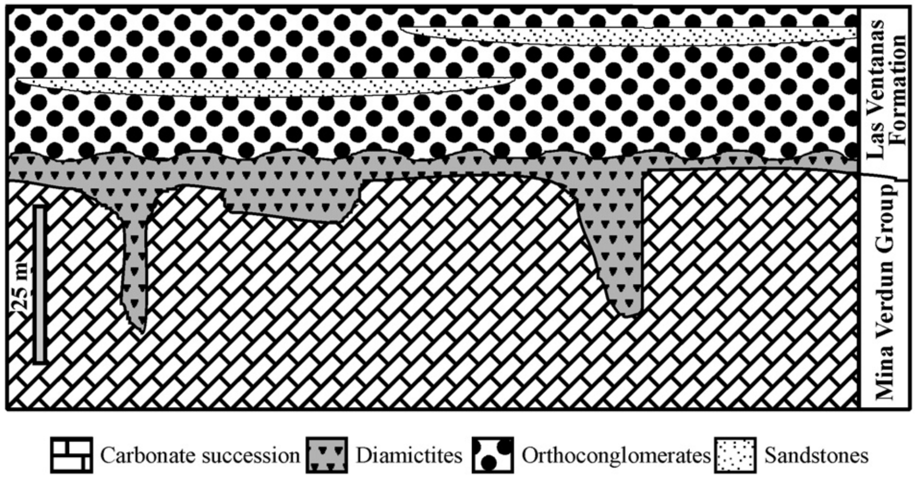

Fig. 8. Stratigraphic relationships between diamictites and orthoconglomerates of the Quebrada de Viera Member and the underlying Mina Verdún Group, as exposed in the CUCPSA limestone quarry near Minas (point 1, Fig. 1). Note palaeokarst surface filled with diamictites, which are in turn truncated by orthoconglomerates.

the basis of carbon isotope chemostratigraphy. A prominent palaeokarst is developed on top of carbonates of the Mina Verdún Group and filled with diamictites (Fig. 8). These are made up of angular to subrounded clasts up to 25 cm in diameter, made up of underlying carbonates, granitoids, rhyolite, metasiltstone, sandstone and quartzite. Clasts are embedded in a reddish, ferruginous mudstone matrix mainly composed of clay and silt. The matrix averages about 35 to 40% by volume, but transitions to clast-free mudstones are common (Fig. 7A, F). Diamictites are massive and chaotic (Fig. 7B) or slightly graded (Fig. 7E–F). Lonestones made up of limestone (Fig. 7B) and metasiltstone also occur, and in one case (Fig. 7C–D) the long axis of the clast is perpendicular to bedding plane, allowing its interpretation as a "bullet-clast" dropstone.

All petrographic features of the described diamictites, along with the occurrence of dropstones, suggest a glacial origin. However, no cap carbonate, like those often seen on top of other Neoproterozoic glacial units (Kennedy, 1996; Hoffman and Schrag, 2002), occurs on top of the diamictites. This may be due to truncation during the events responsible for the overlying, clast-supported conglomerates (Fig. 8), or, alternatively, the absence of a cap carbonate may represent a primary feature of the glacial event in Uruguay, as observed in the type region for the 583 Ma Gaskiers glaciation in Newfoundland (MacGabhann, 2005). Continuing research seeks to identify other glacial features, such as striated and faceted clasts, striated pavements and varves.

The postulated rifting event and – if confirmed – a concomitant glacial event may be temporally associated with the leiosphere-dominated assemblage reported here. The close relationship between rifting and glaciation is well known for the Neoproterozoic (Hambrey and Harland, 1981; Young, 1995). Although preservation potential of glacial deposits is higher in depressed areas like rifts, there might be also a causal relationship, as postulated by Gaucher et al. (2004b, 2005a). These authors suggest that rifting events may have affected plankton communities by pumping and promoting recycling of large amounts of nutrients (Fe, P, N, Si, Mn) in the hydrosphere. These nutrients could have caused phytoplankton blooms and eutrophication of the ocean that may have affected atmospheric CO_2 values, leading ultimately to glaciation (Gaucher et al., 2004b; McMenamin, 2004; Gaucher et al., 2007). The putative temporal association of rift deposits, probable glacial deposits and a low-diversity, relatively high-abundance microflora in the Las Ventanas Formation is consistent with this palaeoceanographic model.

7. Conclusions

Acritarchs and other organic-walled microfossils occurring in palynological macerations of siltstones of Las Ventanas Formation (Quebrada de Viera and El Perdido members) comprise an assemblage including the following species: *L. tenuissima*, *L. minutissima*, *Lophosphaeridium* sp., *S. bossii*, *S. major*, *Soldadophycus* sp. and *V. antiqua*. The acritarch assemblage is characterized by low diversity (six species), dominance of *L. tenuissima*, absence of acanthomorphic acritarchs, and relatively large sphaeromorphs, up to 400 μm in diameter.

Four of the six species, *L. tenuissima*, *L. minutissima*, *S. bossi* and *S. major*, are shared with acritarch assemblages in the overlying Arroyo del Soldado Group. The relative importance of the shared species, however, is markedly different in the two units. Whereas *L. tenuissima* dominates the Las Ventanas assemblage, *S. bossii* and *S. major* dominate the Arroyo del Soldado microflora, along with the acritarch *B. faveolata*, which does not occur in the Las Ventanas Formation. We envisage a transition from a *Leiosphaeridia*-dominated assemblage (Las Ventanas Formation) to a *Soldadophycus–Bavlinella*-dominated assemblage (Fig. 6) up section (Arroyo del Soldado Group). This scheme might contribute to refining the still coarse biostratigraphic zonation of the Ediacaran.

The assemblage preserved in Las Ventanas Formation is assigned to the Ediacaran Leiosphere Palynoflora of Grey et al. (2003) and Grey (2005) equivalent to the Varanger assemblage of Vidal and Moczydlowska-Vidal (1997), deposited between 635 and 582 Ma. Available radiochronological data for basalts of the lowermost Las Ventanas Formation (La Rinconada Member), yielding an age of 615±30 Ma (K–Ar, Sanchez

Bettucci and Linares, 1996), as well as for magmatic units associated with the genesis of the basin, such as the Puntas del Santa Lucia Batholith (633 ± 10 Ma, U–Pb SHRIMP: Hartmann et al., 2002), the Nico Pérez Dyke Swarm (581 ± 13 Ma K–Ar, Rivalenti et al., 1995) and the Pan de Azúcar pluton (579 ± 1.5 Ma Ar–Ar, Oyhantçabal et al., 2006), are consistent with this assignment.

A previously unknown diamictite level is reported within the Quebrada de Viera Member of the Las Ventanas Formation. These diamictites exhibit clasts of carbonate, granitoids, rhyolite, metasiltstone, sandstone and quartzite, embedded in a reddish, ferruginous mudstone matrix averaging about 35 to 40% in volume and mainly composed of clay and silt. Dropstones in laminated siltstones and petrographic characteristics of diamictites suggest a glacial origin. The apparent temporal and spatial relationship of this event with the rifting event that probably formed the Las Ventanas basin (Blanco and Gaucher, 2005) is similar to that reported for other Neoproterozoic successions worldwide. A similar interpretation was put forward for the correlative Playa Hermosa Formation in Uruguay (Pazos et al., 2003). We submit to the association of rifting and glacial events with low-diversity, relatively high-abundance palynofloras, as recorded in the Las Ventanas Formation, rather than merely a artefact of preservation, may, in fact, reflect a causal relationship involving rifting-induced nutrient enrichment, phytolankton blooms, eutrophication, and, ultimately, severe climatic deterioration (Gaucher et al., 2004a, 2007).

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