

Insights in the Neoproterozoic–Early Cambrian transition of NW Argentina: facies, environments and fossils in the proto-margin of western Gondwana

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Abstract: In NW Argentina, over 3000 metres of highly tectonized and metamorphosed siliciclastics of the Puncoviscana Formation underlie the more fossiliferous Cambro–Ordovician strata of the Mesón and Santa Victoria groups. Historically regarded as the non-fossiliferous ‘basal Precambrian shield’ of the region, its age was later found to be in part Phanerozoic, with the discovery of Early Cambrian trace fossils, and more recently refined with geochronological data. Widespread siliciclastic deposits characterize this sequence. A review of trace fossils in the Puncoviscana Formation has added new taxa. Trace fossil assemblages denote? geographical belts, indicating shallower marine conditions to the east (*Nereites* association) and deeper to the west (*Oldhamia* association). Such assemblages related to the palaeomorphology of the basin also represent different temporal levels, and in so doing reflect the overall evolution of the Puncoviscana Sea through time. The use of taxa that characterize Siberian stages in order to date parts of the Puncoviscana Formation should be abandoned as Siberian stages are defined by a specific set of fossils that are absent in the strata of NW Argentina. Thus, careful systematic studies and re-evaluation of the strata and fauna in the Puncoviscana Basin are the only way to improve understanding of the Neoproterozoic–Cambrian transition in the Andean margin of South America.

The Neoproterozoic–Early Cambrian transition records some of the most important events in the evolution of the Earth, from a major plate-tectonic reconfiguration (Scotese & McKerrow 1990; Bengtson 1994), to the diversification of metazoans (Glaessner 1984; Fedonkin 1990; Narbonne 1998; Narbonne & Gehling 2003), the end of the ‘Snowball’ glaciations (Hoffman *et al.* 1998) and profound changes in the isotopic composition of seawater (Kaufman & Knoll 1995; Eriksson *et al.* 1998). These remarkable events triggered major evolutionary biotic evolution.

More than one hundred years of research resulted in the definition of the base of the Phanerozoic at Fortune Head, Newfoundland, Canada (Gradstein *et al.* 2004 with references). Analysis of the discussions held over the last 30 years clearly highlights that most debates concerning this boundary and others, involved data from North America, Africa, Asia and Australia, but lacked information from the Neoproterozoic–Early Cambrian sequences of South America (Glaessner 1984; Fedonkin 1987, 1994). Thus further research is required on the sedimentary and metamorphic rocks of this region.

The Neoproterozoic–Early Cambrian sequence in the central Andean Basin of South America is best exposed in northwestern Argentina, where it

is dominated by thick, heterogeneous slightly metamorphosed and predominantly siliciclastic successions of the Puncoviscana Formation. This unit represents the regional basement (Turner 1960; Aceñolaza & Toselli 1981; Omarini *et al.* 1999a), but its stratigraphy has been obscured by several deformational events. The strata of the Puncoviscana Formation represent multiple sedimentary environments (Jezek 1990; Aceñolaza & Aceñolaza 2003). As a consequence, lithological correlation, dating and precise identification of sequences in the Puncoviscana basin are highly problematic, with the only clear data points provided by trace fossils and rare geochronological input. Based on these studies, it is clear that at least part of the Puncoviscana Formation is Early Cambrian in age (Aceñolaza *et al.* 1999; Omarini *et al.* 1999b with references) (Figs 1–4).

Corsetti & Hagadorn (2000) noted that the ability to correlate and refer sequences from one part of the globe to another is the key to understanding those biological changes across the Neoproterozoic–Cambrian transition. New palaeontological data, complemented with isotopic stratigraphy carried out on the highly deformed sequences of northern Argentina, are dependable tools for correlating strata at an intra- and inter-basinal level (e.g. Knoll & Walter 1992; Grotzinger

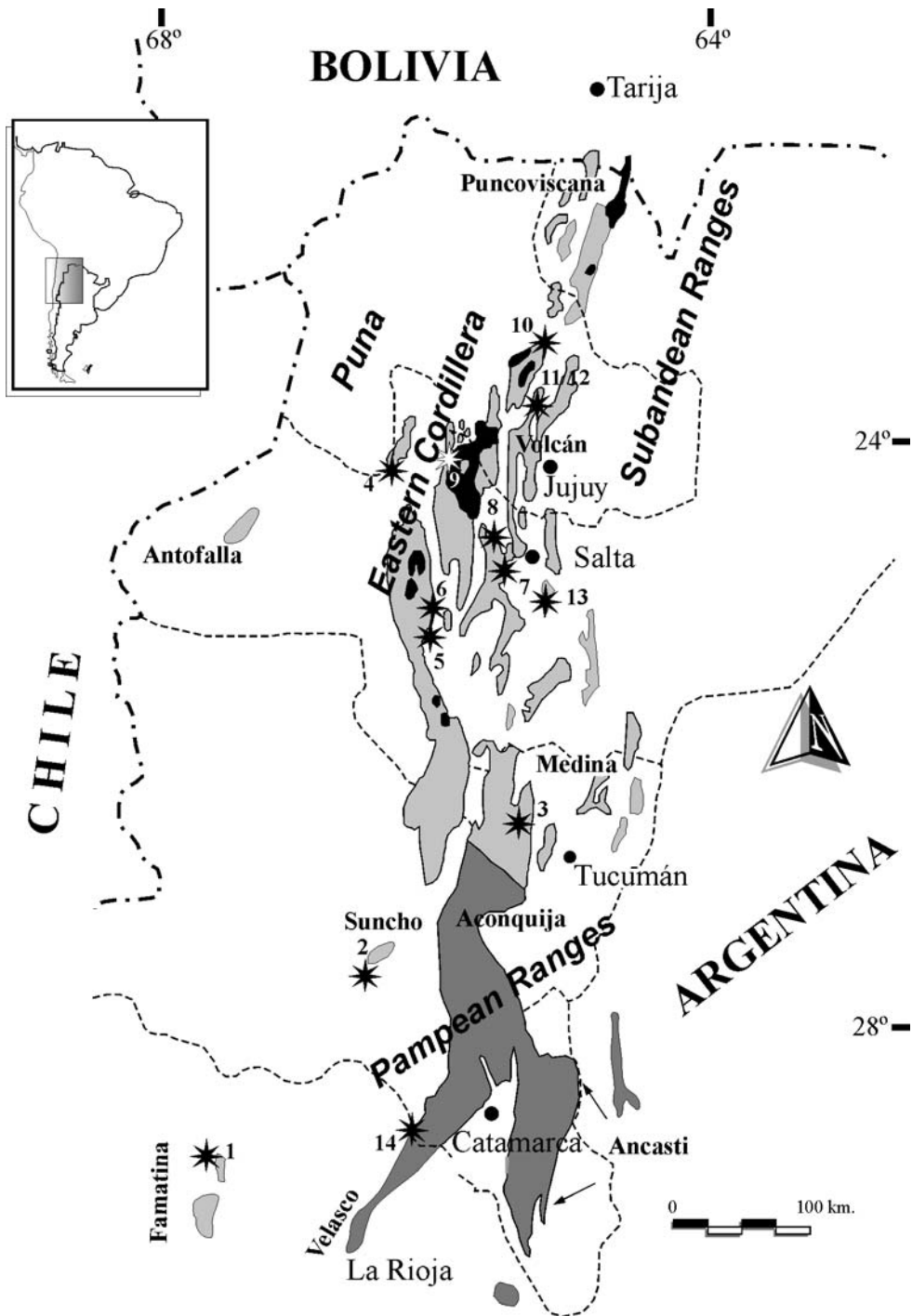


Fig. 1. Outcrops of the Puncoviscana Formation and equivalent units in NW Argentina with fossiliferous localities highlighted (*). Light grey: Puncoviscana *s.l.*; dark grey: low and mid grade metamorphic rocks derived from Puncoviscana *s.l.* Localities: 1, Angulos; 2, Suncho; 3, Choromoro; 4, San Antonio de Los Cobres; 5, Cachi; 6, Payogasta; 7/8, Quebrada del Toro; 9, Abra Blanca/Muñano; 10, Coraya; 11, Purmamarca; 12, Lipán; 13, Los Guachos; 14, La Cébila.

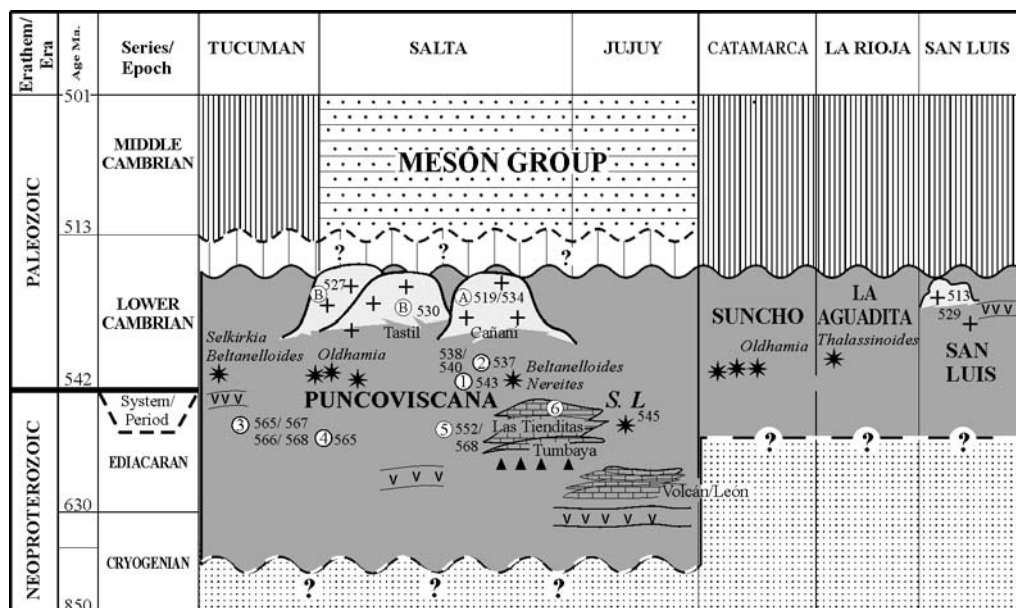


Fig. 2. Stratigraphy of the Puncoviscana Formation *s.l.* with intrusives, sediments and discordances. Radiometric dates are on plutons and metamorphic rocks. A; Cañaní Granite; B; Tastil Granite; 1, Don Bartolo; 2, Quebrada del Toro; 3, Choromoro; 4, San Javier; 5, Cuesta del Obispo; 6, Purmamarca.

et al. 1995; Sial *et al.* 2001; Aceñolaza 2004; García Bellido & Aceñolaza 2005).

This contribution summarizes the current knowledge of the Neoproterozoic–Early Cambrian transition in the Central Andean Basin: the Puncoviscana Formation and related units. It focuses on NW Argentina, where exposures are best developed, and the only region where enough data is available to allow a well-defined lithostratigraphic framework centred on the Proterozoic–Phanerozoic transition.

The Neoproterozoic–Early Cambrian in the South American Central Andean Basin

The sedimentary basement of the Central Andean Basin is best represented by the Puncoviscana Formation *s.l.*, which crops out from Tarija in the southern part of Bolivia (=San Cristobal Formation), to Tucumán in northern Argentina. Even though there are a variety of facies and lithologies, the entire region appears to be part of the same Neoproterozoic–Early Cambrian belt, that continues southwards into the Sierras Pampeanas and northern Patagonia (Turner 1976; Caminos 1979; Ramos 1999; González *et al.* 2002; Sato *et al.* 2002; Schwartz & Gromet 2004) (Fig. 1). An even larger extension has been also proposed, from the highlands of Perú (Díaz Martínez 1996)

to Antarctica, on the basis of lithology and trace fossil content (Tessensohn 1982; Jezek *et al.* 1985). Low-grade metamorphic basins of this type are also recorded eastwards in Australia, as part of a major structural unit, resulting from the break-up of Rodinia (Moore 1991; Ross 1991; Storey *et al.* 1992; Rowell *et al.* 1993).

In Argentina, the northern outcrops are dominated by very low- to low-grade metasedimentary rocks, whereas southwards gneisses and migmatites are more common, all having been affected by Middle Cambrian to Early Ordovician plutonism (Rapela *et al.* 1992, 1998; Keppie & Bahlburg 1999). Ramos (1999) noted that there is no consensus in interpretation of the tectonic setting of the Puncoviscana Basin. Ideas range from: it being a passive margin (Jezek *et al.* 1985; Jezek 1990); to a closing ocean with collision and subduction (Ramos 1988); rifting processes (Omarini & Sureda 1993; Suárez Soruco 1989, 2000; Aceñolaza & Alonso 2001); a foreland basin (Kraemer *et al.* 1995; Keppie & Bahlburg 1999); or even part of an island arc (Omarini *et al.* 1999).

In addition, a spectrum of environmental settings has been identified in the Puncoviscana Formation, with an eastern ‘Nereites belt’ characterized by a particular trace fossil associated with current-rippled sandstones, turbidites and conglomerates from a shallower setting; and a western ‘Oldhamia belt’, with relatively deeper-water facies associated with turbidites, shales and

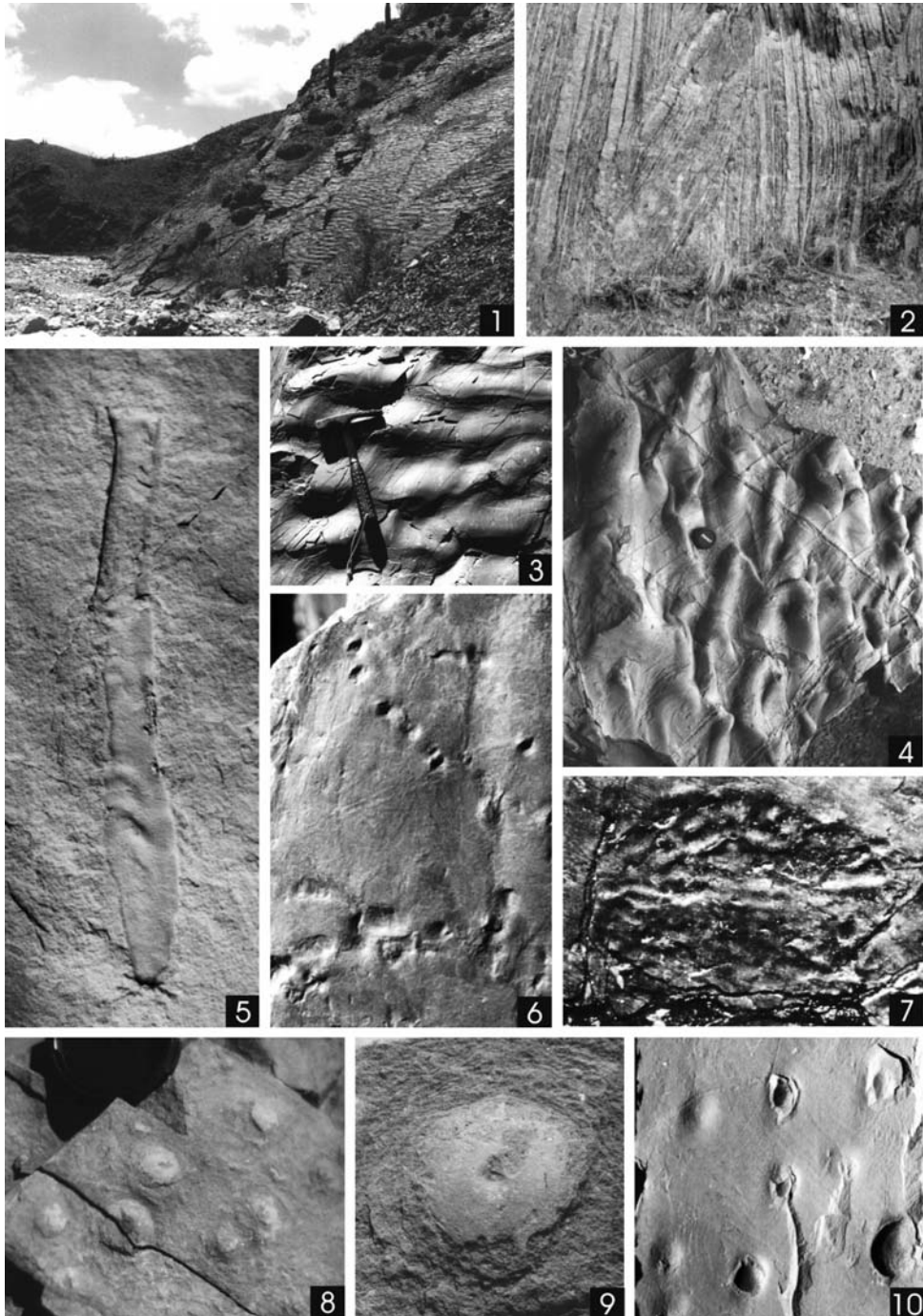


Fig. 3. Outcrops displaying sedimentary rocks and deformation structures, soft-bodied fossils and enigmatic material from the Puncoviscana Formation in northwest Argentina. (1) Rippled surface at Escoipe; Salta Province; (2) Tight folded succession at El Alisal, Quebrada del Toro, Salta Province; (3) Current-rippled surface at Purmamarca, Jujuy Province; (4) Flute marks on sole of sandstones of the Puncoviscana Formation at Escoipe, Salta Province. (5) *Selkirkia* sp. from Choromoro, Tucumán Province ($\times 0.5$). (6, 7, 10) Enigmatic material present in the slates and sandstones of the Puncoviscana Formation from Tucumán Province (6×0.2 ; 7×0.35 ; 10×0.2). (8, 9) *Beltanelloides* sp. from Purmamarca, Jujuy Province (8×0.5 ; 9×1.3).

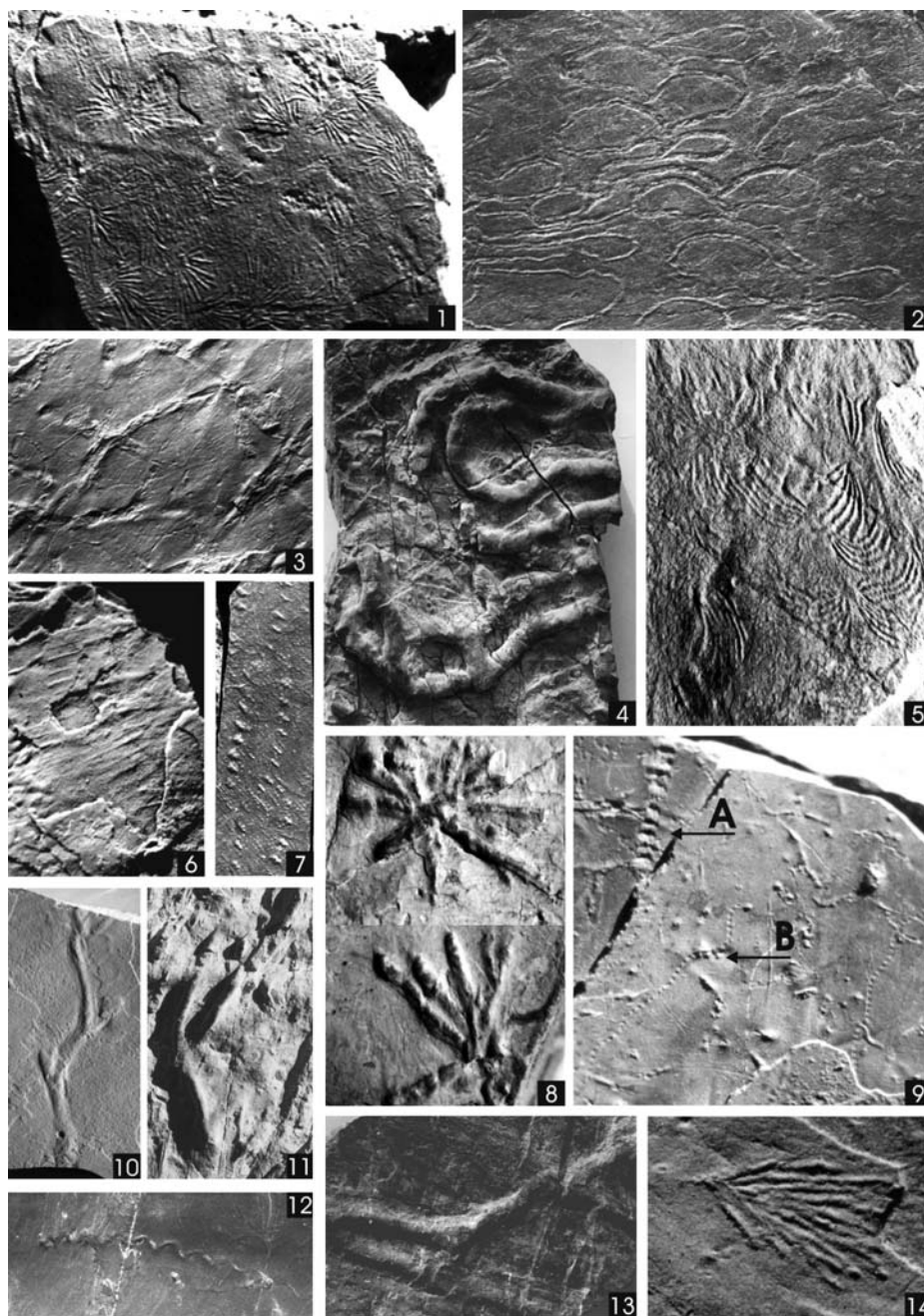


Fig. 4. Selected trace fossils from the Puncoviscana Formation and equivalent units in northwest Argentina. (1) *Oldhamia radiata* from San Antonio de los Cobres, Salta Province ($\times 1.5$); (2) *Nereites saltensis* from Salta Province ($\times 0.15$; non-*Psammichnites saltensis* in Seilacher *et al.* 2005); (3) *Palaeophycus* isp. associated with *Helminthoidichnites tenuis* from Quebrada del Toro, Salta Province ($\times 0.4$); (4) *Helminthoraphe* isp. ($\times 0.2$); (5) *Oldhamia curvata* from Quebrada del Toro, Salta Province ($\times 0.6$); (6) *Monomorphichnus lineatus* from El Alisal, Salta Province ($\times 2.5$); (7) *Tasmanadia cachii* from Cachi, Salta Province ($\times 0.5$); (8) *Glockerichnus* sp. ($\times 1.5$); (9) A: *Neonereites biserialis* ($\times 0.5$). B: *N. uniserialis* ($\times 0.5$) from Salta Province; (10) *Treptichnus* cf. *aequalternus* from Choromoro, Tucumán Province ($\times 0.8$); (11, 13) cf. *Thalassinoides* isp. from San Antonio de Los Cobres, Salta province (11 $\times 0.3$; 13 $\times 0.5$); (12) *Cochlichnus anguineus* from the Quebrada del Toro, Salta Province ($\times 0.45$); (14) *Oldhamia flabellata* from San Antonio de Los Cobres, Salta Province ($\times 0.9$).

pelagic clays (Salfity *et al.* 1975; Jezek *et al.* 1985; Jezek 1986, 1990; Willner 1990; Durand & Aceñolaza 1990; Durand 1993; Aceñolaza & Aceñolaza 2001). Neither belts is characterized by archetypal ichnofacies. Contrary to recent suggestions by Buatois & Mángano (2003*b*), neither Jezek (1990) nor Aceñolaza *et al.* (1999) documented an exclusive deep water setting for the Puncoviscana Formation. Locally, turbidites and sandstones are associated with limestone units (e.g. Volcán and Las Tienditas Fm), whose depositional setting is contentious; they have been interpreted as olistostromal or autochthonous deposits on submarine swells (e.g. Jezek 1986). Aceñolaza (2005) noted that limestones, conglomerates and shales, to mention only some facies represented in the unit, do not form under the same palaeoenvironmental conditions. The Puncoviscana Formation is considered to be a continental margin wedge succession that was deposited during Neoproterozoic–Cambrian times, consisting mostly of shelf, shelf-edge and slope deposits, with a general deepening trend towards the west (Borrello 1969; Aceñolaza *et al.* 1999; Aceñolaza & Alonso 2001 with references).

The facies complexity with tectonically-obscured relationships makes interpretation of the stratigraphic succession difficult (Mon & Hong 1996). In addition, the existence of igneous material interbedded in the Puncoviscana Formation at several localities in Salta and Jujuy (Toselli & Aceñolaza 1984; Chayle & Coria 1987; Manca *et al.* 1987; Toselli & Rossi 1990; Coria *et al.* 1990; Omarini *et al.* 1993) records eruptive events that occurred during the deposition of the unit. Unfortunately, dates for these different magmatic rocks are controversial, highlighting the need of more detailed geochemical investigation (see Omarini *et al.* 1999).

Several attempts have been made to order the sequences in the Puncoviscana Basin (Salfity *et al.* 1975; Baldis & Omarini 1984; Moya 1998), but most of the studies are local to the Valle de Lerma in Salta Province and should not be applied to the basin as a whole.

The Puncoviscana Formation of NW Argentina

The Puncoviscana Formation was originally described by Turner (1960), in the Sierra de Santa Victoria, northern Salta Province. This study described more than 2000 metres of unfossiliferous shales and sandstones, and was later extended to similar strata underlying the highly fossiliferous Cambro-Ordovician rocks.

Even though the term of Puncoviscana Formation (*s.l.*) in northern Argentina has been applied to the Neoproterozoic–Lower Cambrian metasedimentary basin in the region, several other questions and inconsistencies arise as detailed work proceeds (Aceñolaza *et al.* 1999; Durand & Aceñolaza 1990; Ramos 1999; Sial *et al.* 2001; Buatois & Mángano 2003*a, b*) (Fig. 2).

Taking into account that the highly deformed siliciclastic rocks of the type area are depleted of biogenic structure and fossils, and that similar sequences located to the south and west (e.g. Valle de Lerma, San Antonio de los Cobres in Salta and Choromoro in Tucumán), contain fossils, correlation is rather complex. Any correlation must be based on detailed and precisely located information. Lithology changes laterally and rapidly, with common interbeds of conglomerates, limestones and vulcanites; their stratigraphic position is unclear due to the strong deformation of the whole complex. The mentioned differences, far from contributing to a clear understanding of the unit, only increase the complexity of this regional Neoproterozoic–Cambrian transition panorama further.

Omarini (1983), Omarini & Baldis (1984) and Jezek (1986) discussed sedimentary characters of the Puncoviscana Basin, distinguishing lithological types based on texture and internal structures: (a) coarse-grained flysch-like turbiditic sandstones; (b) thick and monotonous sequences of argillites, siltstones, and sandstones; (c) minor diamictites and polymictic conglomerates; and (d) isolated shallow water micritic limestones, reflecting a wide spectrum of sedimentary settings for the Puncoviscana Basin.

In addition, Omarini *et al.* (1999) distinguished at least three episodes within the succession: a basal sequence formed primarily by immature epiclastic sediments associated with ultra-potassic dykes (with interbedded mantle-related volcanic flows); shelf deposits with near-shore sandstones (associated with alkalic and tholeiitic lavas); and an upper sequence with flysch-like, siliciclastic deeper water facies (associated to minor pyroclastites, volcanic layers, breccias and granites). Jezek (1990) provided a detailed sedimentological analysis of the Puncoviscana Formation in Tucumán and Salta provinces, distinguishing several sedimentary facies: Facies 1: ‘conglomerate facies’ described from various localities in Salta Province, are characterized by pebbly sandstones/mudstones and organized/disorganized conglomerates representing different detritic flows in the basin; Facies 2: ‘proximal facies’ characterized by dominance of psammites, representing braided river channels, common in Tucumán Province; Facies 3: ‘intermediate’ with mid- to outer fan

prograding lobes including a wide spectrum of sedimentary structures; Facies 4: ‘distal facies’ with low density and low-velocity turbidites; and Facies 5: dominated by hemipelagic slates. Trace fossils and wrinkle structures are common in facies 2, 3, 4; and all are well represented in the northern sector of the Puncoviscana Basin.

Interbedded dark grey limestone facies are known to occur in the region, with notable outcrops at Volcán, León, Tumbaya (Jujuy) and Las Tienditas (Salta). Recent study of these carbonate bodies (Toselli *et al.* 2005) indicate similar $\delta^{13}\text{C}$ signatures for Las Tienditas and Tumbaya limestones and dolomites, with -1.33 to 2.28% PDB for the latter ones; whereas Volcán and León carbonates display higher values, between -6.11 to 4.58% PDB, probably representing older ages (possibly Sturtian?). Toselli *et al.* (2005) note the possibility that the Las Tienditas and Tumbaya limestones may represent ‘cap-carbonates’, highlighting that in the latter locality dolomites are deposited above basalt. In both localities, underlying strata have been considered as likely glacial (Sial *et al.* 2001; Toselli *et al.* 2005).

Volcanic rocks associated with these carbonate-rich bodies are subalkaline basalts, transitional basalts and alkaline basalts associated with minor dacites and leucitites, either intruding or as lava flows in the sequence. These have been interpreted as a product of rifting associated with the formation of the Puncoviscana Basin, evolving into a passive margin volcanism and a magmatic arc environment (Omarini & Sureda 1999; Omarini *et al.* 1999).

The regional metamorphism which affected the sequences of the Puncoviscana Basin has been referred to the anchizone with a maximum depth of 6 km, developed between Tucumán Province southwards to the Sierras Pampeanas of Catamarca, La Rioja, Córdoba and San Luis (Toselli 1990; Willner 1990). Contact metamorphism with development of hornfels has been described in different areas of the basin, along edges of plutons intruding the Puncoviscana Formation in Salta and Jujuy, at Cañaní, Tipayoc, Fundición, Santa Rosa de Tastil and Cachi (Kilmurray *et al.* 1974; Toselli 1990; Lork *et al.* 1990; Rossi *et al.* 1992; Omarini *et al.* 1999).

Fossils and age

The Puncoviscana Formation *s.l.* contains diverse trace fossils, with a variety of ichnotaxa that provide insights into the biota that produced them and ecology of the Puncoviscana Sea in late Neoproterozoic–Cambrian times. Body fossils are rare, with only two undoubted entries after 30

years of palaeontological research (Aceñolaza 2004, and this paper) (Figs 3 & 4).

Preservation varies from good to fairly good, depending on lithology. Tectonism has played a primary role in preservation. It is almost impossible to distinguish any biological signature where cleavage strongly superimposes primary bedding. Ichnofossils occur throughout the basin, except in the northernmost outcrops, where tight folds and the near-absence of traces precludes dating and correlation of strata. Body fossils are located within the shallower eastern belt (‘*Nereites* belt’ of Aceñolaza & Durand 1973, 1986; Aceñolaza 1990), which implies better environmental conditions and preservation patterns for organisms in these facies.

Trace fossils

More than twenty localities in Jujuy, Salta, Tucumán, Catamarca and La Rioja provinces have yielded a moderately diverse ichnofauna, with locomotion traces, feeding and grazing furrows, trails and tracks, denoting significant biological activity in the Puncoviscana Sea during the Neoproterozoic–Early Cambrian (Fig. 1). The fossils that occur in sediments deposited during this time include several whose taxonomic validity is debated, so the status of several trace fossils described previously have been subject to re-evaluation (i.e. Aceñolaza & Aceñolaza 2001, 2003). Abundance of trace fossils varies, according to facies, and the fossils themselves do not represent typical ichnofacies. The entire sequence in NW Argentina has undergone metamorphism and coeval deformation.

A summary of the ichnofauna is mentioned below, with comments on the taxonomy where possible. Early attempts, with different goals, have been published before (Buatois & Mángano 2003a, b), with assignments broadly recognized but not universally accepted (Aceñolaza & Aceñolaza 2001, 2003; Aceñolaza 2005).

The Puncoviscana ichnofauna includes: *Archaeonassa fossilata*, *Asaphoidichnus* sp., *Cochlichnus anguineus*, *Didymaulichnus lyelli*, *Dimorphichnus obliquus*, *Diplichnites* sp., *Glockerichnus* sp., *Helminthoraphe* sp., *Helminthopsis abeli*, *H. tenuis*, *Helminthoidichnites tenuis*, *Monomorphichnus lineatus*, *M. isp.*, cf. *Multipodichnus*, *Nereites saltensis* (non-*Psammichnites saltensis* of Seilacher *et al.* 2005; Aceñolaza & Aceñolaza 2006), *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*, and a variety of undetermined arthropod-related scratch marks and isolated

imprints (Durand & Aceñolaza 1990; Aceñolaza *et al.* 1999; Aceñolaza & Tortello 2003; Buatois & Mángano 2003a, b; Aceñolaza 2004; Seilacher *et al.* 2005).

The poorly preserved material assigned to *Circulichnis montanus* (Buatois & Mángano 2003a) displays ambiguous morphological characters and lacks diagnostic characters, precluding precise taxonomic assignment. Even though the ichnogenus *Treptichnus* is recognized in the unit (Aceñolaza & Alonso 2001; Aceñolaza 2004), the taxonomic status of *Phycodes*/*Treptichnus*/*Trichophycus* is still a matter of debate, and the taxonomy of these three forms should take into account early interpretations of open burrows or feeding structures (Erdogan *et al.* 2004).

The presence of large-sized, irregular, three-dimensional burrow systems with few dichotomous bifurcations allows the identification of possible trapping or farming networks in the bases of sandstone layers associated with turbidites in San Antonio de Los Cobres (Salta Province). These networks are comparable to *Thalassinoides* isp., where as individual burrows can be identified as large-sized *Palaeophycus tubularis* (Figs 4, 11–13). Branching can be falsely assumed when in reality the traces are superimposed or crossing traces, but undoubted dichotomizations were recorded after a detailed pattern analysis of a single surface of over 20 square metres at one locality. The strata at San Antonio de los Cobres are characterized by a slightly-reworked sedimentary fabric, with a low overall degree of bioturbation restricted to the sandstone–mudstone interval (Durand & Aceñolaza 1990; Buatois & Mángano 2003b). These traces may represent an early attempt to develop possible trapping methods as feeding strategies. Traces penetrate the substratum up to 8 cm, a remarkable depth when compared to the associated traces restricted to the upper few millimetres (*Cochlichnus*, *Oldhamia*, *Helminthopsis*, *Diplichnites* and small *Palaeophycus*).

In general, the ichnological record preserved in the Puncoviscana Formation includes diverse ethological variants, ranging from grazing to feeding and locomotion structures possibly made by vermiform organisms and arthropods. The possible presence of trapping structures in the locality of San Antonio de los Cobres reflects a particular feeding strategy not recorded before in the Early Cambrian of South America.

Body fossils

As stated by Fedonkin (1992), the systematic position of Ediacaran metazoans is controversial. Several interpretations have been presented on their relationships. Glaessner (1984) placed

Precambrian animals in a framework of Phanerozoic invertebrates, but Seilacher (1984, 1989) stressed the uniqueness of Precambrian organisms with no modern analogues. Fedonkin (1983, 1985, 1987) supported a different taxonomic arrangement for Precambrian metazoans based on body plans and further suggested that the metazoan fossil record of the Late Proterozoic, with its much lower diversity than today might be, a preservational artefact (Fedonkin 1992).

Aside from the relatively good record of trace fossils, two undoubted body fossils have been recognized in the Puncoviscana Formation after almost 30 years of palaeontological research: *Selkirkia* sp. (= *Sphenothallus*? sp., in Aceñolaza 2004) occurs in outcrops near Choromoro village in Tucumán Province (García Bellido & Aceñolaza 2005), and well preserved samples of *Beltanelloides* sp., were recovered at Purmamarca village in Jujuy Province. Early references to '*Beltanelliformis*, *Sekwia* and *Nemiana*' have been re-assigned to *Beltanelloides* sp., following the detailed revision of Leonov (2007) (Aceñolaza *et al.* 1999, 2005, with references).

Other biologically induced structures

The knowledge of Neoproterozoic–Early Phanerozoic siliciclastic environments and their biological signature has dramatically increased during the last fifteen years. The Puncoviscana Formation displays some unique surface morphologies that were historically referred as to wrinkle structures associated to certain lithofacies (i.e. Durand *et al.* 1994; Aceñolaza *et al.* 1999 with references). During the 1990s, these structures were re-evaluated as microbial mat-related structures, following ideas of Seilacher & Pflüger (1994), Seilacher (1999), Noffke *et al.* (2001, 2002) and Pflüger (1999). In the case of the Puncoviscana Formation, Omarini *et al.* (1999) were the first to propose these ideas, followed by Buatois *et al.* (2000), Aceñolaza & Aceñolaza (2001, 2003) and Aceñolaza (2004), supporting a microbial mat-related lifestyle of the fauna.

The age of Puncoviscana

So far, the only reliable chronological indicators in the Puncoviscana Basin are the Early Cambrian fossils restricted to certain strata, as well as some limited geochronological data (for summaries, see Aceñolaza & Durand 1986; Do Campo 1999; Omarini *et al.* 1999; Sureda *et al.* 1999). Lork *et al.* (1990) noted a 530 to 560 Ma date for detritic zircons in the Puncoviscana Formation, and Bachmann *et al.* (1987) presented 536 ± 7 Ma and 534 ± 9 Ma dates for plutonic bodies intruding

Puncoviscana Formation, therefore as a minimum date. In addition, Adams *et al.* (1990) recorded metamorphic events between 530 to 540 million years ago, where as Cordani *et al.* (1990) suggested an age ranging from 520 to 538 million years ago, all pointing to a Neoproterozoic–Early Cambrian age for the sedimentation and metamorphism of the unit. Assuming C-isotope stratigraphy is a powerful temporal tool in Precambrian stratigraphy, especially for sediments lacking recognizable fossils (Kaufman 1988), the recent record of a strong C-isotope peak in the upper part of Las Tienditas Formation suggests a Proterozoic–Phanerozoic datum in the upper part of this calcareous unit in the Puncoviscana Formation *s.l.* (Sial *et al.* 2001; Toselli *et al.* 2005). In addition, recent work on these limestone units of Salta and Jujuy (Toselli *et al.* 2005) suggests that possible Sturtian sequences with ‘cap-carbonates’ at Las Tienditas and Tumbaya, supporting early and ignored interpretations of glacial-related sediments associated to the Puncoviscana Formation (Loss & Giordana 1952) (Fig. 2). This, however, needs a more precise age control.

Final remarks and conclusions

Despite the many stratigraphic studies of the rock units representing the Neoproterozoic–Cambrian transition in Argentina, general use of any of the defined units for the whole sedimentary succession will remain problematic until a framework is better understood. Presently, the terms Puncoviscana Basin, Puncoviscana Complex or Puncoviscana Formation *s.l.* are recommended for use in NW Argentina, where no other formal designation has been presented. The sparse fossil record, its uniqueness and its style of preservation, with the complicated structural history of the region, present a complex scenario for the Neoproterozoic–Early Cambrian in the South American Central Andean Basin.

Distinctive facies within this basin, including limestones and conglomerates, should be noted under their original designation (i.e. Volcán Formation, Las Tienditas Formation, El Coro Member, etc.), and the use of the Lerma Group (Salfity *et al.* 1975) should be restricted to the Valle de Lerma in Salta Province.

New palaeontological finds and new geochronological dating are the most reliable sources that provide a more accurate age definition and better correlation of rock units discussed in this paper. The Early Cambrian trace fossils and body fossils are clearly restricted to certain lithologies within the basin, and the geochronological data points to a Neoproterozoic–Early Cambrian age. Until

now, there are no definite indicators, neither palaeontological nor isotopic, that allow a sharper chronological dating of the unit.

The lack of distinct or reference fossil remains (macro- and micro-) in the Neoproterozoic/Cambrian transition interval in the Early Palaeozoic Central Andean Basin, does not allow a biozonation to be defined, allowing correlation to other reference sections (Newfoundland, Siberia, Baltica or China). As recently stated by García Bellido and Aceñolaza (2005), miscorrelation by previous workers occurred because of forcing of unreliable data into a chronological system (systemic divisions, stages, biozones, etc.).

The detailed chronostratigraphic and biostratigraphic correlation of the Puncoviscana rock sequence to the Siberian section is not really possible at present due of the lack of palaeontological data that characterize biostratigraphic subdivisions in the Argentine strata. Linkage of the Neoproterozoic–Early Cambrian strata of NW Argentina to other reference sections around the world must be carried out carefully. A global chronostratigraphy for the lowermost Cambrian has been discussed often (Landing 1992). Interregional correlation based on fossiliferous data at a stage-level (Nemakit–Daldynian, Atdabanian, etc.) is highly speculative in NW Argentina, and names are irrelevant because of the lack of index fossils in the Andean Margin of South America. As noted by Landing (1992), Siberian stages reflect a long-term evolutionary development and immigration of species and communities that define a warm-water faunal province for the Siberian Basin: a very different setting that that of the Argentine sequences and other reference sections around the world (i.e. Avalon).

Early records of *Beltanelliformis*, *Sekwia* and *Nemiana* in the Puncoviscana Formation should be synonymized with *Beltanelloides* sp., and a new fossiliferous locality noted in the province of Jujuy. Material there is preserved in highly tectonized sandstones and shales, that crop out near the village of Purmamarca (Jujuy Province), and yield well-preserved samples of *Beltanelloides* sp. (an element that characterizes Vendian (Ediacaran age) biota of Siberia and those of similar age from other regions of the world (Figs 3, 8–9)).

The presence of microbially-induced structures, mostly restricted to finer-grained lithologies in the Puncoviscana Formation, stresses the importance of sediment binding in the earliest Cambrian, prior to the general substrate revolution (matgrounds being replaced by mixgrounds).

The occurrence of dichotomous traces assigned to cf. *Thalassinoides* network systems in the sediments of San Antonio de los Cobres (Salta Province), adds an interesting new feeding strategy in

the Early Cambrian on the seafloor of the Puncoviscana Sea, with possible primitive trapping structures not previously reported in this unit.

Further efforts are necessary to integrate structural, geochemical, sedimentological and palaeontological data known from the Puncoviscana Formation. Systematic studies and re-evaluation of published material from the in the Puncoviscana Basin, are the only way to obtain reliable data for an in-depth understanding of the Neoproterozoic–Cambrian transition in the Andean margin of South America.

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