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The unusual record of *Nereites*, wrinkle marks and undermat mining trace fossils from the late Silurian–earliest Devonian of central-western margin of Gondwana (Argentina)

Pablo J. Pazos [a,b,*], Carolina Gutiérrez [b], Diana E. Fernández [a,b], Arturo M. Heredia [b], Marcos Comerio [a]

[a] *Instituto de Estudios Andinos (IDEAN), UBA-CONICET. Dpto. de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, Pabellón II. Av. Intendente Güiraldes 2680 (1428), Buenos Aires, Argentina*

[b] *Dpto. de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, Pabellón II. Av. Intendente Güiraldes 2680 (1428), Buenos Aires, Argentina*

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ABSTRACT

Silurian–Devonian deposits of central western Argentina contain one of the most diverse Palaeozoic records of *Nereites* in Gondwana. *Nereites* cf. *cambrensis*, *Nereites irregularis*?, *Nereites jacksoni*, *Nereites macleayii*, *Nereites missouriensis* and *Nereites pugnus* are documented in a turbidite-like succession of the San Rafael Block (Río Seco de los Castaños Formation). The succession, historically assumed as deep-sea deposits or interpreted as a deltaic system, also contains abundant microbially induced sedimentary structures (MISS) such as wrinkle marks. Glossy surfaces indicate abundant biofilms, where the fossil record comprises *N. macleayii*, *N. missouriensis*, scarce arthropod trackways (*Diplichnites*?) and undermat-miner structures. *Nereites*, the pioneer colonizer, is in some cases cross-cut by *Dictyodora*, while undermat miners are the late bioturbators. The succession is dominated by gravity flow deposits, including storm related, turbidite-like deposits and abundant wrinkle marks. These suggest deposition on the shelf rather than the deep sea. This study shows that microbial mats were not restricted to marginal marine environments during the mid Palaeozoic, and documents one of the most diverse Palaeozoic records of *Nereites* in western Gondwana. It also contributes to the record of *Nereites*, *Dictyodora*, and *Zoophycos* found, for first time, in association with microbial mat structures in the late Silurian—earliest Devonian, the *Nereites* ichnofacies together with abundant wrinkle marks.

1. Introduction

The ichnogenus *Nereites* MacLeay (Murchison, 1839) is a conspicuous component of the homonymous ichnofacies in the bathymetric scheme defined by Seilacher (1967) to characterize deep-sea environments. However, from an ichnotaxonomic approach, several morphological features suggested as ichnotaxobases make ichnospecies assignment difficult; comparison is dependent on which scheme is followed (e.g., Rindsberg, 1994; Orr and Pickerill, 1995; Uchman, 1995). Research by Mángano et al. (2000) shed light on the status of several ichnospecies, but the debate about *Neonereites* Seilacher (1960) as a valid ichnogenus is not completely resolved.

Nereites ranges from Cambrian to Holocene (Callow and McIlroy, 2011) and, in the Palaeozoic, is particularly common in the Silurian (Crimes and Crossley, 1991). It occurs in Recent sediments in the South China Sea (Wetzel, 2002), and is mainly recorded in deep-sea rather than shallow-marine deposits (see Wetzel, 1983; Orr et al., 2003; Uchman, 2004).

Nereites is very common in Palaeozoic successions of North America and Europe where pioneering studies took place and most of the ichnospecies were defined (e.g., Murchison, 1839; Emmons, 1844; Delgado, 1910). Additional Palaeozoic successions bearing *Nereites* have been documented in several papers from the Northern Hemisphere (e.g., McCann, 1990, 1993; Crimes, 1992; Crimes and Fedonkin, 1994; Crimes and McCall, 1995; Orr, 1995).

In South America, Palaeozoic records of *Nereites* are scarce. For instance, the record of *Nereites saltensis* Aceñolaza and Durand, 1973 from the Puncoviscana Formation (Ediacaran–Early Cambrian) from NW Argentina (Aceñolaza and Aceñolaza, 2007; Aceñolaza et al., 2009) is controversial. This ichnospecies was retained in *Nereites* by Aceñolaza et al. (2009) but Seilacher et al. (2005), Seilacher (2007) and Buatois and Mángano (2012) relocated it to *Psammichnites* Torrell, 1870.

Indisputable records of *Nereites* with *Neonereites* preservation (see Uchman, 1995 for the *Nereites* and *Neonereites* dilemma), were also documented by Aceñolaza and Aceñolaza (2007) in the Cambrian interval of the Puncoviscana Formation. Specimens described as *Parahelminthoida* isp. by Aceñolaza and Peralta (1985) from the mid Palaeozoic of the Argentinian Precordillera were later included in *Nereites* by Uchman (1995). More recently, Melchor et al. (2013)

* Corresponding author at: Instituto de Estudios Andinos (IDEAN), UBA-CONICET. Facultad de Ciencias Exactas y Naturales, Ciudad Universitaria, Pabellón II, Argentina.
E-mail address: pazos@gl.fcen.uba.ar (P.J. Pazos).

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documented specimens of *Nereites* with tight meanders from the Ordovician? of central-western Argentina. The Ordovician ichnofauna documented in Bolivia by Toro et al. (1990) includes *Dictyodora*, *Cosmoraphe* and material assigned to *Neonereites* (= *Nereites missouriensis*). In Brazil, abundant specimens of *Nereites* isp. were documented in the Devonian Pimenteira Formation by Campanha (1974).

The *Nereites* ichnofacies was subdivided by Seilacher (1974) into *Paleodictyon* and *Nereites* ichnosubfacies, in order to differentiate substrates. The archetypal features of the *Nereites* ichnofacies can be found mainly in Mesozoic and Cenozoic deep-sea fan examples, where it was subdivided into the *Ophiomorpha rudis* ichnosubfacies (characterising sand-rich channel and channel proximal lobe) and the *Paleodictyon* ichnosubfacies typifying thin-bedded turbidites in sand-rich lobe fringes (Uchman, 2001) and external shale flysch deposits for the *Nereites* ichnosubfacies (Uchman, 2004). The ichnogenus *Nereites* is a conspicuous constituent of the *O. rudis* ichnosubfacies, but not exclusively. In contrast to Seilacher (1974), Orr (1995) considered oxygenation level, rather than substrate, to be the controlling factor in deep-sea settings. A combination of both oxygenation and substrate controls was suggested by Callow et al. (2014). Wetzel (2002) analysed this relationship in detail and found oxygen deficient substrates in records of incipient *Nereites* from Recent sediments.

The evolution of the *Nereites* ichnofacies during the lower Palaeozoic was addressed by Buatois et al. (2009), who pointed out some characteristics of the deep-sea ecosystem. For instance, the relationship between graphoglyptids (sensu Seilacher, 1977), microbial mats and structures produced by undermat mining was analysed. It was concluded that the disappearance of microbial mats from the deep sea during the Ordovician allowed the diversification of graphoglyptids. More recently, Buatois and Mángano (2011) suggested that microbial mats persisted, but were restricted to marginal marine environments during the mid Palaeozoic (Silurian—Devonian), before becoming more widespread in the late Palaeozoic (Buatois et al., 2013). Interestingly, *Nereites* ichnofacies is bathymetrically well constrained and characterises deep-sea fan systems in the Mesozoic and Cenozoic times (e.g. Uchman, 2003; Buatois and Mángano, 2011; Heard and Pickering, 2008; Wetzel et al., 2007, among others).

Callow and McIlroy (2011) suggested that *Nereites* is more common in turbidite-bearing formations of the Palaeozoic than the Mesozoic and Cenozoic. The palaeobathymetric control of *Nereites* during the Palaeozoic is therefore questionable. In some cases the *Nereites* ichnofacies is used as an indicator of the deep-sea following the seminal work of Seilacher (1967). However, Uchman (2007) discussed examples within sedimentary rocks deposited very close to storm wave base, raising the possibility of at least some exceptions in the Palaeozoic fossil record.

The relationship between *Nereites* and microbial mats has not been previously explored in Palaeozoic records. Conversely, the relation between graphoglyptids and matgrounds has been examined (e.g., Buatois et al., 2009). This paper documents the ichnogenus *Nereites* with microbial mat structures (wrinkle marks and glossy surfaces) from the late Silurian—earliest Devonian Río Seco de los Castaños Formation (González Díaz, 1981) in the San Rafael Block, in western Argentina.

2. Geological setting

2.1. Tectonic framework

The mid-Palaeozoic successions of central-western Argentina include a plethora of folded, faulted and discontinuously outcropping units. These are part of the San Rafael Block and other blocks included in the Cuyania terrane (Fig. 1a) that collided with the western proto-Andean margin of Gondwana in the Late Ordovician (Thomas and Astini, 2003). Cuyania was intensely deformed from the west during the collision of the Chilenia terrane (Ramos et al., 1986) in the Late Devonian–Mississippian. The units underlying the resulting unconformity usually present a variable grade of metamorphism while the post-collisional units (Mississippian and younger units) are unmetamorphosed. During the time spanning the Cuyania and Chilenia collisions (Late Ordovician–Mississippian), a foreland basin developed and was filled, in some stratigraphic intervals, with thick turbidite-like deposits.

The San Rafael Block is a morphostructural unit that includes a varied Palaeozoic record that is well exposed in Atuel Canyon. The succession there begins with intensely deformed volcanic and metasedimentary units ranging in age from Ordovician to late Silurian—earliest Devonian (Cingolani et al., 2003, 2014; Manassero et al., 2009). These are unconformably overlain by a gently folded Pennsylvanian–Cisuralian succession, volcanic units (Choiyoi volcanism), Triassic sedimentary rift basin deposits (Kleiman and Japas, 2009) and finally Miocene and Quaternary units, including lava flows.

2.2. The Río Seco de los Castaños Formation

Atuel Canyon exposes the stratotype of the Río Seco de los Castaños Formation (RSLC) of late Silurian—earliest Devonian age. This unit is a succession of flysch deposits more than 600 m in thickness, and is distinguishable from other similar units in the region by its very low grade of metamorphism (González Díaz, 1981).

The age of the unit has been approximated using detrital zircons, dating of an intrusion, and by fossil remains. Detrital zircon studies constrain the age of the rocks and trace fossils to the Ludlow–Lochkovian (Cingolani et al., 2013, 2014). Near Atuel Canyon the RSLC Formation is intruded by a tonalite body dated through Sensitive High Resolution Ion Microprobe (SHRIMP) as of Lower Devonian (Emsian) age by Cingolani et al. (2003). Fossil remains (palynomorphs, plant and coral remains) indicate a late Silurian–Lower Devonian age for the unit (see Manassero et al., 2009).

In a regional study, Manassero et al. (2009) recorded gravity flow deposits to the west and storm deposits to the east; these are organised into coarsening-upward and heterolithic intervals. Based on the stacking pattern, the facies trend, charcoal abundance, and plant remains, they interpreted them as the record of a deltaic system.

Pazos et al. (2015) described turbidite-like deposits with convolute lamination and asymmetrical climbing ripples, and also documented wrinkle marks that provide evidence of patchy microbial mats on bedding planes (Pazos et al., 2015, fig. 2b, and this paper). They interpreted the turbidite-like units as storm deposits that were emplaced below normal storm wave base, concluding that they, in combination with wrinkle marks, indicate deposition on the outer shelf.

Ichnologically, the unit has received little study, but Manassero et al. (2009) mentioned the *Cruziana* ichnofacies (following Poiré et al., 2002) from the basin margin and the *Nereites*–*Mermia* ichnofacies (sic Manassero et al., 2009, page 234) for the trace fossils documented in locality 2 of this paper. Recently, Pazos et al. (2015) studied the ichnogenus *Dictyodora* Weiss, 1884 in Atuel Canyon and also mentioned the ichnogenus *Nereites*.

3. Methodology

Special attention was given to precise location of sampled sections in order to allow the comparison with previous work (e.g. Manassero et al., 2009). Locality 1 coincides with the outcrops recently revisited by Pazos et al. (2015) where *Dictyodora* was studied in detail. It is situated between Nihuil dams 1 and 2 along the Atuel River in Atuel Canyon (GPS coordinates: 34°57.529′ S and 68°36. 623′ W). Locality 2 is represented by a series of exposures on Road 144 (Fig. 1b), approximately at kilometre 703. The intense faulting precludes any accurate correlation at the same locality or between them for an integrated logged section, even over short distances. Localities 1 to 4 of Manassero et al. (2009) were numbered from distal to proximal deposits. In this paper, localities 3 and 4 (proximal settings) were not studied; locality 1 of Manassero