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Article

Basin evolution of the margin of Gondwana at the Neoproterozoic/Cambrian transition: the Puncoviscana Formation of Northwest Argentina

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With 4 figures

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Abstract: The Puncoviscana Formation is an important stratigraphic sequence of sandstones and shales, with intercalated conglomerates, limestones and volcanic rocks. It was deposited at the Neoproterozoic-Cambrian boundary in a shallow basin on the western margin of Gondwana. Trace fossils of the Puncoviscana Formation *s.l.* are represented by the *Oldhamia* and *Nereites* ichnoassociations and the geographical distribution of assemblages are aligned as parallel belts, with a shallower eastern *Nereites* association and a deeper western *Oldhamia* association. They represent different temporal levels on the evolution of the basin. Detrital zircon spectra display a wide range of ages, which indicate their provenance from Neoproterozoic to Cambrian source areas as well as Meso- to Paleoproterozoic basement units, exhibiting typical Gondwanan ages. Thick limestone banks are interbedded in the Puncoviscana Formation s.l. that included the siliciclastic sequences, with very low- to medium-metamorphic grade. δ13C values for the limestones vary from -1.57 to +3.40/00 VPDB, while in the Sierras Pampeanas, δ13C values vary from +2.6 to +80/00 VPDB. Also, reported 87Sr/86Sr values allow a clear differentiation of two rock sets. The limestones interbedded with the Puncoviscana Formation yielded values typical for the Neoproterozoic-Cambrian transition, between 0.70868 and 0.70896; while the limestones of the Sierras Pampeanas display values between 0.70748 and 0.70756, common in the middle to late Ediacaran. Deformation and uplift of the Puncoviscana Formation is clearly represented in northern Argentina by the Tilcarian unconformity, which is overlain by the Mesón Group.

Key words: Puncoviscana Formation, *Nereites* and *Oldhamia* associations**,** δ13C values, Neoproterozoic-Cambrian transition.

1. Introduction

The Puncoviscana Formation of NW Argentina represents the basement unit in the South American Early Paleozoic Central Andean Basin. It crops out mostly in the Cordillera Oriental, Puna and Sierras Pampeanas of northwest Argentina, continuing into Bolivian territory, where it is known as San Cristobal Formation (Turner 1960; Turner & Mon, 1979; Suárez Soruco 1992; Aceñolaza et al. 1999; Ramos 1999; Aceñolaza & Toselli 2009).

These Ediacaran-Lower Cambrian rocks are represented by a thick and heterogeneous succession

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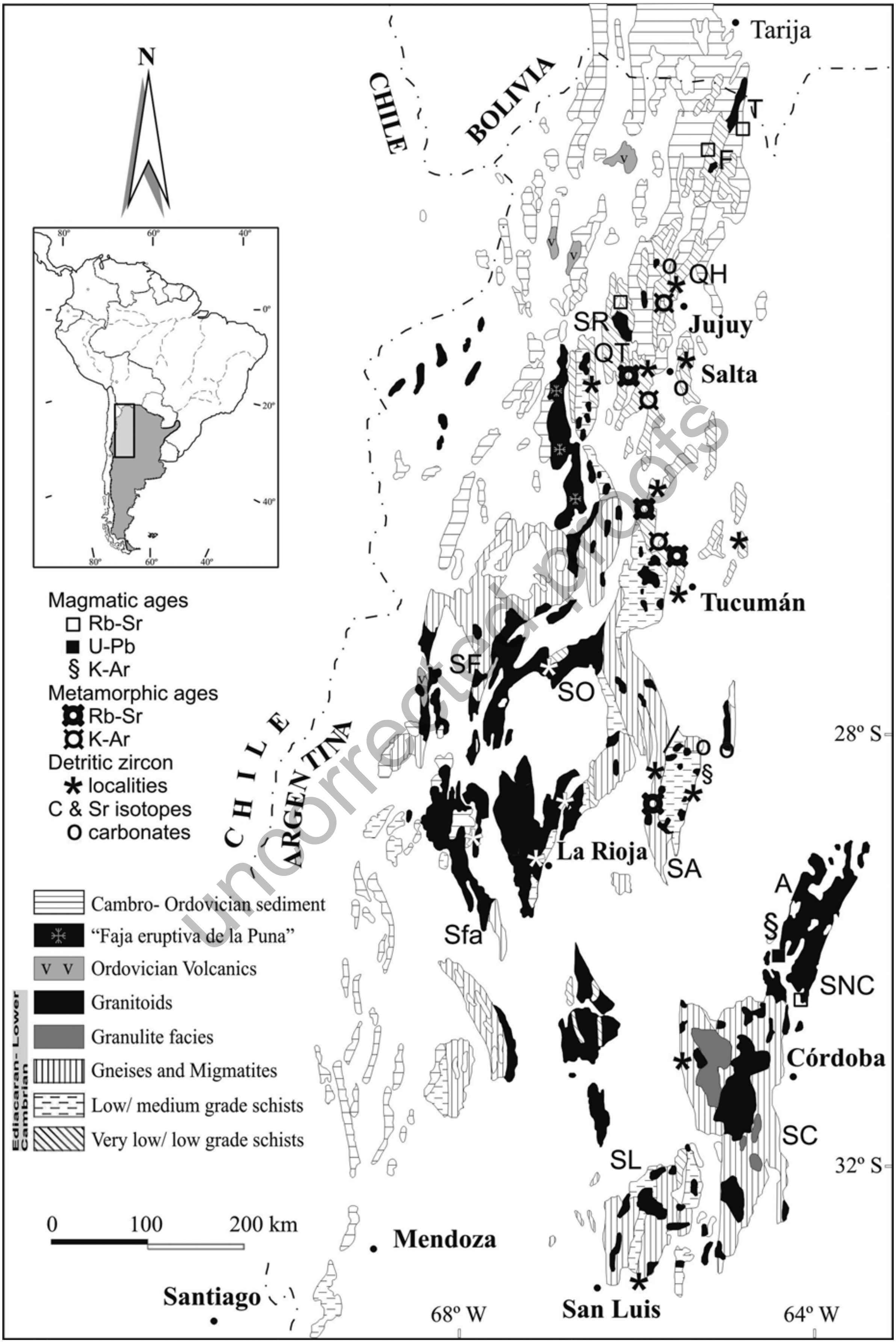

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32º S
Mendoza
Santiago
San Luis
68º W
64º W
CHILE
ARGENTINA
Magmatic ages
Rb-Sr
U-Pb
§ K-Ar
Metamorphic ages
Rb-Sr
K-Ar
Detritic zircon
localities
C & Sr isotopes
carbonates
Cambro- Ordovician sediment
"Faja eruptiva de la Puna"
Ordovician Volcanics
Granitoids
Granulite facies
Gneises and Migmatites
Low/ medium grade schists
Very low/ low grade schists
Ediacaran- Lower Cambrian
0 100 200 km

Fig. 1.

of deformed and slightly metamorphosed sedimentary rocks, with shales, greywackes, sandstones, carbonates, volcanic rocks and conglomerates. Scarce fossiliferous levels occur associated to shale intercalations. The whole sequence is intruded by granitic plutons in several sectors (Aceñolaza & Toselli 2009).

To understand the structural outline of the basin where the Puncoviscana Formation was deposited, the pre-Ediacaran evolution of the Gondwana border needs to be considered. Several hypotheses have been proposed on this matter. We consider this basin as developed from a NNE-SSW- trending aulacogen (Aceñolaza & Durand 1986) that evolved from the "Bolivian Triple Joint", which occurs in the eastern plain regions of the country (Suárez Soruco 1989, 2000).

The Puncoviscana Basin (Pampean Orogen) extends from Bolivia to Central Argentina, limited to the west by the Arequipa-Antofalla terrane and to the east by the Guaporé and Río de la Plata cratons. In the northern part of the basin very low- to low-grade metasedimentary rocks dominate, while the southern area is dominated by gneisses, migmatites and medium-grade metamorphic rocks (Aceñolaza et al. 2002) (Fig. 1). The contacts between isolated very-low to low-grade metasedimentary rocks with the adjacent gneisses and migmatites are mostly not exposed (Caminos 1979). Some authors (Willner 1990; Willner & Miller 1986) argue that the more intensely deformed and metamorphosed rocks represent deeper crustal equivalents of the supra-crustal succession, whereas Mon & Hongn (1991) interpret the variety of metamorphic rocks related to different tectono-metamorphic events. However, both successions are affected by the Tilcaric orogeny and the Middle Cambrian to Early Ordovician plutonic activity (Rapela et al. 1998). The sedimentary aspects of low-grade metasedimentary rocks of the Puncoviscana Formation were described by Omarini (1983), Ježek (1990) and Durand (1990).

The depositional age of the thick clastic sequence is essentially based on trace fossil data (e.g. Durand & Aceñolaza 1990; Aceñolaza & Aceñolaza 2005) that point to an Ediacaran-Early Cambrian age.

Southwards, the San Luis Formation (Prozzi & Ramos 1988; Prozzi 1990) is exposed in two belts of the homonymous range. It consists of alternating phyllites and meta-quartzites with minor meta-conglomerates and meta-rhyolitic rocks (Sato et al. 2002, and references therein). The succession is characterized as a turbiditic sequence and compared with the Ediacaran-Lower Cambrian Puncoviscana Formation. This regional correlation is supported by the U-Pb crystallization age of 529 +/- 12 Ma obtained from meta-magmatic layers (Söllner et al. 2000).

Available Nd-isotope data for the low-grade metasedimentary rocks (Bock et al. 2000) and medium- to high-grade metamorphic rocks (schists, gneisses and calc-silicates; see Pankhurst et al. 1998, Rapela et al. 1998, and Lucassen et al. 2000), represent only restricted areas. Reported model ages vary between 1.5 and 1.8 Ga for the low-grade metasediments, and 1.5-2.1 Ga for the higher-grade metamorphic rocks.

Geochronological data of the eastern Sierras Pampeanas, in the Santiago del Estero and northern Córdoba provinces, show that this area is mainly composed by a series of granitoids of Late Proterozoic-Early Cambrian with ages between 500-567 Ma (Koukharsky et al. 2003; Castellote 1989). These intruded into a metamorphic basement constituted by schists, gneisses, amphibolites and migmatites with K/Ar ages between 407 +/- 10 and 665 +/- 20 Ma (Castellote 1989). These metamorphic rocks and granitoids are intruded by volcanic rocks known as Los Burros Dacite (513 Ma, Leal et al. 2003), dykes of the Oncán Rhyolite (Rb-Sr isochron of 494 Ma, Rapela et al. 1991), and basaltic and andesitic to dacitic rocks that comprise the Balbuena Formation with an K-Ar age of 514 +/- 15 Ma (Koukharsky et al. 2003).

Fig. 1. Simplified geological map of Northwestern Argentina, showing the distribution of Ediacaran – Paleozoic sedimentary, metamorphic and magmatic rocks of the Puncoviscana Formation and equivalents, including Ordovician outcrops. Locations are: SA: Sierra de Ancasti; SF: Sierra de Fiambalá; SFa: Sierra de Famatina; SC: Sierras de Córdoba; SNC: Sierra Norte de Córdoba; SL: Sierras de San Luis, and SO: Sierra de la Ovejería. QH: Quebrada de Humahuaca, and QT: Quebrada del Toro. Granites are: A: Ambargasta; C: Cañaní; T: Tipayoc, and SR: Santa Rosa). Localities with magmatic and metamorphic ages, C and Sr isotopes and detrital zircons are shown and discussed in the text.

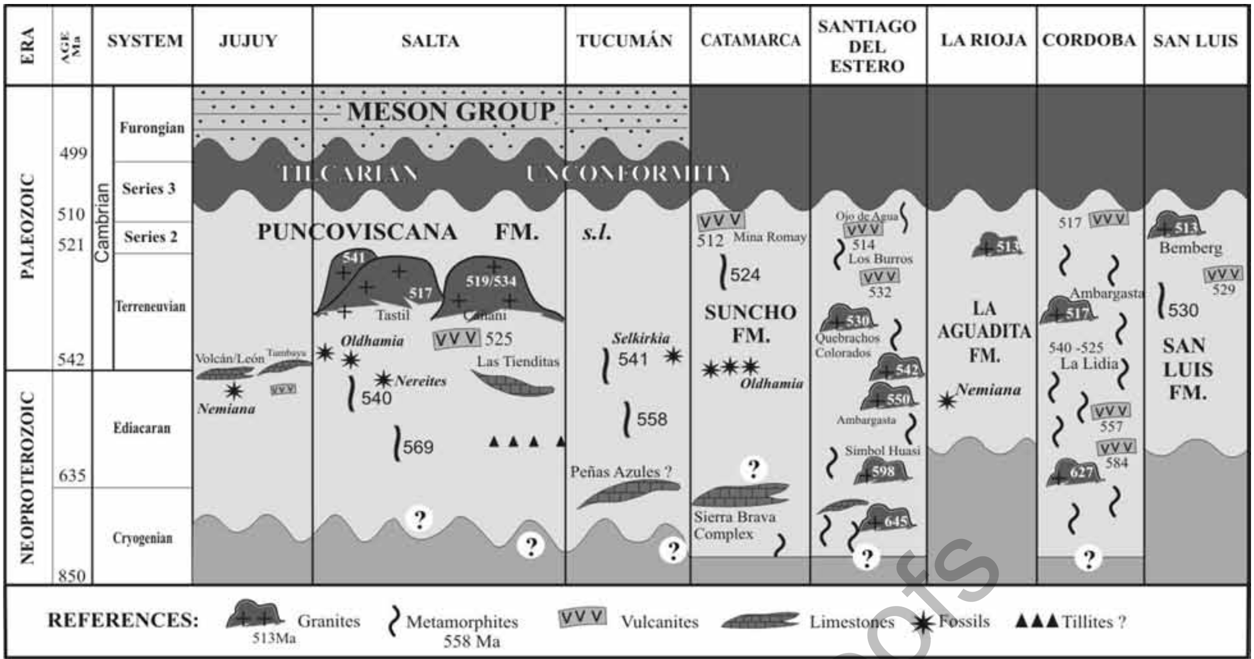

Fig. 2. Correlation chart of the Puncoviscana Formation and equivalents including granites, volcanic rocks, limestones, metamorphic ages and trace fossils (modified after ACEÑOLAZA & TOSELLI 2009).

2. Geological setting

Ediacaran-Lower Cambrian rocks that constitute the Puncoviscana Formation (TURNER 1960) are represented in northwest Argentina by a thick and heterogeneous succession of deformed and slightly metamorphosed sedimentary rocks. These are shales, greywackes, sandstones, carbonates, volcanic rocks and conglomerates, with sparse fossiliferous levels. Continuous stratigraphic sections are rare, which makes formal subdivision impossible. However, maximum ages of detrital zircons from the turbiditic facies of the Puncoviscana Formation and equivalent units suggest a certain decrease of ages of this facies from east to west. In addition, whereas limestones are bound to the lower parts of the Puncoviscana Formation s.l., volcanic rocks mostly occur in younger sections (Fig. 2) Large tracts of higher-grade metamorphic equivalents occur to the south, in Catamarca and Tucumán provinces (ACEÑOLAZA & MILLER 1982).

Sedimentological features indicate a range of environments, ranging from above wave-base, shallow-water mainly in the east, to mid-fan turbidites mainly in the west. Greywacke (dominant)–siltstone-mudstone graded-bed successions (Fig. 3) are widespread; limestones and intercalated volcanic rocks are rare.

The sediments of the Puncoviscana Formation and their higher metamorphic equivalents have been identified as greywackes and lithic arenites by JEŽEK et al. (1985), JEŽEK & MILLER (1986). Geochemically the source area corresponds to an uplifted orogen within a stable continental margin (JEŽEK et al. 1985; DO CAMPO & RIBEIRO GUEVARA 2005).

Within the clastic sediments JEŽEK et al. (1985) distinguished 5 facies types: proximal, intermediate, distal, pelagic and channel facies. The proximal facies is characterized by massive graywackes, lithic greywackes and subgreywackes of a psammite/pelite ratio > 5. Load casts, and flute marks are typical surface structures. The intermediate facies consists of greywackes, siltstones and pelites, of a psammite/pelite ratio of 1 to 5. Flute and ripple marks are frequent. There are typical turbidites with Bouma sequences starting with a scoured bed overlied by a massive A bed, represented by the coarsest material settled out of suspension as the turbidite current slowed. Above, the plane laminated sandstones (unit B) represents

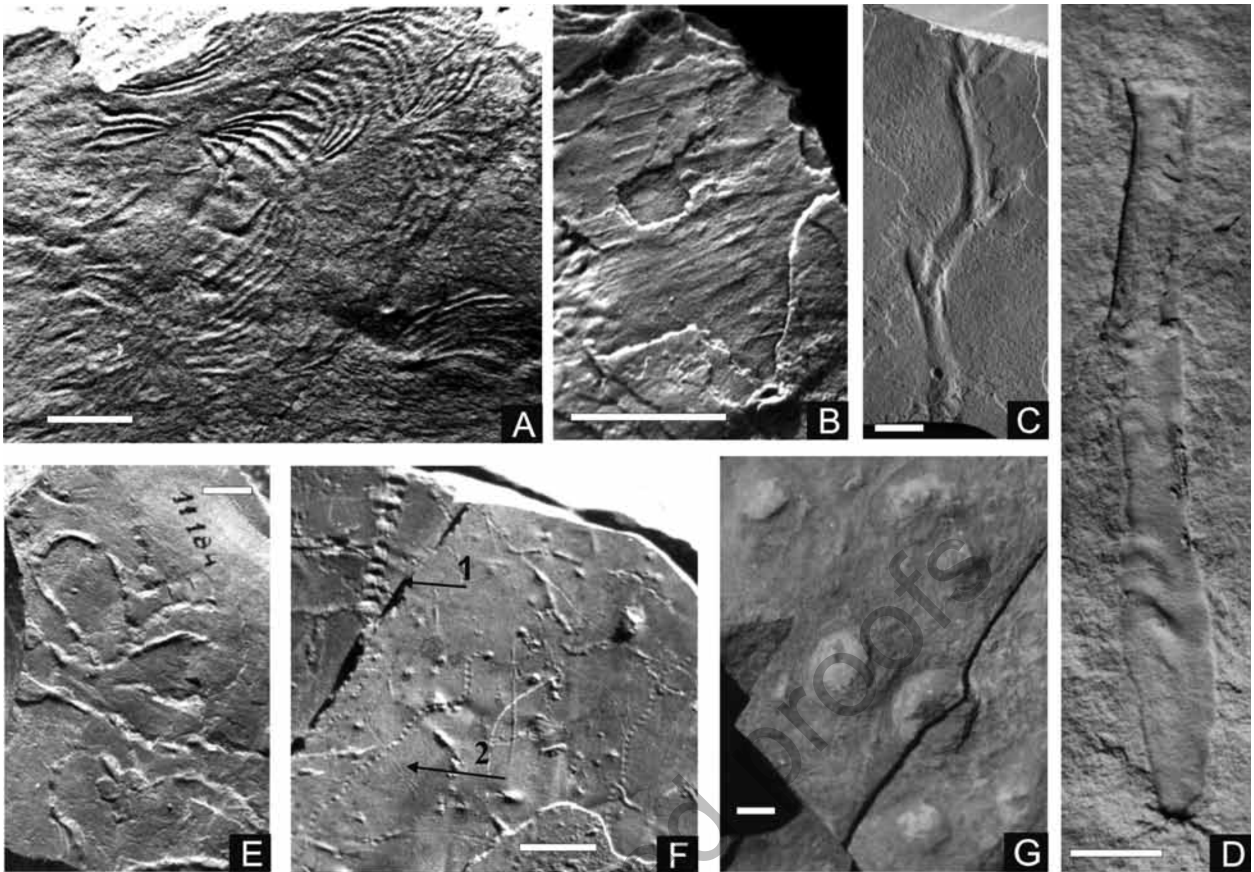

Fig. 3. Facies and structures of the Puncoviscana Formation in NW Argentina; **A** – Heterolithic section with ripple-bedded top at Cachiñal locality, Salta; **B** – Limestone facies at Ancaján, Catamarca; **C** – Tight folds at El Alisal, Salta; **D** – General view of the Tilcara unconformity showing the Mesón Group overlying the Puncoviscana Formation at the homonymous locality in Jujuy; **E** – Conlomerates at Papachacra with slates, limestone and volcanic clasts, Catamarca; **F** – Limestones interbedded with shales at Papachacra Range, Catamarca; **G** – Folded slates cropping out at Quebrada Don Braulio, Salta; **H** – Sandstone and slate beds in the western facies of Puncoviscana close to El Mojón locality, Salta; **I** – Ripple-bearing sandstones cropping out at Purmamarca, Jujuy.

highflow-regime plane beds. These are followed by ripples and wavy lamination (unit C), indicative of lower flow regime. Rarely the unit D is identified in the unit by laminated silt. The distal facies type is characterized by bed thicknesses < 10 cm which are plane-parallel bedded, grain size is clay to silt, siltstones and interbedded pelites. The psammite/pelite ratio is <1. The pelitic facies is characterized by red, structureless pelites possibly representing background sedimentation. The channel facies, composed of conglomerates, deserves a particular description (see below).

Paleocurrent directions were obtained from diverse structures: mostly from ripple marks, but also from flute marks, pebble imbrication in conglomerates and from the vergence of slump folds (Ježek et al. 1985). Most data show flow directions from 45° to 150° that is from the East (Ježek et al. 1985). Fining-upward successions indicate transgressive trends during a uniform continuous subsidence period causing basinward migration of the fan system. Thus, deposition was continuously bound to the upper parts of a slope with relatively regular shallow water conditions.

The geochemical and petrological features of the sediments suggest a recycled-orogen provenance (Ježek et al. 1985; Ježek & Miller 1976; Ježek 1990; Pankhurst & Rapela 1998; Do Campo & Guevara

2005; Zimmermann 2005). Omarini (1983) and Omarini et al. (1999b) considered the Puncoviscana Formation to be mostly Late Proterozoic in age, with only a minor Early Cambrian part but, on faunal evidence, Durand & Aceñolaza (1990) and Aceñolaza & Aceñolaza (2005) assigned it mostly to the Early Cambrian, and only minor parts to the Neoproterozoic. This latter assignment is supported by Early Cambrian U-Pb ages of euhedral (volcanic) detrital zircons in greywackes near Cachi (Lork et al. 1990). This initial geochronological work was considerably extended with new U-Pb (single crystal) detrital zircon and Rb-Sr metamorphic age studies (Adams et al. 2005, 2008, 2009, 2010) of the Puncoviscana Formation, and similar work on possibly correlative rocks in central and western Argentina (Schwartz & Gromet 2004; Finney et al. 2005; Escayola et al. 2007; Rapela et al. 2007; Gómez Peral et al. 2007).

In northwest Argentina, the Puncoviscana Formation was strongly folded and weakly metamorphosed, and then intruded by granitoids during the Tilcarian Orogeny in mid-Cambrian times. This orogenic event is also known from metamorphic rocks of provinces to the south, Catamarca and La Rioja, and in central Argentina from the Sierras de Córdoba and San Luis. These metamorphic rocks have been compared with the Puncoviscana Formation by Aceñolaza & Miller (1982); Prozzi (1990); von Gosen & Prozzi (1998); Söllner et al. (2000) and Pankhurst & Rapela (1998), and more recently confirmed by Steenken et al. (2008), in contrast to Steenken et al. (2004).

Conglomerate deposits are interbedded with psammites and shales of the Puncoviscana Formation and metamorphosed equivalents; this facies constitutes about 1% (Ježek 1990). They are subdivided in: pebbly sandstones (Seclantás), pebbly mudstones (Escalchi, Tin-Tin, Corralito and Las Tienditas), unorganized conglomerates (Seclantás) and massive conglomerates (Las Tienditas and Corralito). These outcrops are located in Cordillera Oriental and Northwestern Sierras Pampeanas.

In the Cordillera Oriental the conglomerates of Corralito, Las Tienditas, Tin-Tin and Seclantás are significant, which were studied among others by: Durand (1988, 1990); Spalletti & Durand (1987); Omarini & Baldis (1984) and Ježek (1986, 1990). They are generally classified as polymictic conglomerates, consisting of rounded granules to blocks, embedded in a psammitic matrix (5%). Clasts in the Seclantás conglomerate consist of greywackes, quartzites, purple mudstones and rhyolites.

In the Northwestern Sierras Pampeanas Durand (1990) described at Sierra de la Ovejería a polymictic conglomerate, with well rounded clasts of quartzites, greywackes, sandstones, quartzites, limestones, rhyolites and ignimbrites. According to Durand (1990) the conglomerates are intercalated in the turbidite sequences of the Suncho Formation (equivalent to the Puncoviscana Formation), which can be interpreted as submarine fans, in which gravitational flows of sliding, slumping and debris flows (Ježek 1990). The provenance of clastic material is probably from consolidated sedimentary regions and low-grade metamorphic rocks, and also from outcrops of acid volcanics and limestones (Spalletti & Durand 1987; Durand 1988).

The San Luis Formation (Prozzi & Ramos 1988) is exposed in two belts of the central and western parts of the Sierra de San Luis. It consists of alternating phyllites and meta-quartzites with minor meta-conglomerates and acid meta-magmatic rocks. The succession was characterized as a turbiditic sequence, and compared with the Puncoviscana Formation by Prozzi (1990) and v. Gosen & Prozzi (1998). The metamorphic grade is lower- to middle-greenschist facies.

3. Chemostratigraphy of carbonates

Thick limestone banks are interbedded in the Puncoviscana Formation s.l. in the Salta, Jujuy, Tucumán, Catamarca, Santiago del Estero and Córdoba provinces. They are interbedded in the siliciclastic sequences, ranging from very low- to medium- metamorphic grade (Fig. 1).

In the Salta province, limestones crop out in the Castillejo Range and are known as Las Tienditas Formation. This formation, 160 to 240m thick, is composed of fine-grained, dark limestones, alternating with marls and brecciated limestones (Ortiz 1962; Salfity et al. 1975; Baldis & Omarini 1984).

In Jujuy, limestones are known at the localities of Quebrada de Humahuaca at León and Volcán. These are represented by highly deformed, dark, fine-grained micritic limestones that, in some sectors, are found interbedded with shales and sandstones (Loss & Giordana 1952). Scanavino & Guichón (1971) measured for the sequence a maximum thickness of 800 meters, decreasing laterally.

δ13C values for the Las Tienditas Formation vary from -1.57 to +3.4 ‰ VPDB, with the highest positive values close to the base of the sequence and decreasing upsection, displaying a negative excursion at 15 meters below the top of the sequence. This excursion has been formerly interpreted as the possible Precambrian-Cambrian boundary (Sial et al. 2001). The Volcán-León limestones display δ13C values from +6.11 to +4.58‰ VPDB (Toselli et al. 2008).

The Sierra de Ancasti (Sierras Pampeanas of Catamarca) is represented by the Ancasti and Sierra Brava formations and the El Portezuelo Complex (Aceñolaza & Toselli 1977). Among them, the Sierra Brava Formation displays the carbonatic La Calera Member, integrated by a heterolithic sequence of fine- to medium-grained limestones, interbedded with quartzites and schists. Granoblastic texture is common, with the presence of quartz and opaque minerals (magnetite and graphite). Muscovite and dispersed calcite can be observed as well (Toselli et al. 2008).

In the La Calera Member, δ13C values start up with +2.6‰ VPDB reaching a plateau around +8‰ upsection. It is interesting to highlight that the homogeneity of δ13C close to +8‰ is recognized worldwide to the lapse of 600 to 730 Ma (Jacobsen & Kaufman, 1999; Melezhik et al. 2001). Recent papers display additional data on δ13C values occurring ca. 850 and 750, and again around 670-650 Ma (e.g. Halverson et al. 2010). 87Sr/86Sr values allow to clearly differentiate two sets of rocks:

(a) Limestones interbedded to the Puncoviscana Formation (Las Tienditas and Volcán formations) yielded values typical for the Neoproterozoic-Cambrian transition, between 0.70868 and 0.70896 (Toselli et al. 2010).

(b) Limestones of the Sierras Pampeanas of Catamarca (La Calera and Ancaján) display values of 0.70748 and 0.70756 (Toselli et al. 2010), common in the middle to late Ediacaran (e.g. Gaucher et al. 2009a). The latter Sr-isotope values fit δ13C data between -1.0 and +1.0‰VPDB, typical for the early Cambrian period, while δ13C values around +5‰VPDB are common in the Ediacaran period. These current data suggest older ages for the analyzed limestones of the Sierras Pampeanas (Catamarca) and, younger ages for the carbonates in the Cordillera Oriental (Salta and Jujuy).

4. Paleontologic associations

As mentioned earlier, the Puncoviscana Formation (s.l.) records a variety of trace fossils, few body fossils and some problematical bio-sedimentary structures, being all of them restricted to the slates and sandstone facies of the unit (Fig. 4). No fossils have been found yet in the associated limestone nor in the conglomerates (Aceñolaza & Aceñolaza 2007).

The existence of exclusively Ediacaran fossils is not clear due to the lack of a precise link between the chronological data and the fossiliferous strata.

An updated review of the trace fossils in the Puncoviscana Formation provides the following list: *Archaeonassa fossulata*, *Asaphoidichnus* isp., *Cochlichnus anguineus*, *Didymaulichnus lyelli*, *Dimorphichnus obliquus*, *Diplichnites* isp., *Glockerichnus* isp., *Helminthoraphe* isp., *Helminthopsis abeli*, *Helminthopsis tenuis*, *Helminthoidichnites tenuis*, *Monomorphichnus lineatus*, *Monomorphichnus* isp., cf. *Multipodichnus*, *Nereites saltensis*, *Neonereites uniserialis*, *N. biserialis*, *Oldhamia alata*, *O. antiqua*, *O. curvata*, *O. flabellata*, *O. geniculata*, *O. radiata*, cf. *Thalassinoides* isp., *Palaeophycus tubularis*, *Palaeophycus* isp., *Protichnites* isp., *Protovirgularia* isp., *Tasmanadia cachii*, *Treptichnus* isp., *Treptichnus* cf. *aequalternus*, and *T. pollardi* (Aceñolaza et al. 2009).

The trace fossils of the Puncoviscana Formation s.l. are represented by the *Oldhamia* and *Nereites* ichnoassociations, named after the homonymus trace fossils (Aceñolaza & Durand 1986; Aceñolaza & Aceñolaza 2005). The spatial distribution of assemblages display a remarkable alignment as parallel belts, with a shallower eastwards *Nereites* association, and a deeper westwards *Oldhamia* associacion, that do not represent archetypal ichnofacies. These are related to the morphology of the basin, the chronological record of the ichnofaunas, and may also represent different temporal levels on the evolution of the Puncoviscana sea.

Within the *Oldhamia* association most trace fossils are small-sized, parallel to bedding planes, and bioturbation is essentially restricted to the first millimeters of strata. Deeper burrowers are recognized in the base of sandstone layers of the sequences. This spatial restriction of bioturbation with the frequent presence of wrinkle marks denotes a mostly – but not only – microbial mat related lifestyles of the fauna as it happens in other Neoproterozoic/Early Cambrian basins (McCall 2006). Within the *Nereites* association, a more diverse trace fossil set is recognized, with large and mid size grazing and crawling traces developed in sand-mud interfaces. Arthropod traces are common in this association.

Although most trace fossils were found in the Salta Province (NW Argentina), other material from Jujuy, Catamarca, Tucumán and La Rioja is important to complete the picture of the Puncoviscana Basin, and

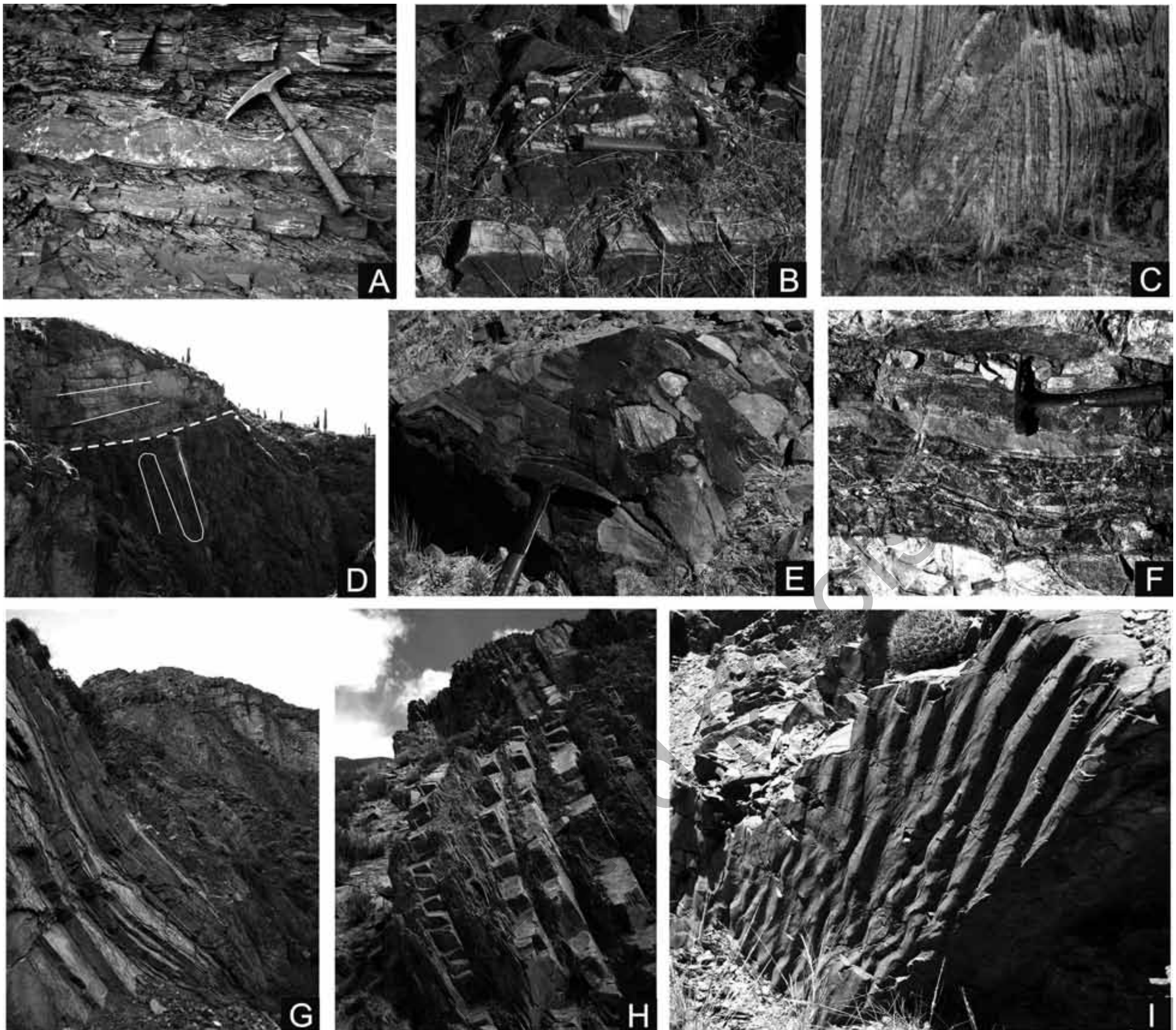

Fig. 4. Selected fossils of the Puncoviscana Formation and equivalent units of NW Argentina. **A** – *Oldhamia curvata*; **B** – *Monomorphichnus lineatus*; **C** – *Treptichnus* cf. *aequalaternus*); **D** – *Selkirkia* sp.; **E** – *Nereites saltensis* (non *Psammichnites saltensis*); **F** – 1: *Neonereites biserialis*; 2: *N. uniserialis*; **G** – *Nemiana* sp.; Scale = 1 cm

their significance for the Ediacaran-Early Cambrian strata in the SW margin of Gondwana.

The co-existence of different tiering structures and the non-exclusively biomat-related feeding strategies require a more complex ecological structure for the Puncoviscana Formation than previously suggested (Aceñolaza & Aceñolaza 2001; Buatois & Mángano 2003; Aceñolaza 2005).

A few body fossils have been described from the Puncoviscana Formation, such as *Selkirkia* sp. and *Ivesheadia* sp. that are mentioned for the sandstone levels cropping out at Choromoro locality, in the Tucumán province. Additional material has been recently discovered and assigned to *Sewkia, Aspidella* and *Nemiana* from the Cordillera Oriental of Salta and Jujuy (Aceñolaza & Aceñolaza 2008), all data supporting the existence of Ediacaran levels in the basin. Westwards of Salta, possible Ediacaran strata have been recognised with the presence of algal impressions (fucoid type material).

The sedimentary characteristics of the unit and the presence of this particular suite of trace fossils, body fossils, algal and microbial-mediated structures empathises a sedimentation on a wave and tide affected sea platform within the euphotic zone.

5. Detrital zircons, origin and maximum depositional ages

The heavy mineral analyses including zircon grains have been used as a method for correlation of depositional settings of sediments and their provenance areas. Furthermore, detrital zircon ages provide a maximum age estimate for deposition of sedimentary and metasedimentary rocks.

The detrital zircon ages show that Puncoviscana Formation age patterns contain three broad groups: Paleoproterozoic-Mesoproterozoic (2400-1400 Ma), late Mesoproterozoic-early Neoproterozoic (1150-850 Ma) and late Neoproterozoic-Early Cambrian (650-515 Ma) (Adams et al. 2008, 2010). The 2400-1400 Ma ages are scarce and statistically not significant. The 1150-850 Ma age components are dominant in greywackes with oldest late Neoproterozoic components >600 Ma. The former diminish considerably when late-Neoproterozoic components become dominant and younger, reaching 515 Ma. A northernmost greywacke sample from Purmamarca (Jujuy) is distinctive: whilst its zircon age pattern partly resembles other Puncoviscana Formation samples, it contains no Cambrian-late Neoproterozoic ages, the youngest ages being early-Neoproterozoic.

The youngest age components, c. 515 Ma, in a greywacke from Rancagua (Cachi, Salta province), dominate an almost unimodal pattern suggestive of contemporary volcanic sources at a late Early Cambrian depocentre, similar to those obtained by Lork et al. (1990) of 527 Ma.

An almost constant feature of the U-Pb detrital zircon age patterns is the persistence of zircons derived from a Late Mesoproterozoic source; in general, in the range 1000-1090 Ma (Adams et al. 2005, 2008, 2010; Drobe et al. 2009). These zircon sources must originate in extensive and voluminous complexes of plutonic and metamorphic rocks, rather than more limited and superficial volcanic successions. Clearly a Precambrian craton offers the best environment, and provides the possibility of an additional and variable supply of older Paleoproterozoic and Archean zircons (Adams et al. 2008; Drobe et al. 2009). A Mesoproterozoic orogen would probably undergo prolonged and substantial erosion in the Neoproterozoic-Early Cambrian interval, and thus one could also expect the amount of Mesoproterozoic zircons to decrease during the period of deposition of the Puncoviscana Formation, which lasted perhaps more than 50 million years. The late Neoproterozoic group of zircons is probably related to the rising Brasiliano Orogen of south-eastern and central south Brazil (Adams et al. 2008, 2010) and possibly also to a magmatic belt of the Eastern Sierras Pampeanas (Llambías et al. 2003).

6. Igneous rocks, petrology and geochemistry

Volcanic and plutonic rocks are present in the Puncoviscana Formation. They can possibly be divided in two phases: A) pre-Tilcarian (pre-mid Cambrian) events and, B) Tilcarian (Middle Cambrian) events.

A) The existence of volcanogenic levels interbedded in the Puncoviscana Formation was recognized at several localities of the Cordillera Oriental, Puna and Eastern Sierras Pampeanas; they correspond to the pre-Tilcarian event. In most cases, the volcanic rocks are interbedded bodies usually less than 3 m in thickness. They are grey or greenish grey with porphyritic texture. The outcrops in the Eastern Cordillera and Puna are mostly tholeiitic and alkaline basalts (Coira et al. 1990). The petrographic and geochemical characteristics of the volcanic rocks have been published by Chayle & Coira (1987); Coira et al. (1990) and Omarini et al. (1999a).

The magmatism might be interpreted as a consequence of several tectonic events and is recorded in three different groups of volcanic rocks. They vary from intraplate alkaline basalts and transitional tholeiitic basalts (between continental and oceanic to island arc basalts emplaced next to the continent). This indicates a tectonic evolution from an intraplate setting (alkaline basalts) becoming extensional (continental and oceanic tholeiitic basalts) and finally turning into a compressional subduction phase typical of oceanic islands arc (oceanic basalts).

Geochronological data in the Santiago del Estero and north of Córdoba provinces, show that the regional geology of this area is mainly composed of a series of Late Proterozoic-Early Cambrian granitoids with ages between 500-567 Ma (Koukharsky et al. 1999; Castellote 1982) which intruded in a metamorphic basement made up of schists, gneisses, amphibolites and migmatites. Dacitic to rhyolitic domes and dikes were intruded during the last stages of the batholiths, and rhyolitic ignimbrites sheets, with a conventional U-Pb zircon age of 584+22/-14 Ma, are intercalated with the metaconglomerates of the La Lidia Formation (Llambias et al. 2003).

B) The Tilcarian plutonic event of the Pampean Cycle is classically restricted to the Jujuy and Salta provinces, although rocks belonging to this cycle have also been recognized further south in the Ancasti (Catamarca province), Ambargasta and Córdoba ranges. The granites described from the northern sector of Argentina are represented by the Cañaní, Tipayoc, Santa Rosa de Tastil and Mojotoro plutons, all of which are post-tectonic, and related to the diastrophic Tilcarian orogenic phase, with ages between 536 and 514 Ma (Omarini et al. 1987a, b, 1999b; Bachmann et al. 1987; Matteini et al. 2008; Hongn et al. 2010; Hauser 2011). The petrographic characteristics show that the plutons are mainly tonalites, hornblende granodiorites, trondhjemites and biotite granites, and together with the geochemical data that defines them as calc-alkaline and meta- to peraluminous. The initial 87Sr/86Sr ratio of 0.7050 allowed Omarini et al. (1996, 1999) to propose an origin by partial fusion of the continental crust beneath a continental arc or related to continental collision. Hauser (2011) also suggested a subduction-related origin.

Basic and ultrabasic rocks associated to the Puncovicana Formation have been described from different localities in the northwestern Sierras Pampeanas. In the Sierra de Ancasti, Bassi (1952) and Schalamuk et al. (1983) described the Albigasta and Icaño basic-ultrabasic rocks with K-Ar ages between 512 and 468 Ma, which intrude in the Ancasti Formation. Their mineralogy consists of hornblende, plagioclase, biotite, titanite, epidote and sulphides. In the Sierra de Fiambalá, Grisson et al. (1998) recognized a two phase metamorphic event, one related to greenschist-amphibolite facies with ages between 550 and 540 Ma, and other associated to a 510-515 Ma old gabbronorite.

At the Santiago del Estero and north of Córdoba provinces, late Proterozoic-early Cambrian granitoids are intruded by sub-volcanic rocks known as Los Burros Dacite (513 Ma, Leal et al. 2003), the rhyolitic dykes known as the Oncán Rhyolite (Rb-Sr isochron of 494 Ma, Rapela et al. 1991), and basaltic, andesitic to dacitic rocks that give rise to the Balbuena Formation with a K-Ar age of 514 +/- 15 Ma (Koukharsky et al. 2003). Small outcrops of metasedimentary rocks in the Sierra Norte de Córdoba are intruded by granodioritic and monzogranitc plutons of Cambrian age.

According to Leal et al. (2003), the magmatic arc might have developed during the Late Precambrian to Early Cambrian as the result of eastward subduction. This collision may have controlled extensive deformation and metamorphism at 530 Ma (Kraemer et al. 1995; Sims et al. 1998; Miró 1998; Miró et al. 2004).

The meta-sedimentary sequence of the San Luis Formation (Prozzi & Ramos 1988) is correlated with the Puncoviscana Formation (Prozzi 1990; v. Gosen & Prozzi 1998). This correlation is supported by lithological similarity and the U-Pb crystallization age of 529 +/- 12 Ma obtained from two meta-magmatic layers (Söllner et al. 2000).

The Neoproterozoic silicic ignimbrites, together with the Cambrian calc-alkaline batholiths and related volcanic rocks indicate the existence of a magmatic arc associated with the active margin of the Gondwana continent. This arc was active since Neoproterozoic times, with a duration of more than 60 Ma. A correlation of the late Neoproterozoic metasedimentary and volcanic rocks of the Sierra Norte de Córdoba with the Puncoviscana Formation of Northwestern Argentina was suggested by Llambias et al. (2003).

7. Metamorphic ages

Rb-Sr whole rock isochron ages were obtained by Adams et al. (2008b) from slates in the Puncoviscana Formation at Rio Choromoro (541 +/- 23 Ma), Quebrada del Toro (540 +/- 33 Ma), and Quebrada Don Bartolo (504 +/- 15 Ma). The ages from the Quebrada del Toro and Rio Choromoro samples place the metamorphism in the Early Cambrian or latest Neoproterozoic, and are consistent with the maximum possible depositional age that is constrained by the youngest detrital zircon peaks at 636 +/- 7 Ma and 551 +/- 5 Ma, respectively, from greywackes at the same localities. The anomalously young Rb-Sr age of 504 +/- 5 Ma from Quebrada Don Bartolo is likely due to the sample being located within the thermal aureole of younger granites exposed nearby at La Punilla.

8. Tilcarian Orogeny

The deformation process as well as the metamorphism and associated plutonism which affected the Puncoviscana basin begun in the Early Cambrian and finished in the early Middle Cambrian. These processes were active through the closure of the basin, probably related to the Arequipa-Antofalla Terrane colliding with the western Gondwanan margin, and the activity of the Paleo-Pacific Plate, resulting in folding with open to closed structures and an axial plane cleavage, mostly recognized in the pelitic facies. This folding was characterized by Willner & Miller (1986), and Willner (1990) as F1 and F2. Axial planes of these folds arranges are roughly NS and show a variable vergence to the E or W in depending on the studied location. There are areas where chevron folds and flank slides are quite frequent.

Nevertheless, the metamorphic events north of Tucumán were of low grade with syn-kinematic and thermal characteristics that are particularly distinguished near the granitic plutons. Metamorphism usually generates a weak recrystallization of the matrix and an oriented biotite growth. In some areas metamorphism reaches the chlorite zone and even higher, as in the Sierras Pampeanas south of Tucumán. In these localities it is not easy to determine whether the metamorphic events correspond to the Tilcarian Orogeny or to later Ordovician events (Famatinian Cycle, *sensu* Aceñolaza & Toselli 1976).

It is important to point out that from Tucumán to the north, the Tilcarian Orogeny terminates at the base of the mid to late Cambrian Mesón Group which unconformably overlies the Puncoviscana Formation s.l.

9. Geodynamic model

Various geodynamic interpretations have been put forward for the Puncoviscana Basin. In different papers we have supported the idea of a typical aulacogenic basin developed at the western margin of Gondwana (Aceñolaza & Toselli 2009, with references).

The opening of the Puncoviscana Basin was due to the interaction of continental plates and the paleo-Pacific ocean plate, generating a distensive process that allowed the sinking of the area and favoured the development of an extensive epicontinental sea. These characteristics are supported by the sedimentary record, with dominance of siliciclastic facies and minor carbonatic bodies. Associated distensive volcanism, faunal and trace fossil content and the overall environmental interpretation, support a relatively shallow sea with a moderate bottom relief allowing the formation of turbidite flows (Ježek 1990; Aceñolaza & Toselli 2009, with references).

Other interpretations (Omarini & Sureda, 1993; Omarini et al. 1999) support a plate tectonic concept that implies collisional models between different terranes named as Cuyania-Antofalla-Belén-Arequipa (CABA). Within collisional schemes Keppie & Bahlburg (1999), Loewy (2003), Pankhurst et al. (2006), Drobe et al. (2009), Siegesmund et al. (2009), and Rapela et al. (2010) consider a geodynamic interpretation with the interaction of the Kalahari Craton and the terrane represented by the Puncoviscana Formation. A major problem in these hypotheses is the lack of the characteristic high pressure metamorphic units associated to these schemes.

Finally, contributions by Ramos (2010a, b, with references) include a complex terrane transfer between Laurentia and Gondwana, considering displacements, detachments and amalgamations that include a hypothetic craton named “Pampia Terrane”. The latter is proposed to collide with the western margin of Gondwana on a problematic model that considers its accretion to the Amazonia Craton, remaining attached to it after the Rodinia amalgamation.

Considering both models there must be mentioned that there is no typical collisional effect verified for the region.

10. Conclusions

Neoproterozoic to Cambrian sedimentation, metamorphism, plutonism, and orogenesis constitute the “Pampean Cycle” that is recorded in the Pampean Orogen. The sedimentation and associated phenomena were developed on a peri-Gondwanan position. Zimmermann (2005), based on petrographic and geochemical data, considered that the Puncoviscana Group represents a foreland basin deposit, developed during the Neoproterozoic to Early Cambrian on the western part of the Mesoproterozoic belt or the Rio de la Plata Craton.

Even though the eastern facies of the Puncoviscana Formation accumulated in a shallow marine setting, the generally accepted “deep-water” model for the western facies is challenged by the present authors. A deeper area is accepted when compared to the eastern facies, but an overall shallow marine environment, deepening towards the west, is supported by sedimentary and ichnological data (Aceñolaza et al. 2009).

Whereas exclusively Ediacaran fossils have not been recognized in the Puncoviscana Formation, metamorphic ages indicate that Ediacaran strata exist in the basin. Trace fossil associations and new data on body fossils shall provide additional elements to improve the biochronological knowledge of the unit. In addition, the co-existence of different tiering structures and the non-exclusively biomat-related feeding strategies of trace fossil producer organisms require a more complex ecological structure for the unit than previously suggested.

The distribution of Detrital zircon age populations suggests a sediment provenance from a continental hinterland having a stabilized, extensive Late Mesoproterozoic – Early Neoproterozoic orogen, 1080-850 Ma, with minor Paleoproterozoic and Archean precursors (>1800 Ma), and more variable Late Neoproterozoic (650-540 Ma) regions. Source of these sediments may have been the Brazilian shield and Rio de la Plata craton, Mesoproterozoic belts (Sunsás) and Late Neoproterozoic orogens (Brasiliano), which are considered the main sediment source for the rivers flowing towards the passive margin of the palaeo-Pacific ocean (Adams et al. 2005, 2008; Gaucher et al. 2009a, b).

The youngest U-Pb detrital zircon ages in greywackes of the Puncoviscana Formation probably originated from contemporary volcanic sources, indicating a maximum depositional age of late Early Cambrian, and this age range might extend down into the latest Neoproterozoic.

The morphology of zircons supports a coeval volcanic provenance for these youngest beds, which occurred in the Early Cambrian near the depositional areas of the Puncoviscana Formation. Contemporary volcanism developed in the Early Cambrian close to depositional sites in Cachi (Salta) and La Ovejería (Catamarca) ranges.

In addition, biostratigraphical and isotopic data are consistent, suggesting a depositional age for the Puncoviscana Formation, encompassing the Ediacaran-early Cambrian (Aceñolaza & Aceñolaza 2007; Aceñolaza et al. 2009, and references therein).

The limestones are interbedded in the Puncoviscana Formation and in the phyllites and schists of the northwestern Sierras Pampeanas. The 87Sr/86Sr values allow to clearly differentiate two sets of rocks (Toselli et al. 2010): (a) Limestones interbedded to the Puncoviscana Formation (Las Tienditas and Volcán formations) yielded values typical for the Neoproterozoic-Cambrian transition, between 0.70868 and 0.70896, and (b) Limestones of the Sierras Pampeanas of Catamarca (La Calera and Ancaján) display values of 0.70748 and 0.70756, common in middle to late Ediacaran. The former Sr-isotope values fit δ13C data between -1.0 and +1.0‰VPDB, typical for the early Cambrian period, while δ13C values around +5 ‰VPDB are common in the Ediacaran period. These current data suggest older ages for the analyzed limestones of the Sierras Pampeanas (Catamarca) and, younger ages, for the carbonates in the Cordillera Oriental (Salta and Jujuy).

Rb-Sr and K-Ar metamorphic ages of slates, in the range 540-500 Ma (Adams et al. 1990, 2008; Cordani et al. 1990), are consistent with an Ediacaran- Early Cambrian depositional age.

The magmatic rocks associated with the Puncoviscana Formation can be adscribed to two events, pre-Tilcarian (pre-mid Cambrian), and Tilcarian (mid Cambrian). The first one is related to the evolution of the Puncoviscana Formation, with intraplate alkaline basalts and transitional evolution to tholeiitic basalts, typical of extensional settings, and finally oceanic basalts that correspond to a subduction phase, present in oceanic island arcs. In the Santiago del Estero and northern Córdoba provinces, granitoids intruded into a high-grade metamorphic basement, and rhyolitic domes with ignimbrites are interpreted as part of a calc-alkaline magmatic arc (Llambias et al. 2003).

Tilcarian granitic plutons occur in Jujuy and Salta provinces, and likewise in the Sierras Pampeanas, with ages between 536 and 514 Ma. Their geochemical calc-alkaline affinity is probably related to a continental arc or continental collision environment (Omarini et al. 1996, 1999). In the Sierras Pampeanas basic-ultrabasic rocks are associated with granites.

We envisage a geodynamic model that considers the Puncoviscana Basin as a large aulacogenic structure developed at the western margin of Gondwana.

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