N. Jb. Geol. Paläont. Abh. 277/2 (2015), 177–188
Stuttgart, August 2015

Article

Ichnological research in Lower Cretaceous marginal-marine facies from Patagonia: outcrop studies, SEM examinations and paleontological/sedimentological integration

Diana Elizabeth Fernández and Pablo José Pazos

With 6 figures

Abstract: In-depth ichnological studies of Lower Cretaceous, marginal-marine facies from the Agrio Formation (Patagonia, Argentina) have been carried out during the past few years. Several ichnofossils were identified and described for the first time in this unit, including a new ichnospecies (*Hillichnus agrioensis*) produced by tellinid bivalves, xiphosurid trackways (the first record from the Early Cretaceous worldwide) and dinosaur tracks (one of the few examples from Early Cretaceous carbonates in Gondwana). The sedimentological information showed the presence of marginal-marine intervals previously interpreted as open marine. The outcrop studies resulted in the finding of indirect evidence of microbial mats, while SEM examinations resulted in the direct evidence of their presence in certain levels; this has taphonomical implications. Both ichnological and sedimentological results allowed to challenge previous facies model belts that suggested permanent submerged littoral facies for this part of the basin during the Early Cretaceous. The inferred paleoenvironment for the top of the unit is shallower and more tidally-influenced than previously thought.

Key words: Agrio Formation, Patagonia, Trace Fossils, Ichnology, Lower Cretaceous, Xiphosurid Trackways, Dinosaur Tracks, MISS, SEM, Marginal Marine

1. Introduction

Trace fossil assemblages are particularly useful when studying marginal-marine paleoenvironments, given the high variations in sedimentological parameters and the complex facies organization found in these depositional settings. Abundant trace fossils occur in the normal marine Mesozoic successions of the Neuquén Basin (e.g., Lazo et al. 2005; Ballent et al. 2006; Bressan & Palma 2009; Kietzmann & Palma 2010; Kietzmann et al. 2010). Only a handful of studies refer to marginal marine environments (e.g., McIlroy et al. 2005; Schwarz et al. 2006; Rodríguez et al. 2007), but these are lacking detailed systematic analyses. During the past few years, the first in-depth ichnological studies of Lower Cretaceous, marginal-marine facies from the Agrio Formation (Neuquén Basin, Northern Patagonia, Argentina) have been carried out (e.g., Fernández et al. 2010; Pazos & Fernández 2010; Fernández & Pazos 2012a; Pazos et al. 2012). The aim of this work is to summarize these recent findings and to provide information about a case study in which integration between outcrop analyses, including sedimentological and ichnological data, and microscopical examination has produced innovative results for the area.

2. Geological setting and study area

The study area is located in the center of the Neuquén Province. The results summarized here correspond to

www.schweizerbart.de
DOI: 10.1127/njgpa/2015/0500
0077-7749/2015/0500 $ 3.00

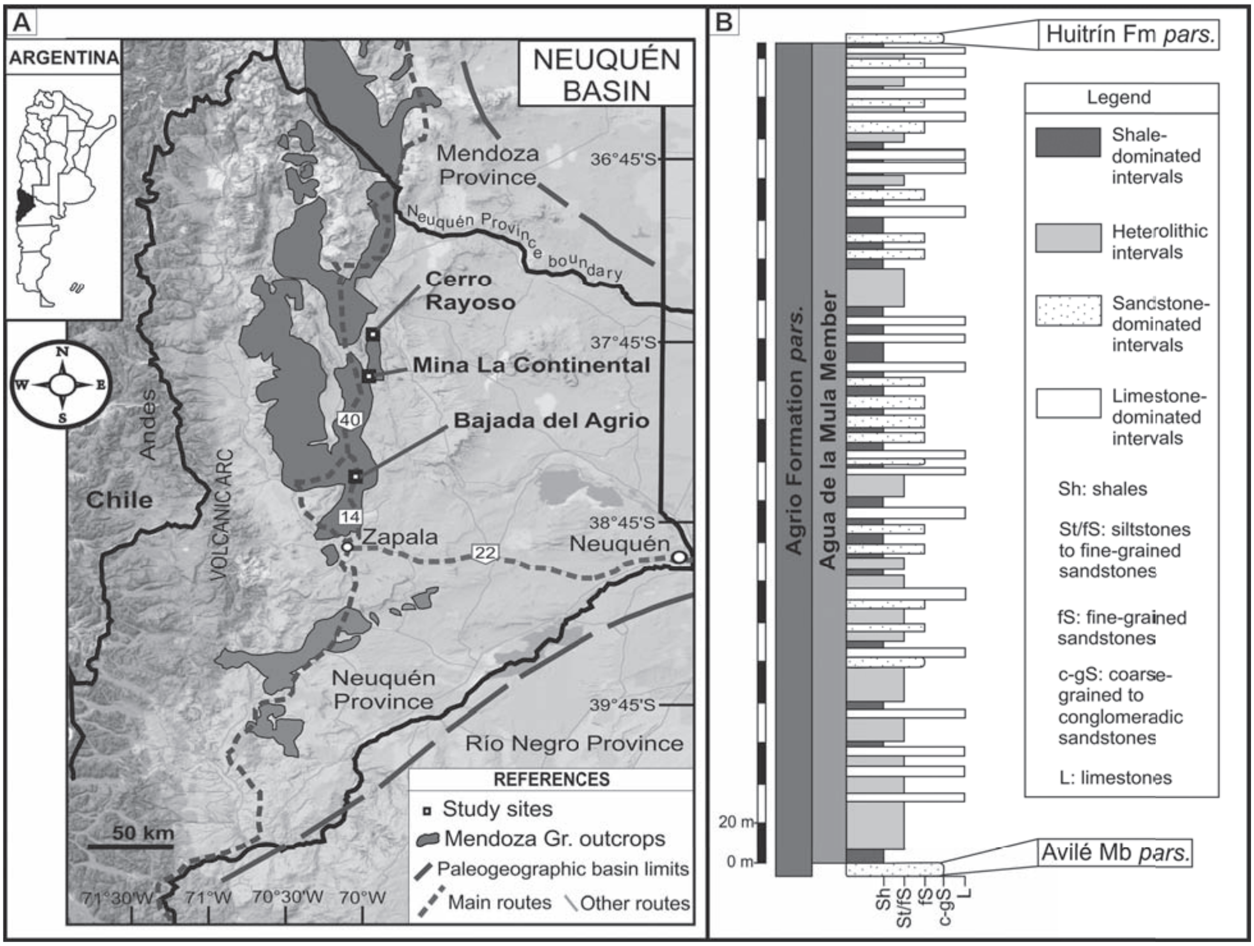

Fig. 1. Neuquén Basin, Mendoza Group and the Agua de la Mula Member. **A.** Map of the Neuquén Basin and its location in Argentina. Note the location of the Mendoza Group outcrops and the studied localities. **B.** Idealized stratigraphic column of the Agua de la Mula Member (Agrio Formation, Mendoza Group).

findings from localities along the north-south directed National Route 40 (Fig. 1A), particularly Bajada del Agrio (Agrio Formation's type locality; 38°25' S, 70°00' W), Cerro Rayoso (37°44-45' S, 69°55-56' W) and Mina La Continental (37°51' S, 69°59' W). The Neuquén Basin (Fig. 1A) is located in west-central Argentina (northern Patagonia) between 34° and 41°S. The basin contains more than 7000 m of marine and continental deposits of Late Triassic to Paleogene age (Vergani et al. 1995; Legarreta & Uliana 1999). This succession was deposited in three tectonic stages (Vergani et al. 1995; Ramos & Folguera 2005): the Late Triassic-Early Jurassic synrift stage, the Early Jurassic-Early Cretaceous postrift stage, and the Late Cretaceous-Cenozoic foreland basin stage. Most of the Jurassic and Early Cretaceous deposits are composed of diverse, highly fossiliferous marine facies associated with transgressions from the Pacific Ocean (Howell et al. 2005). This basin is also the most important hydrocarbon-producing area in southern South America (Howell et al. 2005).

The Agrio Formation (Weaver 1931) is the last unit of a mainly marine interval within the Mendoza Group. The Upper Member, or Agua de la Mula Member (Leanza et al. 2001) of the Agrio Formation is a Late Hauterivian-Early Barremian (Aguirre-Urreta et al. 2007, 2008) unit (Fig. 1B). During the Early Cretaceous, the Neuquén Basin was connected to the Pacific Ocean through an island arc chain to west (Fig. 2), and was affected by eustatic sea-level variations (Zapata & Folguera 2005). The Agua de la Mula Member is a mixed carbonate–siliciclastic unit which contains a remarkable cyclicity; in a sequence stratigraphic framework, the lower sequences are

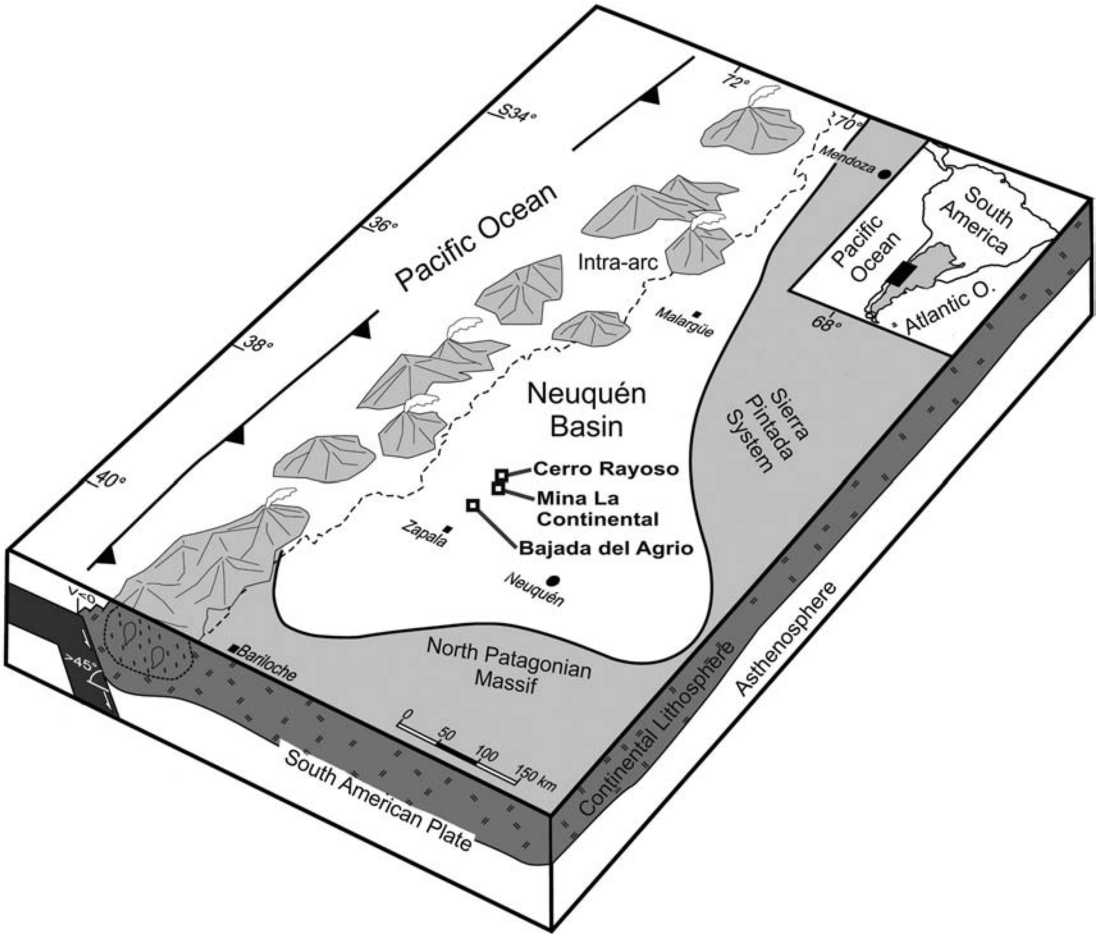

Fig. 2. The Neuquén Basin during the Early Cretaceous and approximate position of the studied localities. Modified from SCHWARZ et al. (2006). The changes which are consequence of the latest findings (see section 6.3) were not introduced here.

dominantly siliciclastic, and the upper one is mainly carbonatic (ARCHUBY & FÜRSICH 2010). In the latest sequence stratigraphy study performed in Bajada del Agrio four sequences are defined (GULER et al. 2013).

3. Material and methods

Along with the sedimentological work on this unit, in these recent analyses (PAZOS & FERNÁNDEZ 2010; PAZOS et al. 2012; FERNÁNDEZ & PAZOS 2013) the focus was on the study of trace fossils. The logged sections were analysed in detail and facies analysis was carried out. Emphasis was made on the uppermost part of the unit (sequence 4 *sensu* GULER et al. 2013). The scale of the studies ranges from outcrop studies up to SEM examinations. Rock samples were taken for microscopical analysis; this included petrographic studies of thin-sections and vertical sections analysed under scanning electron microscopes. For further information on the SEM analyses methodology see TUNIK et al. (2009), PAZOS et al. (2012) and FERNÁNDEZ & PAZOS (2013).

Whenever possible, representative hand samples of the trace fossils were taken and stored in the collection of the Área de Paleontología, Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires (CPBA).

4. Paleontological and paleoenvironmental background

The Agua de la Mula Member of the Agrio Formation is a mixed carbonate-siliciclastic marine unit (SPALLETTI et al. 2001a), traditionally interpreted as an open marine ramp (SPALLETTI et al. 2001b; BALLENT et al. 2006). In the central and northern areas of the Neuquén Province, LAZO et al. (2005) interpreted the unit as consisting of shoreface and inner to middle-outer shelf deposits. Studies based on gastropods, serpulids and bryozoans indicate that salinity fluctuations may have taken place during the deposition of the top of this member (Taylor et al. 2009).

In Bajada del Agrio in particular, Brinkmann (1994) considered the basal deposits as prodeltaic and found evidence of subaerial exposure at the top of the unit. Spalletti et al. (2001b) described this unit as representative of an open marine ramp, with shallow subtidal to proximal offshore sub-environments influenced by fair weather and storm waves. Pazos & Cirigliano (2006) documented tidal-flat deposits. Lazo et al. (2008) reported mainly euhaline conditions (salinity range of 30-40‰) for Bajada del Agrio (and other localities not included here), and hyperhaline conditions (over 40‰) towards the top of the unit. Micropaleontologic studies in the area (Concheyro et al. 2009) indicated hypo- to hypersalinity for most levels; the lowermost deposits present evidence of oxygen restriction, while the uppermost ones show the establishment of shelf conditions with small coast-line oscillations and eventual variations in oxygen content in the sediment-water interface. Archuby et al. (2011) described this member as open marine ramp deposits, without indications of departures from normal salinity, and with high nutrient levels and a relatively good oxygen content (only lowered at some periods).

The fauna of the Agua de la Mula Member is varied and abundant. Body fossils include bivalves, corals, ammonoids, gastropods, bryozoans, serpulids, sponges, echinoids, decapods, foraminifera and ostracods (e.g., Aguirre-Urreta & Rawson 1997; Cichowolski 2003; Lazo 2005; Lazo et al. 2005; Ballent et al. 2006; Rodríguez 2007; Taylor et al. 2009; Aguirre-Urreta et al. 2011; Cataldo 2013; Luci et al. 2013).

5. Current sedimentological developments

The sedimentological information gathered recently (see Fig. 3 for examples) allowed to highlight the presence of marginal-marine intervals previously interpreted as open marine. In Mina La Continental, Tunik et al. (2009) and Pazos & Fernández (2010) recorded evidence of a very shallow marine, mixed carbonate-siliciclastic setting with subtidal to supratidal conditions and mixture of marine and meteoric waters and phreatic diagenesis. For Cerro Rayoso, Pazos et al. (2012) have recently reported marginal-marine facies and provided a thorough discussion of paleoenvironmental conditions that confirm a tidal domination instead of storms as the previous interpretation of the upper unit of the Mendoza Group. In Bajada del Agrio, hyperpycnal flow and meandering channel deposits are found. Heterolithic deposits (Fig. 3A), particularly inclined heterolithic stratification (Fig. 3C) and flat-topped ripples (Fig. 3B) are present in open tidal-flat facies. The presence of miliolids in the open to restricted tidal-flat deposits indicates fluctuating salinity and/or hypersalinity conditions (Fernández & Pazos 2012a).

As a whole, the sedimentological datasets indicate this marine depositional setting was tidally influenced. This is suggested, for instance, by the presence of bipolar sedimentary and reactivation surfaces. It also underwent variations in exposure and energy (Tunik et al. 2009; Pazos & Fernández 2010; Pazos et al. 2012; Fernández & Pazos 2012a, 2013).

6. Trace fossils

6.1. Ichnotaxonomy and ichnodiversity

In the last years, several ichnotaxa have been identified and described for the first time in this unit. A new ichnospecies, *Hillichnus agrioensis* Pazos & Fernández, 2010, was described (Fig. 4A). It is a compound trace fossil (an ichnofossil which arises from a behavioral change of a single producer, *sensu* Pickerill 1994) produced by bivalves, a complex trace fossil that required a three-dimensional reconstruction (Pazos & Fernández 2010). Another kind of bivalve compound trace fossil, *Protovirgularia* cf. *dichotoma* intergrading with *Protovirgularia* cf. *rugosa* (Fig. 4B) was reported for the first time (Fernández et al. 2010).

Some other ichnotaxa are: *Asteriacites* cf. *quinquefolius* (Quenstedt, 1876), *Chondrites*? *intricatus* (Brongniart, 1823) (Fig. 4C), *Gyrochorte comosa* Heer, 1865, *Lockeia siliquaria* James, 1879, *Ophiomorpha nodosa* Lundgren, 1891, *Nereites* Macleay, 1839 (*in* Murchison 1839), *Palaeophycus tubularis* Hall, 1847, *Rosselia socialis* Dahmer, 1937, *Skolithos verticalis* (Hall, 1843), *Teichichnus rectus* Seilacher, 1955, *Thalassinoides suevicus* Rieth, 1932, *Trypanites* Mägdefrau, 1932. Arthropod trackways, tetrapod swimming traces (Fig. 4D) and invertebrate trails have also been described (Fernández & Pazos 2012a, b).

Particularly interesting are the findings of xiphosurid (horseshoe crab) trackways (Fig. 5A-B) in

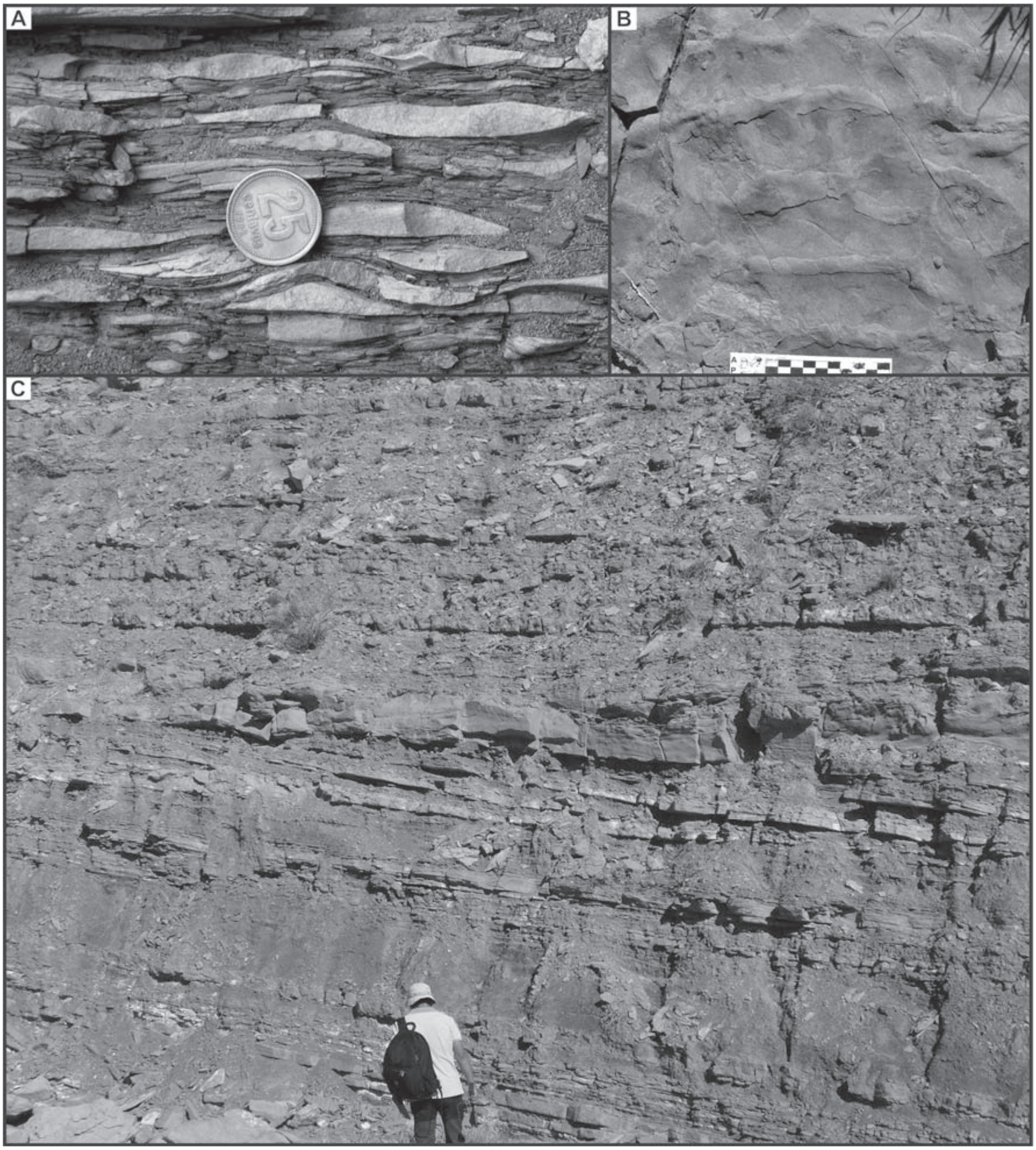

Fig. 3. Examples of sedimentary features that indicate marginal marine conditions in the Agua de la Mula Member in Bajada del Agrio. **A.** Heterolithic deposits in restricted tidal-flat facies. Coin diameter for scale: 23 mm. **B.** Flat-topped ripples in tidally-influenced lower foreshore deposits. The ruler is in cm increments. **C.** Inclined heterolithic stratification (IHS) in open tidal-flat deposits

Cerro Rayoso (Fernández & Pazos, 2013) and dinosaur tracks (Fig. 5C-D) in Cerro Rayoso and Mina La Continental (Pazos et al. 2012). The xiphosurid trackways were assigned to *Kouphichnium* Nopcsa, 1923. The appendages of xiphosurids are morphologically distinctive and therefore are able to leave very characteristic tracks. The first four pairs of legs can leave V-shaped, bifid or more simple linear to semicircular tracks, while the pusher legs may leave any of these morphologies as well as trifid or birdfoot-like tracks. The opisthosoma (posterior tagma) bears a telson, which is a long pointed structure that, while

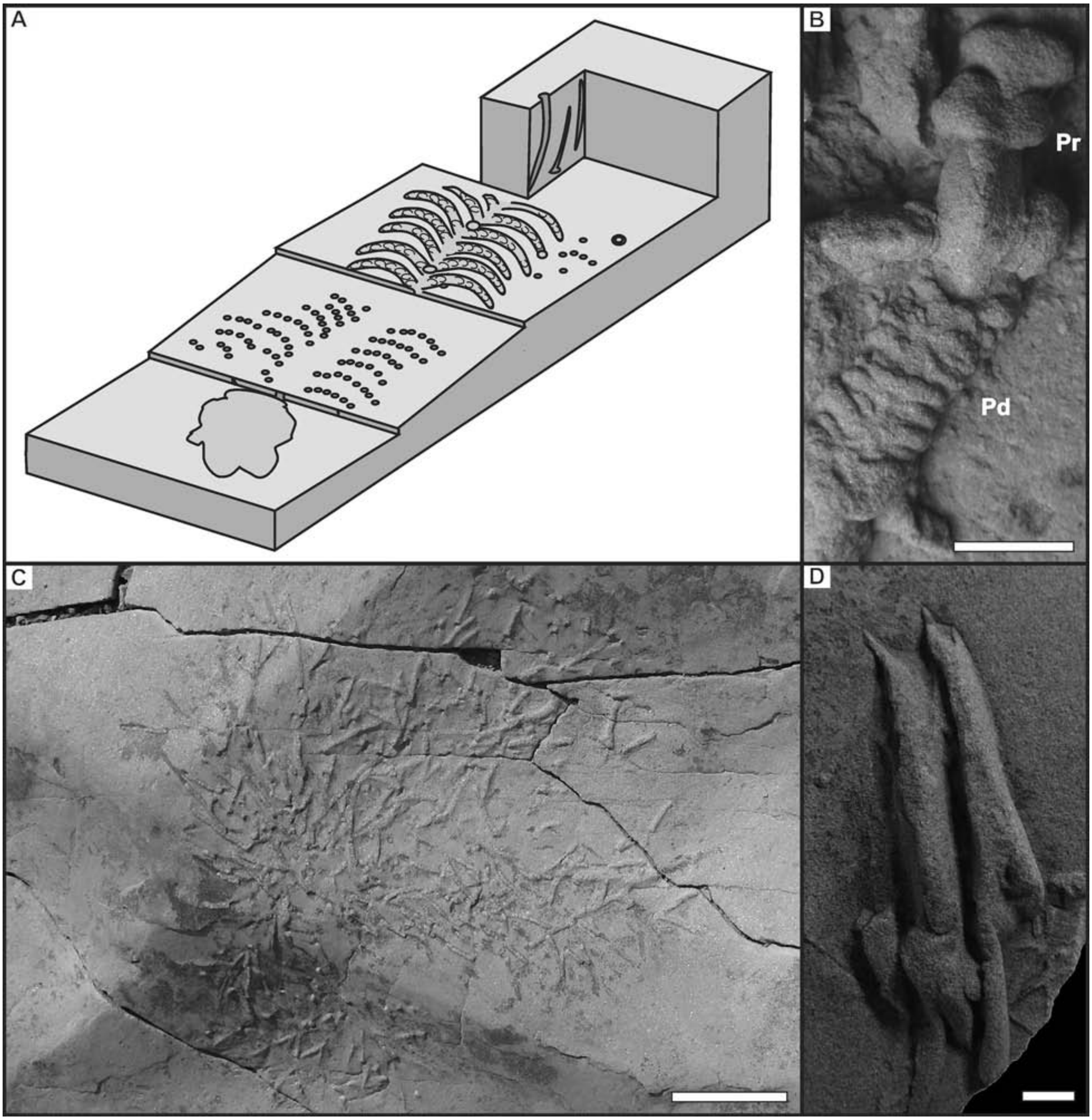

Fig. 4. Ichnofossils found in the Agua de la Mula Member. **A.** Reconstruction of *Hillichnus agrioensis* with the four levels in which different behaviours are recorded. Modified from Pazos & Fernández (2010). **B.** Compound trace fossil containing *Protovirgularia* cf. *dichotoma* (Pd; CPBA 20431) intergrading with *Protovirgularia* cf. *rugosa* (Pr; CPBA 20432). Scale bar: 1 cm. See Fernández et al. (2010). **C.** *Chondrites* ?*intricatus* in heterolithic deposits, Bajada del Agrio. Scale bar: 2 cm. **D.** Tetrapod swimming trace (CPBA 20438). See Fernández & Pazos (2012).

rigid throughout its length, is highly mobile (Caster 1938; Ruppert & Barnes 1994). The tridactyl dinosaur tracks were assigned to cf. *Therangospodus pandemicus* Lockley et al., 1998; they were produced by medium-sized non-avian theropods.

6.2. Trace fossil taphonomy and ichnological/sedimentological integration

The term “microbially induced sedimentary structures” (MISS; Noffke et al. 1996) refers to microbial

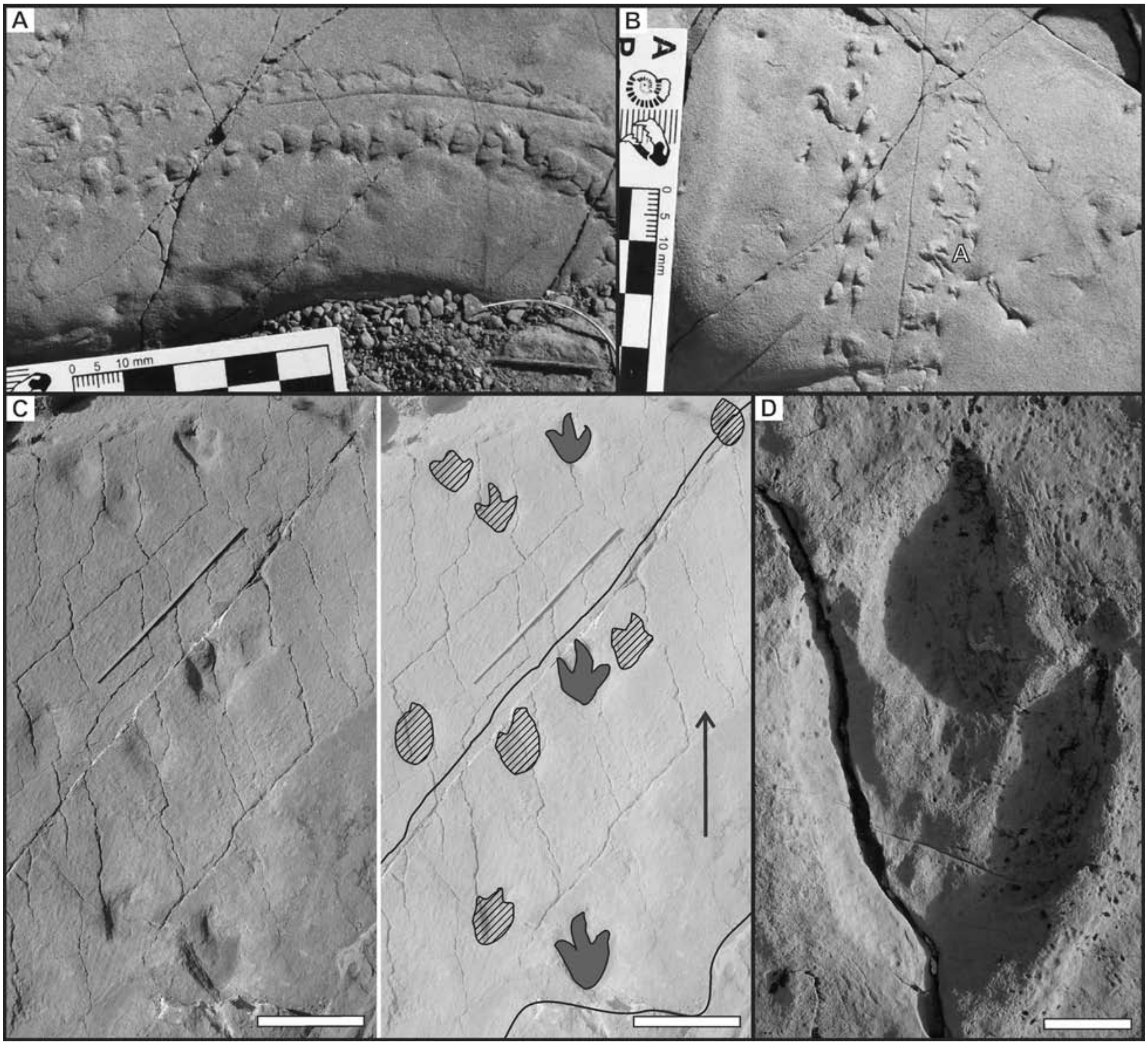

Fig. 5. Xiphosurid trackways and dinosaur tracks found in the Agua de la Mula Member. See Pazos et al. (2012) and Fernández & Pazos (2013). Scale bars: 1 m in C, 5 cm in D. The ruler is in cm increments. **A.** Trackway where the typical push-back pile and anterior drag piles of xiphosurid trackways are present. **B.** Xiphosurid trackway running perpendicular to a ripple crest. Note the shallow pusher-leg undertracks with anterior drag piles (A). Also, the bifid, trifid and other more irregular marks, the particular markings of the pusher leg left when it stretched out forward and posteriorly and the telson marking (medium drag mark). **C.** Dinosaur track-bearing surface at Mina La Continental. Field photograph and interpretative line sketch. Stripped lines indicate the footprints that are superimposed by ripples. **D.** Tridactyl dinosaur footprint (detail of C).

traces in sandy deposits, the counterpart to stromatolites that occur in carbonate settings. However, MISS do not resemble stromatolites (Noffke 2010). They present varied morphologies, and occur in modern sediments as well as in fossil sedimentary environments (e.g., Mata & Bottjer, 2009). Their presence, and therefore the presence of microbial mats, have been found in deposits of Phanerozoic, Proterozoic, and Archean ages (Noffke et al. 2008 and references therein).

Microbially induced sedimentary structures are common in the Agrio Formation. The presence of wrinkle structures (a type of MISS) on certain siliciclastic levels, indicates the involvement of microbial

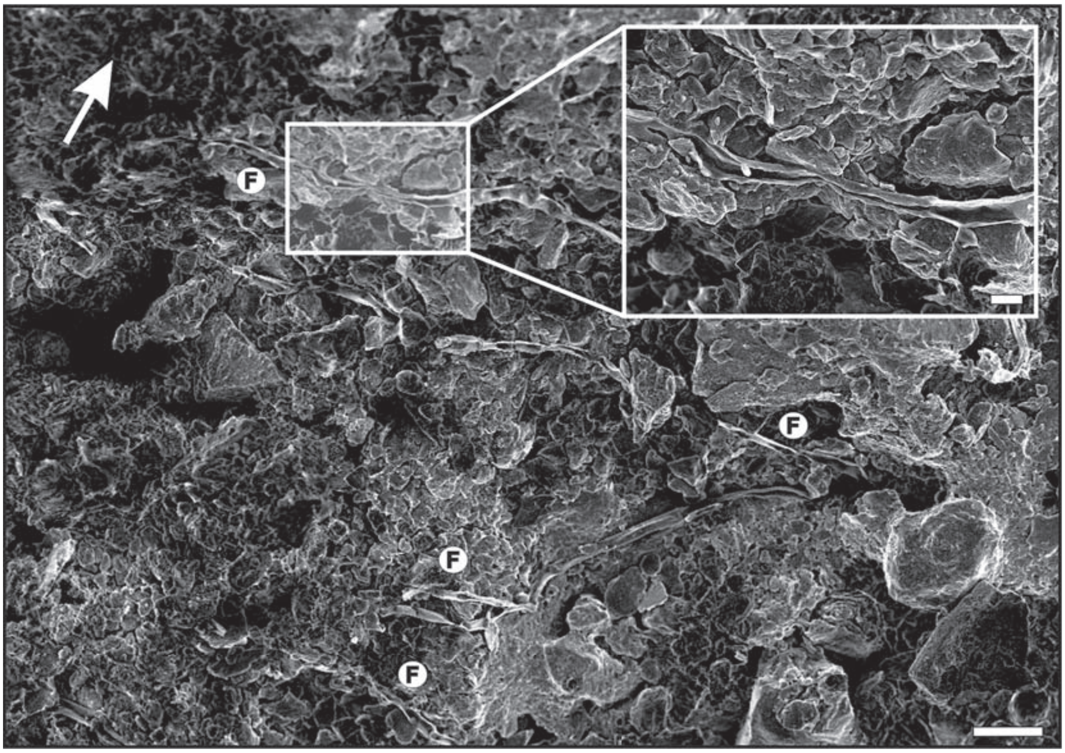

Fig. 6. SEM photograph of fragment of the uppermost part of the surface studied in FERNÁNDEZ & PAZOS (2013). Filament-like forms (F) parallel to the bedding plane and detail showing a filament sheath. Scale bars: 10 µ and 2 µ, respectively. The arrow points to and is perpendicular to the bedding plane.

mats (HAGADORN & BOTTJER 1997) in this unit. Fragments of a particularly interesting surface, bearer of extremely well-preserved xiphosurid (horseshoe crab) trackways and also wrinkle structures in some particular areas, were photographed under a scanning electron microscope (FERNÁNDEZ & PAZOS 2013). The results showed filament-like microstructures present between the sand particles of the uppermost few millimeters of the surface. Most are oriented parallel to the surface and are laterally continuous (Fig. 6), and some are perpendicular to the bedding plane. They were identified as filament sheaths of bacteria or cyanobacteria such as those from ancient tidal flats described in the literature (NOFFKE 2010). Ensheathed forms are one of the most common morphotypes of benthic cyanobacteria involved in mat and biofilm formation (GERDES et al. 2000). Energy-Dispersive X-Ray Spectroscopy analyses (EDS analyses) performed show that the filament sheaths are mainly composed of carbon (C = 50.51%).

In summary, the outcrop studies resulted in the finding of indirect evidence of microbial mats, such as wrinkle structures, together with the preservation of trace fossils. SEM examinations resulted in direct evidence of endobenthic microbial mats. The trace fossils were apparently preserved through the binding and biostabilization, which counteracted erosion (NOFFKE 2010) and induced early cementation (CARMONA et al. 2012 and references therein). In ancient tidal flats, SEM analyses were little conducted, and most studies focus on thin-section analysis.

6.3. Paleoecological and paleogeographic implications

The ichnological interpretations enhanced the recorded paleodiversity for the unit; some inhabitants had not been documented through body fossils. For example, deposit-feeding tellinid and palaeotaxodont (Protobranchia) bivalves (PAZOS & FERNÁNDEZ 2010;

Fernández et al. 2010), asteroids (Fernández et al. 2013) and small unidentified tetrapods (Fernández & Pazos 2012) amongst other organisms.

The local biota, mainly infaunal/epifaunal invertebrates, were not necessarily the only tracemakers in these shallow marine environments. Motile organisms, whether due to seasonal migrations, reproductive cycles or other factors (e.g., climatic one), may have been visitors instead of permanent inhabitants. This is the case of the finding and description of the xiphosurid trackways and dinosaur tracks (Fig. 5); none of their producers had been recorded through body-fossil remains.

Xiphosurids, most likely of the subfamily Limulinae, seem to have used these Lower Cretaceous shallow marine settings of the Neuquén Basin as high-tide mating grounds (Fernández & Pazos 2013). This information was inferred through an actualistic approach. Modern horseshoe crabs only come ashore to beaches and tidal flats at the new and full moon high tides during the mating season in spring and summer (e.g., Caster 1938; Brockmann 1990).

For the first time, an Early Cretaceous record of the presence of non-avian theropod dinosaurs in the Neuquén Basin was found (Pazos et al. 2012). This precedes by dozens of million years the body-fossil record of non-avian dinosaurs in the area, and they constitute one of the scarce undisputable Early Cretaceous non-avian theropod tracks, particularly in Gondwanan carbonates and worldwide. This clearly challenges previous facies model belts that suggested permanently submerged littoral facies for this part of the basin during the Early Cretaceous.

7. Conclusions

The ichnological and sedimentological characteristics of the Agua de la Mula Member show that:

– the ichnodiversity is greater than shown by previous works. This has consequences on the paleodiversity and ethological information for the unit. Regardless, the ichnotaxonomical analysis is far from over. Much more material is currently under study;

– microbial mats enhance the preservation of certain traces;

– for ancient tidal flat deposits bearing MISS, most studies focus on thin-section observation with petrologic microscopes. We believe that, even though this last technique is useful, examinations under SEM are also informative, and can complement or sometimes replace such analyses if, for instance, EDS analyses are also part of the objectives. This is an example of the strenght of sedimentological-ichnological data integration;

– the inferred paleoenvironment for the top of the unit is shallower and more tidally-influenced than previously thought;

– sedimentological-ichnological data integration is key for paleocoastline reconstructions. Its results can be applied in the oil industry as a paleobathymetric control.

Acknowledgements

We are very grateful to Alfred Uchman and Francisco Javier Rodríguez-Tovar for their comments. We would also like to thank the Organizers of the 23rd Latin American Colloquium (LAK 2014), particularly Christina Ifrim. This study was financially supported by ANCyT (PICT-189) and CONICET (PIP 5960) to M. Beatriz Aguirre-Urreta, UBACyT to Pablo J. Pazos, and by the Bunge and Born Foundation through a grant given to Diana E. Fernández. This is contribution R-124 of the Instituto de Estudios Andinos Don Pablo Groeber.

References

Aguirre-Urreta, M.B., Mourgues, F.A., Rawson, P.F., Bulot, L.G. & Jaillard, E. (2007): The Lower Cretaceous Chañarcillo and Neuquén Andean basins: ammonoid biostratigraphy and correlations. – Geological Journal, **42**: 143-173.

Aguirre-Urreta, M.B., Pazos, P.J., Lazo, D.G., Fanning, C.M. & Litvak, V.D. (2008): First U–Pb SHRIMP age of the Hauterivian stage, Neuquén Basin, Argentina. – Journal of South American Earth Sciences, **26**: 91-99.

Aguirre-Urreta, M.B. & Rawson, P.F. (1997): The ammonite sequence in the Agrio Formation (Lower Cretaceous), Neuquén Basin, Argentina. – Geological Magazine, **134**: 449-458.

Aguirre-Urreta, M.B., Lazo, D.G., Griffin, M., Vennari, V., Parras, A.M., Cataldo, C., Garberoglio, R. & Luci, L. (2011): Megainvertebrados del Cretácico y su importancia bioestratigráfica. – In: Leanza, H.A., Arregui, C., Carbone, O., Danieli, J.C. & Vallés J.M. (Eds.): Relatorio del XVIII Congreso Geológico Argentino, Geología y Recursos Naturales de la Provincia del Neuquén, 465-488; Neuquén.

Archuby, F. & Fürsich, F. (2010): Facies analysis of a highly ciclic sedimentary unit: the Late Hauterivian to Early Barremian Agua de la Mula member of the Agrio Formation, Neuquén Basin, Argentina. – Beringeria, **4**: 1-54.

Archuby, F.M., Wilmsen, M. & Leanza, H. (2011): Integrated stratigraphy of the Upper Hauterivian to Lower

Barremian Agua de la Mula Member of the Agrio Formation, Neuquén Basin, Argentina. – Acta Geologica Polonica, **61**: 1-26.
Ballent, S., Concheyro, A. & Sagasti, G. (2006): Bioestratigrafía y paleoambiente de la Formación Agrio (Cretácico Inferior), en la Provincia de Mendoza, Cuenca Neuquina, Argentina. – Revista Geológica de Chile, **33**: 47-79.
Bressan, G.S. & Palma, R.M. (2009): Trace fossils from the Lower-Middle Jurassic Bardas Blancas Formation, Neuquén Basin, Mendoza Province, Argentina. – Acta Geologica Polonica, **59**: 201-220.
Brinkmann, H.D. (1994): Facies and sequences of the Agrio Formation (Lower Cretaceous) in the central and southern Neuquén Basin, Argentina. – Zentralblatt für Geologie und Paläontologie, **1**: 309-317.
Brockmann, H.J. (1990): Mating behavior of horseshoe crabs, *Limulus polyphemus*. – Behaviour, **114**: 206-220.
Brongniart, A.T. (1823): Observations sur les Fucoïdes. – Mémoire de la Société d'Histoire Naturelle de Paris, **1**: 301-320.
Carmona, N.B., Ponce, J.J., Wetzel, A., Bournod, C.N. & Cuadrado, D.G. (2012): Microbially induced sedimentary structures in Neogene tidal flats from Argentina: Paleoenvironmental, stratigraphic and taphonomic implications. – Palaeogeography, Palaeoclimatology, Palaeoecology, **353-355**: 1-9.
Caster, K.E. (1938): A restudy of the tracks of *Paramphibius*. – Journal of Paleontology, **12**: 3-60.
Cataldo, C.S. (2013): A new Early Cretaceous nerineoid gastropod from Argentina and its palaeobiogeographic and palaeoecological implications. – Cretaceous Research, **40**: 51-60.
Cichowolski, M. (2003): The nautiloid genus *Cymatoceras* from the Cretaceous of the Neuquén and Austral basins, Argentina. – Cretaceous Research, **24**: 375-390.
Concheyro, A., Lescano, M., Caramés, A. & Ballent, S. (2009): Micropaleontología de la Formación Agrio (Cretácico Inferior) en distintos sectores de la cuenca Neuquina. – Revista de la Asociación Geológica Argentina, **65**: 342-361.
Fernández, D.E. & Pazos, P.J. (2012a): Ichnology of marginal marine facies of the Agrio Formation (Lower Cretaceous, Neuquén Basin, Argentina) in its type locality. Ameghiniana. – Ameghiniana, **49**: 505-524.
Fernández, D.E. & Pazos, P.J. (2012b): *Nereites*-like trace fossils in Lower Cretaceous marginal-marine environments from Patagonia: preservational variants and ichnotaxonomic discussion. – In: McIlroy, D., Callow, R., Dufour, S. & Herringshaw, L. (Eds.): The Third International Congress on Ichnology (ICHNIA), Abstracts, 33; Saint John's.
Fernández, D.E. & Pazos, P.J. (2013): Xiphosurid trackways in a Lower Cretaceous tidal flat in Patagonia: Palaeoecological implications and the involvement of microbial mats in trace-fossil preservation. – Palaeogeography, Palaeoclimatology, Palaeoecology, **375**: 16-29.
Fernández, D.E., Pazos, P.J. & Aguirre-Urreta, M.B. (2010): *Protovirgularia dichotoma – Protovirgularia rugosa*: an example of a compound trace fossil from the Cretaceous (Agrio Formation) of the Neuquén Basin, Argentina. – Ichnos, **17**: 40-47.
Fernández, D.E., Pazos, P.J., Pérez, D.E. & Luci, L. (2013): Asteroid trace fossils from a Lower Cretaceous shallow marine paleoenvironment in Patagonia: the first record of starfishes for the Agrio Formation. – In: Bedatou, E., Sostillo, R. & Varela, J.A. (Eds.): IIº Latin-American Symposium on Ichnology, Abstracts, 39; Santa Rosa.
Gerdes, G., Klenke, T. & Noffke, N. (2000): Microbial signatures in peritidal siliciclastic sediments: a catalogue. – Sedimentology, **47**: 279-308.
Guler, M.V., Lazo, D.G., Pazos, P.J., Borel, C.M., Ottone, E.G., Tyson, R.V., Cesaretti, N. & Aguirre-Urreta, M.B. (2013): Palynofacies analysis and palynology of the Agua de la Mula Member (Agrio Formation) in a sequence stratigraphy framework, Lower Cretaceous, Neuquén Basin, Argentina. – Cretaceous Research, **41**: 65-81.
Hagadorn, J.W. & Bottjer, D.J. (1997): Wrinkle structures: Microbially mediated sedimentary structures common in subtidal siliciclastic settings at the Proterozoic-Phanerozoic transition. – Geology, **25**: 1047-1050.
Hall, J. (1843): Geology of New York. Part 4. Survey of the Fourth Geological District. – 683 pp.; Albany (Carroll & Cook).
Heer, O. (1865): Die Urwelt der Schweiz. – 662 pp.; Zürich (Friedrich Schultheß).
Howell, J.A., Schwarz, E., Spalletti, L.A. & Veiga, G.D. (2005): The Neuquén Basin: An overview. – In: Veiga, G.D., Spalletti, L.A., Howell, J.A. & Schwarz, E. (Eds.): The Neuquén Basin, Argentina: A case study in sequence stratigraphy and basin dynamics. – Geological Society London, Special Publications, **252**, 1-14.
James, U.P. (1879): Description of new species of fossils and remarks on some others, from the Lower and Upper Silurian rocks of Ohio. – The Paleontologist, **3**: 17-24.
Kietzmann, D.A., Blau, J., Fernández, D.E. & Palma, R.M. (2010): Crustacean microcoprolites from the Upper Jurassic–Lower Cretaceous of the Neuquén Basin, Argentina: Systematics and biostratigraphic implications. – Acta Palaeontologica Polonica, **55**: 277-284.
Lazo, D.G. (2005): Análisis preliminar de las facies de corales del techo de la Formación Agrio, Cretácico Inferior de cuenca Neuquina. – Actas del XVI Congreso Geológico Argentino, **3**: 337-342.
Lazo, D.G., Aguirre-Urreta, M.B., Price, G., Rawson, P., Ruffell, A. & Ogle, N. (2008): Palaeosalinity variations in the Early Cretaceous of the Neuquén Basin Argentina: evidence from oxygen isotopes and palaeoecological analysis. – Palaeogeography, Palaeoclimatology, Palaeoecology, **260**: 477-493.
Lazo, D.G., Cichowolski, M., Rodríguez, D.L. & Aguirre-Urreta, M.B. (2005): Lithofacies, palaeoecology and palaeoenvironments of the Agrio Formation, Lower Cretaceous of the Neuquén Basin, Argentina. – In: Veiga, G.D., Spalletti, L.A., Howell, J.A. & Schwarz, E. (Eds.): The Neuquén Basin, Argentina: A case study in sequence stratigraphy and basin dynamics. – Geological Society London, Special Publications, **252**: 295-315.
Leanza, H.A., Hugo, C.A. & Repol, D. (2001): Hoja geológica 3969-I, Zapala, Provincia del Neuquén. Instituto de Geología y Recursos Minerales. Boletín 275. – 128

pp.; Buenos Aires (Servicio Geológico Minero Argentino).

Legarreta, L. & Uliana, M.A. (1999): El Jurásico y Cretácico de la Cordillera Principal y la Cuenca Neuquina. I, Facies sedimentarias. – In: Caminos, R. (Ed.): Geología Argentina, 399-416; Buenos Aires (SEGEMAR).

Lockley, M.G., Mayer, C.A. & Moratalla, J.J. (1998): *Therangospodus*: trackway evidence for the widespread distribution of a Late Jurassic theropod with well-padded feet. – Gaia, **15**: 339-353.

Luci, L., Garberoglio, R.M. & Lazo, D.G. (2013): Serpulids and other calcareous tube dwelling encrusting polychaetes from the Early Cretaceous Agrio Formation (Neuquén Basin, Argentina). – Geobios, **46**: 213-224.

Lundgren, B. (1891): Studier öfver fossilförande lösa block. – Geologiska Föreningen i Stockholm Förhandlinger, **13**: 111-121.

Mägdefrau, K. (1932): Über einige Bohrgänge aus dem unteren Muschelkalk von Jena. – Paläontologische Zeitschrift, **14**: 150-160.

Mata, S.A. & Bottjer, D.J. (2009): The paleoenvironmental distribution of Phanerozoic wrinkle structures. – Earth-Science Reviews, **96**: 181-195.

McIlroy, D., Flint, S., Howell, J.A. & Timms, N. (2005): Sedimentology of the tide-dominated Jurassic Lajas Formation, Neuquén Basin, Argentina. – In: Veiga, G.D., Spalletti, L.A., Howell, J.A. & Schwarz, E. (Eds.): The Neuquén Basin, Argentina: A case study in sequence stratigraphy and basin dynamics. – Geological Society London, Special Publications, **252**, 83-107.

MacLeay, W.S. (1839): Note on the Annelida. – In: Murchison, R.I. (Ed.): The Silurian System, part II, Organic Remains, 699-701; London (Murray).

Noffke, N. (2010): Geobiology: microbial mats in sandy deposits from the Archean era to today. – 194 pp.; Berlin (Springer-Verlag).

Noffke, N., Beukes, N., Bower, D., Hazen, R.M. & Swift, D.J.P. (2008): An actualistic perspective into Archean worlds – (cyano-)bacterially induced sedimentary structures in the siliciclastic Nhlazatse Section, 2.9 Pongola Supergroup, South Africa. – Geobiology, **6**: 5-20.

Noffke, N., Gerdes, G., Klenke, T. & Krumbein, W.E. (1996): Microbially induced sedimentary structures – examples from modern sediments of siliciclastic tidal flats. – Zentralblatt für Geologie und Paläontologie, **1**: 307-316.

Nopcsa, F. (1923): Die Familien der Reptilien. – Fortschritte der Geologie und Paläontologie, **2**: 1-210.

Pazos, P.J. & Cirigliano, R. (2006): La sección superior de la Formación Agrio en su localidad tipo. – In: 4° Congreso Latinoamericano de Sedimentología & 11° Reunión Argentina de Sedimentología, Resúmenes, 171; Bariloche.

Pazos, P.J. & Fernández, D.E. (2010): Three-dimensionally integrated trace-fossils from shallow marine deposits in the Lower Cretaceous of the Neuquén Basin: *Hillichnus agrioensis* isp. nov. – Acta Geologica Polonica, **60**: 105-118.

Pazos, P.J., Lazo, D.G., Tunik, M.A., Marsicano, C.A., Fernández, D.E. & Aguirre-Urreta, M.B. (2012): Paleoenvironmental framework of dinosaur tracksites and other ichnofossils in Early Cretaceous mixed siliciclastic-carbonate deposits in the Neuquén Basin, northern Patagonia (Argentina). – Gondwana Research, **22**: 1125-1140.

Pickerill, R.K. (1994): Nomenclature and taxonomy of invertebrate trace fossils. – In: Donovan, S.K. (Ed.): The Palaeobiology of Trace Fossils, 3-42; Chichester (John Wiley and Sons).

Quenstedt, F.A. (1876): Petrefaktenkunde Deutschlands. 4. Die Asteriden und Encriniden nebst Cysti und Blastoideen. – 742 pp.; Leipzig (Fuess).

Ramos, V.A. & Folguera, A. (2005): Tectonic evolution of the Andes of Neuquén: constraints derived from the magmatic arc and foreland deformation. – In: Veiga, G.D., Spalletti, L.A., Howell, J.A. & Schwarz, E. (Eds.): The Neuquén Basin, Argentina: A case study in sequence stratigraphy and basin dynamics. – Geological Society London, Special Publications, **252**: 15-35.

Rieth, A. (1932): Neue Funde spongeliomorpher Fucoiden aus dem Jura Schwabens. – Geologische und Paläontologische Abhandlungen, **19**: 257-294.

Rodríguez, D.L. (2007): Equinoideos mesozoicos de las cuencas andinas del centrooeste de Argentina. Tesis doctoral – 398 pp; Universidad de Buenos Aires (Unpublished thesis).

Rodríguez, D.L., Pazos, P.J. & Aguirre-Urreta, M.B. (2007): Cretaceous ophiuroid trace fossils from the Neuquén Basin. – In: Bromley, R.G., Buatois, L.A., Mángano, M.G., Genise, J.F. & Melchor, R.N. (Eds.): Ichnology at the crossroads: A Multidimensional Approach to the Science of Organism-Substrate Interactions. – Society for Sedimentary Geology, Special Publication, **88**: 7-105.

Schwarz, E., Spalletti, L.A. & Howell, J.A. (2006): Sedimentary response to a tectonically-induced sea-level fall in a shallow back-arc basin: the Mulichinco Formation (Lower Cretaceous), Neuquén Basin, Argentina. – Sedimentology, **53**: 55-81.

Seilacher, A. (1955): Spuren und Fazies im Unterkambrium. – In: Schindewolf, O.H. & Seilacher, A. (Eds.): Beiträge zur Kenntnis des Kambriums in der Salt Range (Pakistan). Abhandlungen der Akademie der Wissenschaften und der Literatur in Mainz, mathematisch-naturwissenschaftlichen Klasse, **103**: 117-143.

Spalletti, L.A., Poiré, D., Pirrie, D., Matheos, S. & Doyle, P. (2001a): Respuesta sedimentológica a cambios en el nivel de base en una secuencia mixta clástica-carbonática del Cretácico de la cuenca Neuquina, Argentina. – Revista de la Sociedad Geológica de España, **14**: 57-74.

Spalletti, L.A., Poiré, D.G., Schwarz, E. & Veiga, G.D. (2001b): Sedimentologic and sequence stratigraphic model of a Neocomian marine carbonate-siliciclastic ramp: Neuquén basin, Argentina. – Journal of South American Earth Sciences, **14**: 609-624.

Taylor, P.D, Lazo, D.G. & Aguirre-Urreta, M.B. (2009): Lower Cretaceous bryozoans from Argentina: a ‘by-catch’ fauna from the Agrio Formation (Neuquén Basin). – Cretaceous Research, **30**: 193-203.

Tunik, M.A., Pazos, P.J., Impiccini, A., Lazo, D. & Aguirre-Urreta, M.B. (2009.): Dolomitized tidal cycles in the Agua de la Mula Member of the Agrio Formation (Early

Cretaceous), Neuquén Basin, Argentina. – Latin American Journal of Basin Analysis, **16**: 29-43.

Vergani, G.D., Tankard, A.J., Belotti, J. & Welsink, H.J. (1995): Tectonic evolution and paleogeography of the Neuquén Basin, Argentina. – In: Tankard, A.J., Suárez, R. & Welsink, H.J. (Eds.): Petroleum basins of South America. – American Association of Petroleum Geologists Memoir, **62**, 383-402.

Weaver, C.E. (1931): Paleontology of the Jurassic and Cretaceous of West Central Argentina. Memoir 1, 469 pp.; University of Washington.

Zapata, V.A. & Folguera, A. (2005): Tectonic evolution of the Andes of Neuquén: constraints derived from the magmatic arc and foreland deformation. – In: Veiga, G.D., Spalletti, L.A., Howell, J.A. & Schwarz, E. (Eds.): The Neuquén Basin, Argentina: A case study in sequence stratigraphy and basin dynamics. – Geological Society London, Special Publications, **252**: 37-56.

Manuscript received: March 25th, 2014.
Revised version accepted: January 7th, 2015.

Addresses of the authors:

Diana Elizabeth Fernández (corresponding author), Pablo José Pazos, IDEAN (CONICET-UBA), Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires. Intendente Güiraldes 2160, Pabellón 2, Ciudad Universitaria, Ciudad Autónoma de Buenos Aires, Argentina.
e-mail: elizabeth@gl.fcen.uba.ar; pazos@gl.fcen.uba.ar