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Paleontology, sedimentology and paleoenvironment of a new fossiliferous locality of the Jurassic Cañadón Asfalto Formation, Chubut Province, Argentina

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ABSTRACT

A new Late Jurassic assemblage of "conchostracans", ostracods, bivalves and caddisfly cases from the locality "Estancia La Sin Rumbo", Chubut Province (Patagonia, Argentina) is recorded. The fossils occur in the upper part of an outcropping 45 m thick volcaniclastic lacustrine sequence of yellowish tuffs and tuffites of the Puesto Almada Member, which is the upper member of the Cañadón Asfalto Formation with U/Pb age of 161 ± 3 Ma. The sequence represents one sedimentary cycle composed of a (lower) hemicycle of expansion and a (higher) hemicycle of contraction of the water body. The invertebrates lived in small freshwater bodies during the periods of expansion of the lake. The occurrence of a great number of small spinicaudatans, associated with mud-cracks, is evidence of dry climatic conditions and suggests several local mortality events. The spinicaudatan record of the fushunograptid–orthestheriid (component of the *Eosestheriopsis dianzhongensis* fauna) and the presence of *Congestheriella rauhuti* Gallego and Shen, suggest a Late Jurassic (Oxfordian to Tithonian) age. Caddisfly cases are recorded for the first time in the Cañadón Asfalto Basin.

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RESUMEN

Se presenta una nueva asociación de "conchostracos", ostrácodos, bivalvos y capullos de tricópteros del Jurásico Tardío de la localidad "Estancia La Sin Rumbo", provincia del Chubut (Patagonia, Argentina). Los fósiles se hallaron en la parte superior de una secuencia volcaniclástica lacustre de tobas y tufitas amarillas de 45 m de espesor, del Miembro Puesto Almada, que es el miembro superior de la Formación Cañadón Asfalto, con una edad radimétrica (U/Pb) de 161 ± 3 Ma. La secuencia representa un ciclo sedimentario compuesto de un hemiciclo (inferior) de expansión y un hemiciclo (superior) de contracción del cuerpo de agua. Los invertebrados mencionados vivieron en pequeños cuerpos de agua dulce durante los períodos de expansión del lago. La presencia de un gran número de pequeños "conchostracos", asociados con grietas de desecación, indica condiciones de clima seco y sugiere varios eventos locales de mortandad. El registro de "conchostracos" "fushunográptidos-orthoestheriidos" (componentes de la fauna de *Eosestheriopsis dianzhongensis*) y la presencia de *Congestheriella rauhuti* Gallego y Shen, sugieren una edad jurásico tardío (Oxfordiano a Tithoniano). Capullos de tricópteros son registrados por primera vez en la Cuenca de Cañadón Asfalto.

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1. Introduction

Previous records of Jurassic invertebrates from Patagonia, Argentina (Tasch and Volkheimer, 1970; Vallatti, 1986) are from the lower section (Las Chacritas Member) of the Cañadón Asfalto Formation, at the classical localities situated south of the Cerro Cóndor village (Fig. 1). Gallego et al. (2010) described *Congestheriella rauhuti* Gallego and Shen, the first spinicaudatan from the upper section (Puesto Almada Member) of the same unit. Earlier records of Jurassic continental invertebrate faunas from Argentina are known only from two Patagonian areas (Deseado Massif: La Matilde Formation, and Extra-andean Chubut: Cañadón Asfalto Formation). Piatnitzky (1933, 1936), Feruglio (1949) and Frenguelli (1949) reported the first Jurassic invertebrates (as "*Estheria*" sp.) from Chubut and Santa Cruz provinces (for more data see Gallego, 1994). The first descriptions of spinicaudatans from the Cañadón Asfalto Formation are those of Tasch and Volkheimer (1970). At the moment, fourteen species of Jurassic spinicaudatans have been described, ten of them from the Cañadón Asfalto Formation (Tasch and Volkheimer, 1970; Vallatti, 1986; Gallego, 1994 and Gallego et al., 2010).

In 1994, one of us (WV) and Helga Smekal (Bariloche Paleontological Association) collected samples at the locality "Estancia La Sin Rumbo", near the Chubut provincial road N° 12 (km 88.7), 41 km north of Cerro Cóndor village (GPS 43° 16′ 49.2" S, 69° 07′ 45.3" W) (Fig. 1). These original samples include spinicaudatans, bivalve and gastropod mollusks, ostracods and rare trichopteran fossil cases. They are assigned to the Cañadón Asfalto Formation. Their exact stratigraphic provenance was unresolved until now. During December 2007 and March 2009, our research team carried out detailed collections and the study of the sedimentary sequence.

The first studies of the Cañadón Asfalto Formation of Extra-andean Patagonia in the middle Chubut river valley are those of Piatnitzky (1936), who named this sequence "Estratos con Estheria" (Beds with Estheria). Later on, Flores (1948) described it as "Sección Esquistosa de la Serie Porfírica" (Schistosy Section of the Porphyritic Series). Feruglio (1949) included it into the upper section of the Complex of Sierra de Olte, making up part of the "Chubutense". Frenguelli (1949) performed the first studies of the fossil flora of this unit, indicating a Callovian-Oxfordian age, by comparison with the Middle to Upper Jurassic La Matilde Formation. Stipanicic et al. (1968) defined it formally as the Cañadón Asfalto Formation and Nullo (1983) divided it into a lower and an upper section. Later Silva Nieto et al. (2003) divided the formation into the Las Chacritas and Puesto Almada members. Detailed stratigraphic descriptions were realized by Cabaleri et al. (2008b) and Cabaleri et al. (2010b). In earlier papers (Figari and Courtade, 1993; Rauhut, 2006) the Cañadón Calcáreo Formation (Proserpio, 1987) is correlated with the upper part of the Cañadón Asfalto Formation ("Estratos de Almada"; Musacchio, 1995, p. 180). New palynologic and radiometric data indicate a Late Jurassic age for the Puesto Almada Member and an Early Valanginian age for the middle section of the Cañadón Calcáreo Formation (Cabaleri et al., 2010b,c; Volkheimer et al., 2009). Homovc et al. (1991), Figari and García (1992), Figari and Courtade (1993), Figari et al. (1992, 1996) interpreted the tectosedimentary evolution of the Cañadón Asfalto Basin as different stages (youth and mature) of a half-graben basin. These authors distinguish four megasequences corresponding to different moments of the rift system. They include in the Megasequence II the Cañadón Asfalto Superior Formation, the Cañadón Calcáreo Formation and the "Estratos de Almada" with an age from Middle Kimmeridgian to Middle Hauterivian for Figari y Courtade (1993, p. 68) and Middle Kimmeridgian-Berriasian for Figari (2005, p. 39). Later, Silva Nieto et al. (2002a, b) published the geologic map of Cerro Cóndor and a genetic-structural analysis of the Cañadón Asfalto Formation, defining a pull-apart type basin for the area of Cerro Cóndor. Cabaleri and Armella (1999, 2005), and Cabaleri et al. (2005, 2006, 2008a, 2010a,b) and Silva Nieto et al. (2007) presented a detailed study of the Cañadón Asfalto Formation, its depocenters, paleoenvironments and paleoclimates. The important paleontologic record of the Cañadón Asfalto Formation was the object of important publications, including the analysis of the taphofloras (Stipanicic et al., 1968; Stipanicic and Bonetti, 1969; Cortés and Baldoni, 1984; Baldoni, 1990; Escapa et al., 2008). Assemblages of palynomorphs were studied by Volkheimer et al. (2008) and invertebrates by Tasch and Volkheimer (1970), Vallatti (1986), Gallego (1994), Genise et al. (2002), Gallego and Cabaleri (2005) and Gallego et al. (2010). Calcareous microfossils were studied by Musacchio et al. (1990) and Musacchio (1995). The vertebrate record of the Cañadón Asfalto Formation was recently reviewed by Volkheimer et al. (2008, p. 90).

The objectives of this paper are to communicate a new locality of paleontological and sedimentologic interest in the Cañadón Asfalto Basin (Puesto Almada Member of the Cañadón Asfalto Formation), with first records of insect (caddisfly) fossil cases, associated with spinicaudatans, ostracods and bivalve mollusks and to define the paleoenvironments during the silting of the Cerro Cóndor Depocenter and characterize the border of the paleolake.

2. Geologic setting

In Extraandean Chubut, several depocenters have been described for the Cañadón Asfalto Basin (Cabaleri et al., 2006; Silva Nieto et al., 2007) and interpreted as pull-apart type basins. The sequences representing the fillings of these depocenters consist of lacustrine limestones (Cabaleri and Armella, 1999), associated with pyroclastic deposits and basaltic rocks of the Las Chacritas Member (Silva Nieto et al., 2003; Cabaleri et al., 2008a,b; 2010a,b). The silting of the depocenters is principally represented by tuffs, intercalated with laminated rhythmites, pelites and sandstones of the Puesto Almada Member. The pre-Mesozoic basement (Fig. 2) is composed by Precambrian metamorphic and intrusive rocks of the Cushamen Formation and Late Paleozoic mesosilicic plutonites of the Mamil Choique Formation and equivalents. These formations are unconformably covered by the fluvio-deltaic deposits of the Las Leoneras Formation and equivalents (Depositional Cycle 0 of Figari et al., 1992) and, in the study area, by mesosilicic to basic volcanites of the Lonco Trapial Formation (Lesta and Ferello, 1972), of early Middle Jurassic age, from which Silva Nieto (2005) obtained a radiometric age (K/Ar) of 173.1 ± 9.4 Ma (Aalenian).

At this locality, the Puesto Almada Member (Cañadón Asfalto Formation) is unconformably covered by Cretaceous sandstones and quartzitic conglomerates of the Campanian/Maastrichtian Paso del Sapo Formation (Lesta and Ferello, 1972), of marine littoral origin and also corresponding to braided rivers of a deltaic plain. This sequence interfingers laterally with fossiliferous sandstones, pelites and gray and greenish claystones of estuarine environments, corresponding to the Lefipán Formation (Lesta and Ferello, 1972). During the Cretaceous (Barremian–Campanian) new extensional forces produced the fracturing, basculating and rotation of blocks, together with the reactivation of pre-existing faults (Figari and Courtade, 1993), initiating a new subsidence of the basement, regulating the deposition of the Chubut Group (Megasequence III; Figari, 2005), and producing an angular unconformity over the Cañadón Asfalto Formation. The facies of the filling of these basins correspond to prograding fluvial cycles of the Los Adobes Formation (Barremian; Codignotto et al., 1979). The posterior thermal subsidence and a pyroclastic cycle of large areal

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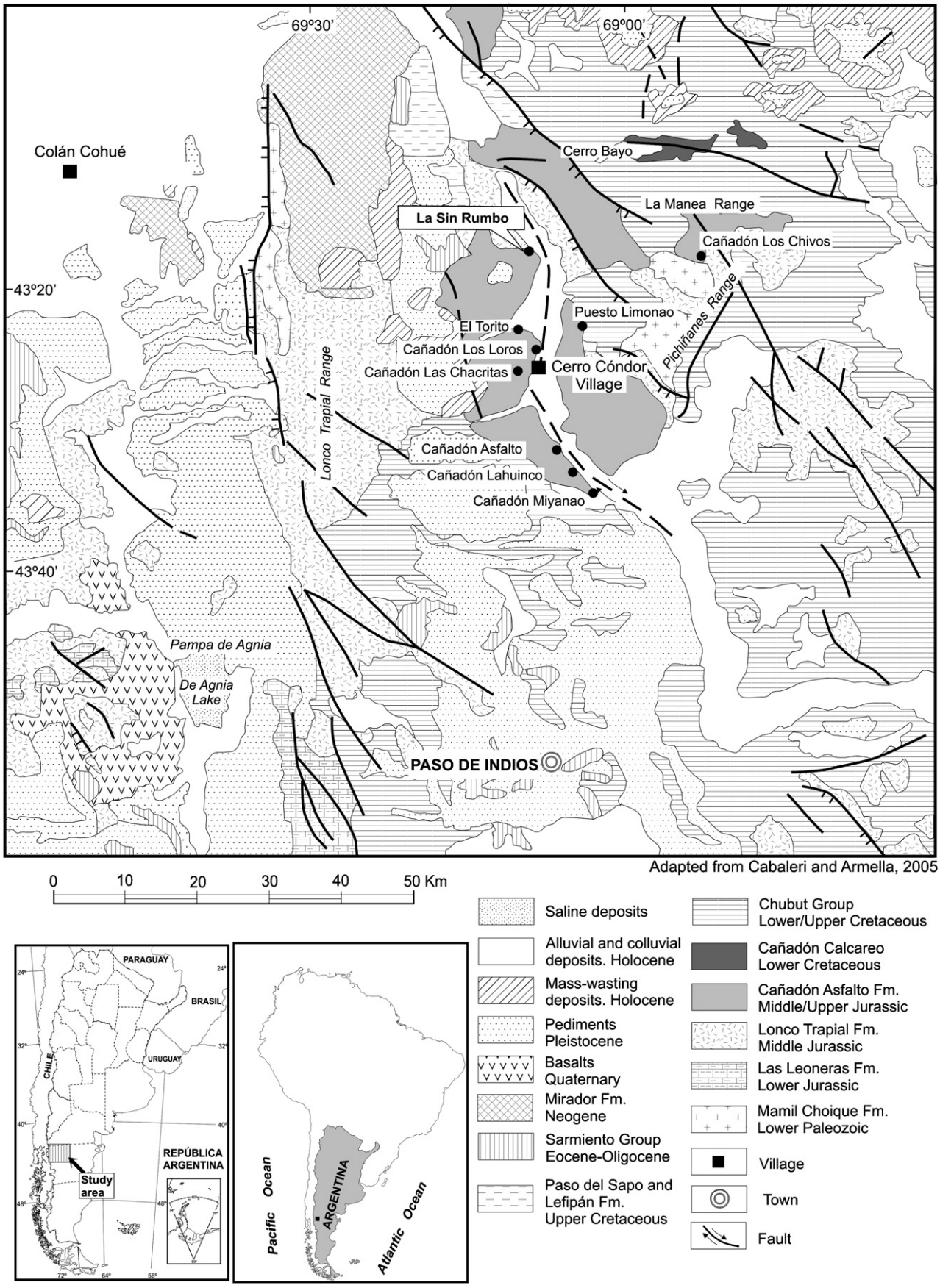

Fig. 1. Location map and geologic sketch of the Cerro Cóndor area.

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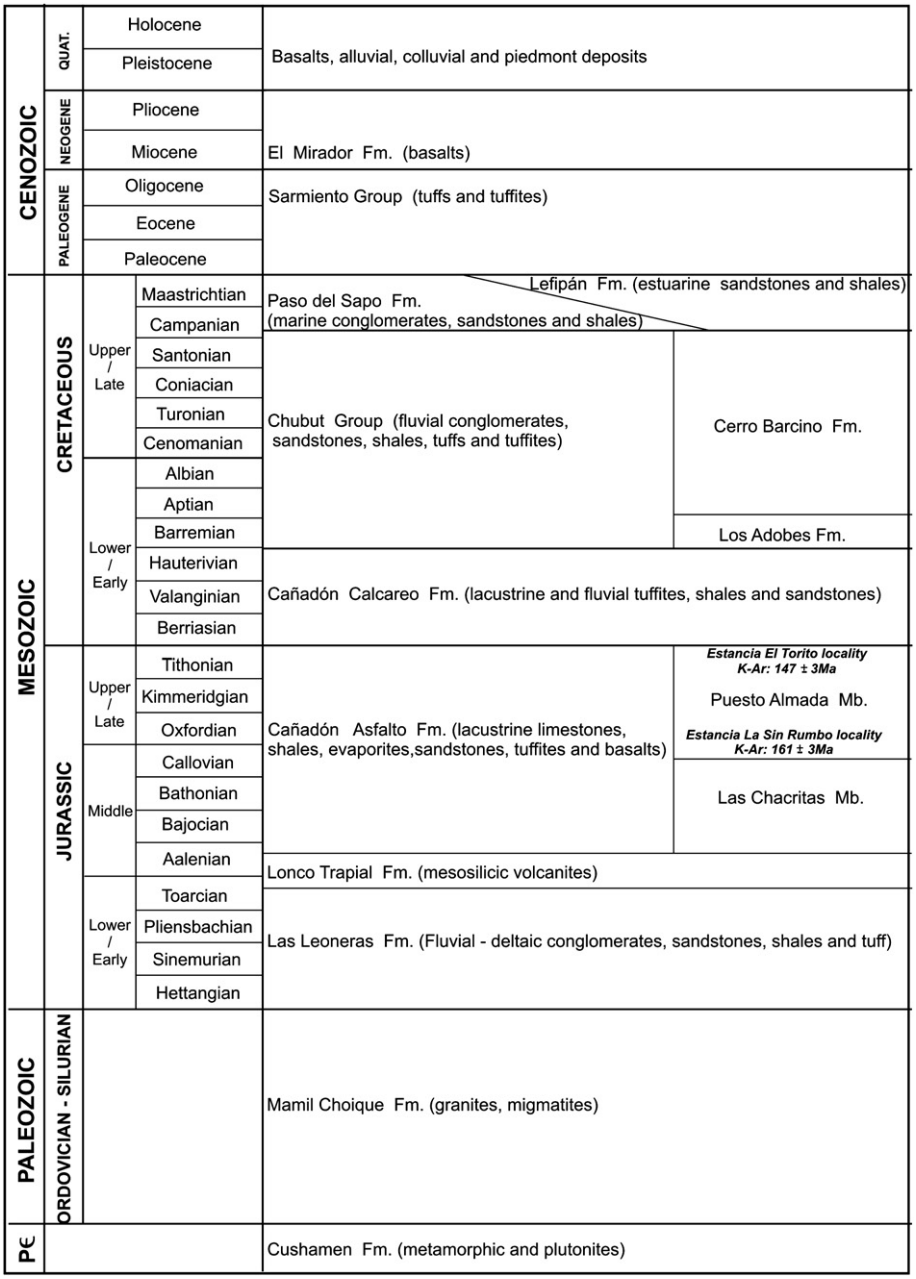

Fig. 2. Generalized stratigraphic chart of the northwestern part of the Cerro Cóndor depocenter, showing the position of the studied section (Puesto Almada Member of the Cañadón Asfalto Formation) and the section at the type locality of the Puesto Almada Member at Estancia El Torito locality. At Estancia La Sin Rumbo locality is outcropping the lowermost part of the Puesto Almada Member, while at the type locality is outcropping the upper part of the members.

extension correspond to the Cerro Barcino Formation (Aptian to Campanian; Codignotto et al., 1979).

The Paleogene of the study area is represented by tuffs and yellowish-white sandy tuffites of the Sarmiento Group, of Oligocene age and by Miocene basalts of the El Mirador Formation. The Quaternary is characterized by Pleistocene piedmont deposits and Holocene alluvial, colluvial, eolian and landslide deposits (Fig. 1).

3. Sedimentology

In the studied locality crops out a 45 m sequence of tuffs and tuffites of the upper Member (Puesto Almada Member) of the Cañadón Asfalto Formation. The tuffs are prevailing (Fig. 3). The base is covered.

In the lower section a sequence of 5.8 m of tuffites can be recognized, forming beds of up to 3 m of thickness. There are thin intercalations of claystones with mud-cracks. The only recognizable structures are wave stratifications and scarse borings. This tuffite has a complex microstructure in which can be distinguished a groundmass composed by amorphous tuffaceous material, ceolites and carbonatic cement. The moderately sorted particles (30%) are angular, middle grained, composed by plagioclase, orthoclase, quartz and fragments of volcanic glass and amorphous tuffy material of brown-yellowish color, with disperse oxids of Fe (Fig. 4A).

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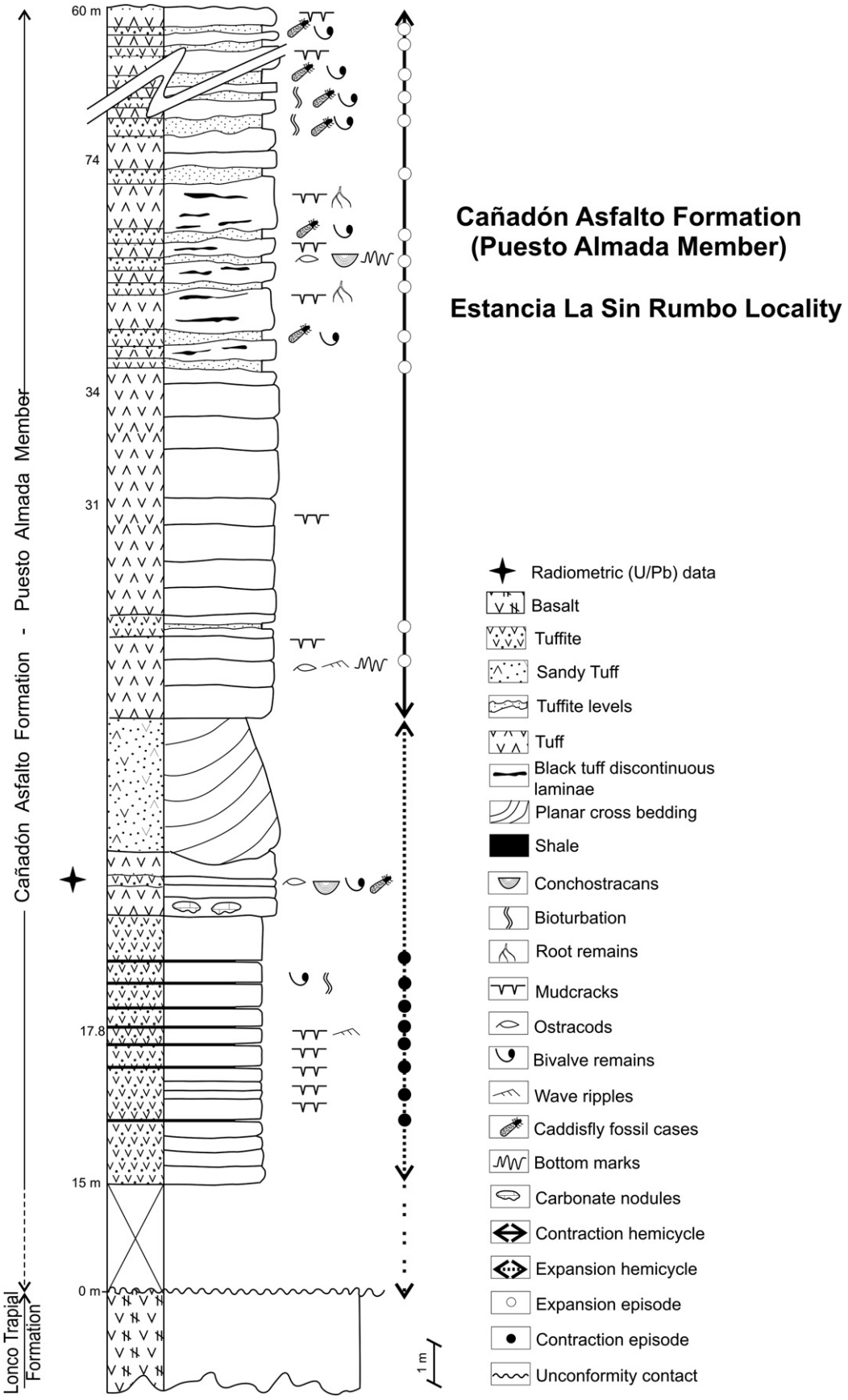

Fig. 3. Columnar section of the Puesto Almada Member of the Cañadón Asfalto Formation at the "Estancia La Sin Rumbo" locality.

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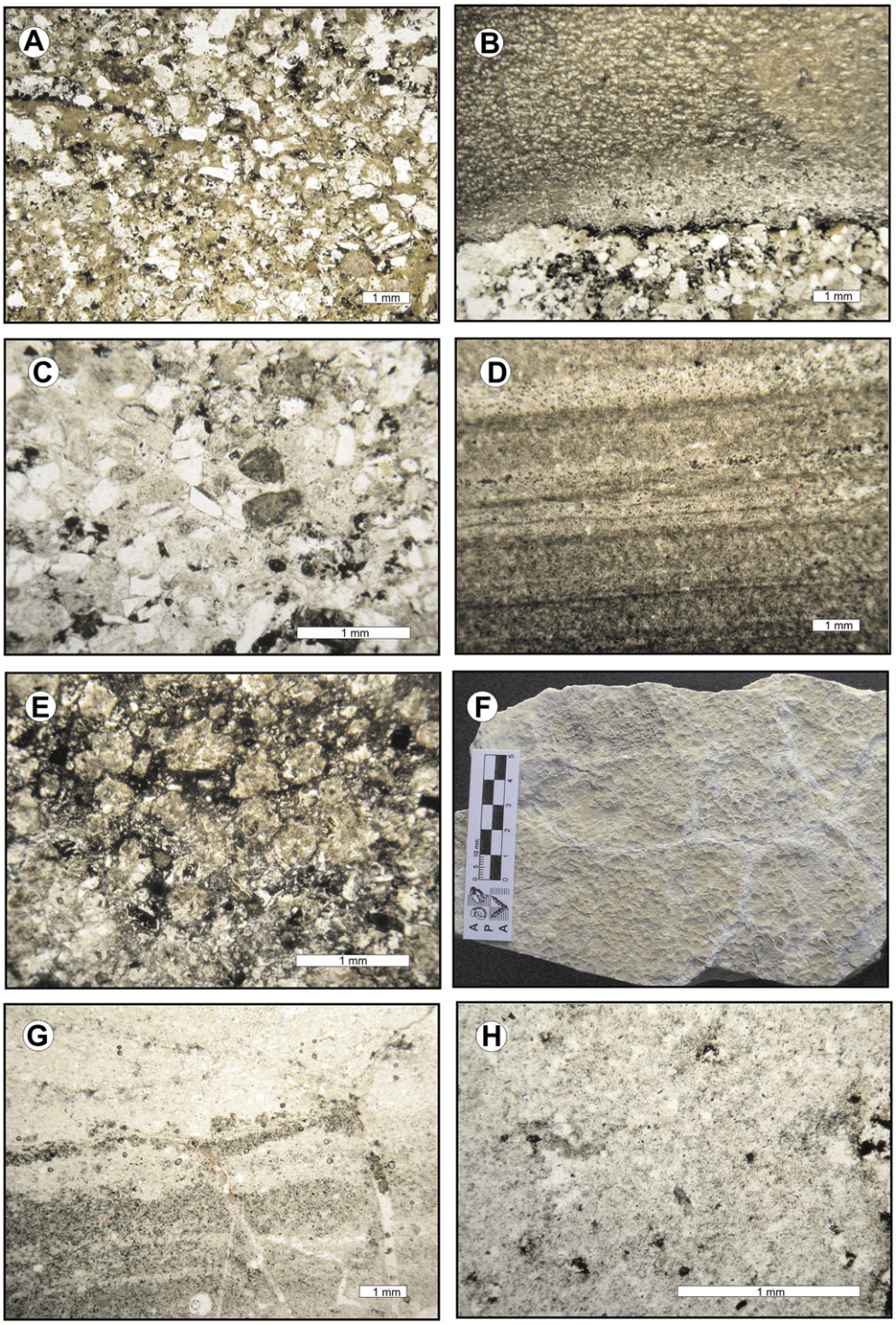

Fig. 4. Photomicrographs of the lithofacies and a hand sample present in the Puesto Almada Member. A: Groundmass amorphous tuffaceous material, iron oxides, plagioclase, orthoclase, quartz and volcanic glass fragments. CASN1. B: Pumiceous fragment in contact with quartz; plagioclase, orthoclase rounded in vitreous groundmass. CASN2. C: Intraclast, siliciclasts, vitreous groundmass and argillaceous microgranules. CASN3. D: Microstructure complex with a lamination produced by the differential content of argillaceous material. The groundmass is homogeneous, composed by glass with fluidal structure and aligned microgranules of clay. CASN5. E: Fine levels of tuffites of red color. CASN 6. F: Hand sample with the mudcraks and spinicaudatans (MPEF-PI1187). CASN 6. G: Root bioturbation. CASN4. H: Microstructure complex, the groundmass is homogeneous. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

Levels of clear brown-yellowish tuff (1.40 m), disposed in beds of 30–40 cm, showing a complex laminated structure with a vitreous microcrystalline groundmass, with microaggregates of clay continuing upwards. The particles are pumaceous fragments, fresh and angular crystals of plagioclase, quartz, orthoclase and concentric radial carbonatic ooids (Fig. 4B).

Above these levels of tuff, and with an erosive contact, a channelled deposit of sandy tuffites continues, forming a lens of 8 m of length and a thickness varying between 3.40 m and 1.60 m, with oblique stratification, which pinches out at the edges. The microstructure is massive; the groundmass, of clear brown color, is composed of amorphous tuffaceous material, clay, devitrificated

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glass and carbonatic cement. The medium-grained clasts (45%) are well sorted, angular to rounded and composed of quartz, orthoclase, plagioclase, microcline, micas, carbonatic intraclasts and rounded vitroclasts of microcrystalline silica, pumaceous fragments and argillaceous microgranules (Fig. 4C).

A sequence of 34 m of tuffs, deposited in beds of 0.50–1.0 m, of yellowish brown color, wave stratification, bottom marks and mud-cracks continues upwards. There are characteristic intercalations of thin and fine discontinuous black pumaceous levels. The microstructure is complex, with a lamination produced by the differential content of argillaceous material. The groundmass is homogeneous, composed of glass with fluidal structure and aligned microgranules of clay (Fig. 4D).

In the above described sequence the intercalations of fine levels of 4–20 cm of tuffites of red color (Fig. 4E) are characteristic, with bottom marks, mud-cracks (Fig. 4F) and root bioturbation (Fig. 4G). Their microstructure is complex and the groundmass is homogeneous (Fig. 4H), with argillaceous material of circular birefringent fabric and crumbs of disperse iron oxides. The clasts are fine sand (20%), with moderate sorting, composed of subangular and subrounded crystals of quartz, orthoclase, plagioclase and pumaceous fragments (Fig. 4E).

4. Paleontology and age

4.1. Paleontology

4.1.1. Insects

The insect record of the studied section is composed of immature stages of Trichoptera, commonly known as caddisflies. The fossils reported here are composed of trichopteran larval cases (Genise et al., 2002; Monferran et al., 2008, 2009). The Order Trichoptera is the second largest lineage of aquatic insects based on the total species number (11,500 extant and 642 fossil species, Grimaldi and Engel, 2005; Ivanov and Sukatsheva, 2007). This group has small free-flying adult forms with moth-like feature. The aquatic (rarely semiaquatic or terrestrial) larval forms can live free or make larval cases to protect themselves. These cases may be constructed with different kinds of materials (fragmentary or complete) including plants (leaves, stems and seeds), animals (ostracod and spinicaudatan carapaces or snail and bivalve shells, fish scales or bones) and minerals (sand or clay grains). The selection of the construction material is mainly conditioned by the availability in the environment or with larval preferences. Recent trichopteran larval forms inhabit both lentic and lotic (with water currents) environments.

The fossils reported here are preserved as imprints or compressed moulds. The cases are mainly constructed by fragments of carapaces or less frequently complete carapaces of spinicaudatans (fushunograptids), complete ostracod valves (mainly *Penthesilenula sarytirmenensis*) and sand grains. The composition of the constructed material is monotypic; in these examples they only use spinicaudatan, ostracod and sand grains. Thus they are tentatively assigned to different ichnogenera respectively: *Conchindusia* Vialov and Sukatcheva (Fig. 5A,G), *Ostracindusia* Vialov (Fig. 5B,H) and *Terrindusia* Vialov (Fig. 5I) (Monferran et al., 2008, 2009). These kinds of fossils are studied as traces or ichnofossils; rarely are they preserved with the body inside them, making it difficult to attribute them to particular extant families. The taxonomic position of the case builder cannot be determined with certainty at a level lower than suborder, based on the case structure. The oldest larval caddisfly cases are found in the Middle Jurassic of Siberia and Mongolia. Some of them resemble the tubes of the modern Suborder Hydropsychina, and others show no differences from the cases of the Suborder Phryganeina (Sukatsheva, 1998; Ivanov and Sukatsheva, 2007).

4.1.2. Spinicaudatans

Since the description of the spinicaudatan faunas of the Cañadón Asfalto Formation by Tasch and Volkheimer (1970) and Vallatti (1986), our knowledge on this group of bivalved crustaceans has increased noticeably. Seven species have been described in the mentioned papers, but now more than fourteen species are recorded in the Depocenter Cerro Cóndor (Gallego and Cabaleri, 2005; Gallego et al., 2010). The new localities are: "Estancia El Torito", "Puesto Limonao", "Cañadón de los Chivos", "Cañadón Los Loros", "Cañadón Las Chacritas", "Cañadón Asfalto", "Cañadón Lahuincó", "Cañadón Miyanao" and in this contribution "Estancia La Sin Rumbo". This fauna is mainly composed of species of the families Euestheriidae and Eosestheriidae and secondarily Afrograptidae and Anthronestheriidae. Gallego et al. (2010) restudied the specimens described by Vallatti (1986) from the Cerro Bayo locality, at the east of Puesto Almada (now: Estancia El Torito), and assigned them to the Family Afrograptidae (*Congestheriella rauhuti*). This species occurs together with species of the families Anthronestheriidae (*Pseudestherites* sp.) and Euestheriidae. The beds that crop out in the Sierra de la Manea and Cañadón de los Chivos localities also carried this fauna.

The spinicaudatans Euestheriidae *Euestheria volkheimeri*, Fushunograptidae "*Lioestheria*" sp., Eosestheriidae *E. taschi*, "*L.*" *patagoniensis* and, in addition, a new species have been recognized from the Las Chacritas Member. In the Puesto Almada Member the identified spinicaudatans are: Eosestheriidae, Afrograptidae *Congestheriella rauhuti*, Anthronestheriidae *Pseudestherites* sp. and Euestheriidae *Euestheria* (Gallego and Cabaleri, 2005; Gallego et al., 2010). The spinicaudatans studied from this new locality are characterized by: ovate outline, small dimensions (3–3.8 mm length and 2.2–3 mm width; width/length ratio 0.5–0.97), short and arched dorsal margin, anterior and posterior margins with equal convexity and length, subcentral umbo and growth bands ornamented with irregular thick radial lirae with numerous thin cross-bars (knit lattice-like reticulation with small punctae) in the dorsal-medium (upper third) of the carapace, changing to straight thick radial lirae with few cross-bars restricted to the upper half of the growth band in the ventral third of carapace and terminal radial lirae are expanding into subtriangular shape part. The morphological features (outline and ornamentation) and size of the carapace, allow us to assign this species probably to the Family Fushunograptidae (orthestheriids) (Fig. 5A,C).

The fushunograptid of the studied locality is related to older species such as "*Liograpta" zavattieri* Gallego from the Cerro de Las Cabras Formation (Middle Triassic; Gallego, 1999), "*Lioestheria*" *striolatissima* Rusconi from the Potrerillos-Cacheuta formations (Upper Triassic; Gallego, 1999) and probably also to *Polygrapta troncosoi* Gallego from the Upper Triassic La Coipa and Río Biobío beds from Chile (Gallego and Covacevich, 1998; Gallego et al., 2005). It is also related to Middle/Upper Jurassic fushunograptid species, as "*Lioestheria" malacaraensis* Tasch from the La Matilde Formation (Middle-Upper Jurassic; Tasch, 1987) from Argentina and *Orthestheria* (*Migransia*) *ferrandoi* Herbst from Tacuarembó Formation (Upper Jurassic -Lower Cretaceous; Shen et al., 2004) from Uruguay.

The Fushunograptidae (orthestheriid) spinicaudatan from "Estancia La Sin Rumbo" locality may represents a new genus and species of the family. Nevertheless, these specimens are somewhat approaching to Qinghaiestheria Wang from the Upper Jurassic Hongshuigou Formation in Qinghai (northwestern China) and Penglaizheng Formation in Sichuan (southwestern China) (Wang, 1983; Shen and Chen, 1982; Li, 2004) in its ornamentation, but the latter has serrated structure along the lower margin of the growth lines.

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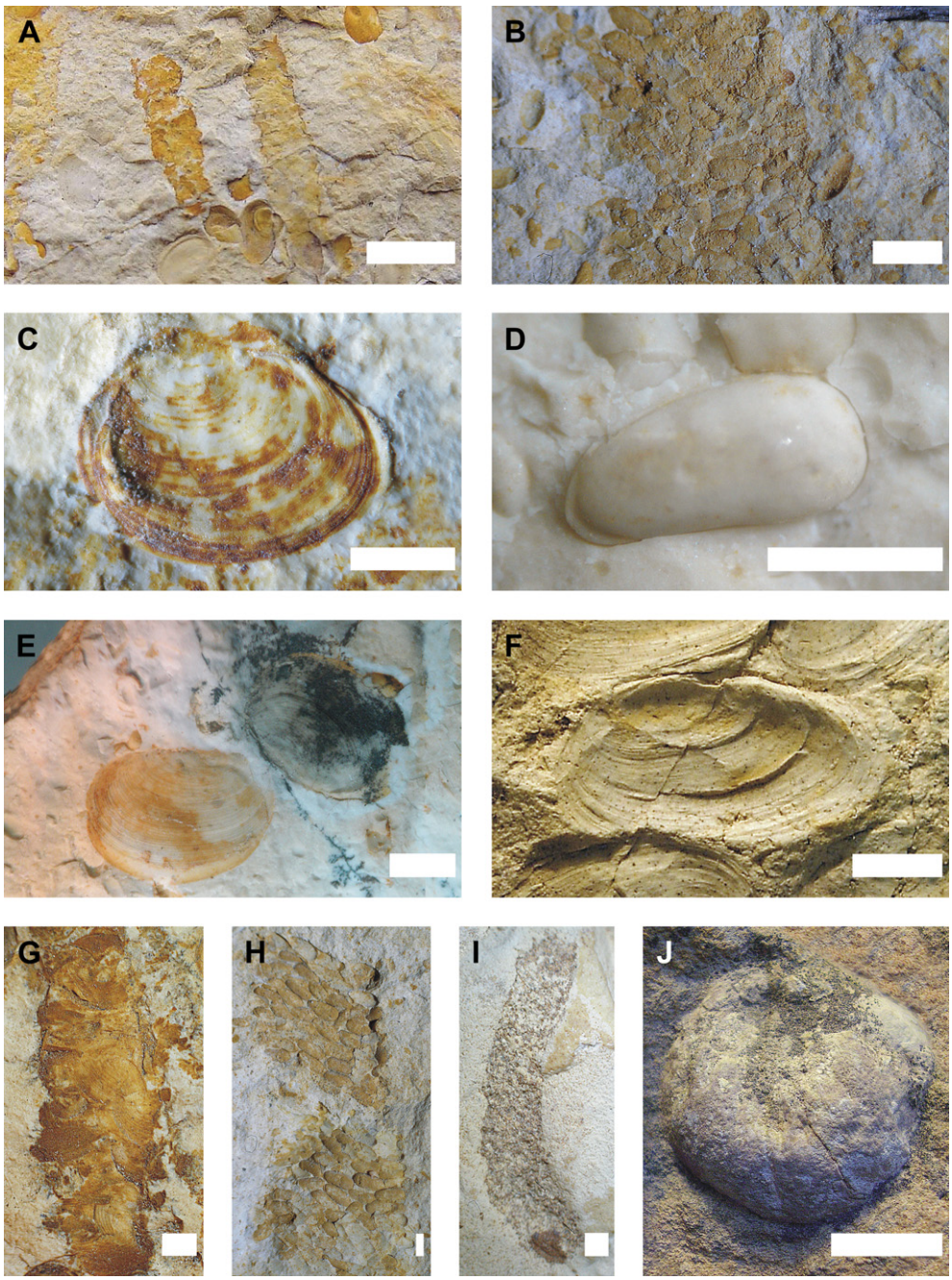

Fig. 5. Invertebrate fauna from "Estancia La Sin Rumbo" locality, Puesto Almada Member, Cañadón Asfalto Formation (Extraandean Patagonia, Argentina). A: Fushunograptid spinicaudatan and *Conchindusia*, MPEF-PI 1178. B: *Penthesilenula sarytirmenensis* and *Ostracindusia*, MPEF-PI 1179. C: Fushunograptid, MPEF-PI 1180. D: *Penthesilenula sarytirmenensis*, MPEF-PI 1181. E: Fushunograptid and *Penthesilenula sarytirmenensis* MPEF-PI 1182. F: cf. *Diplodon* MPEF-PI 1183. G: *Conchindusia*, MPEF-PI 1178. H: *Ostracindusia*, MPEF-PI 1185. I: *Terrindusia*, MPEF-PI 1186. J: Gastropoda indet MPEF-PI 1184, Scale bars: A, B, E, F, G-J. = 5 mm, C = 1 mm, D = 0.5 mm.

4.1.3. Ostracods

The ostracods of the studied section are moderately preserved. They are abundant, mostly thin shelled and large to very large in size. The association is of low diversity and is composed of articulated valves (closed carapaces) filled with material that does not allow for observation of internal features. Specimens preserved as internal moulds are also frequent. Three genera have been identified, each represented by a single species: *Penthesilenula sarytirmenensis* (Sharapova) of Mandelstam (1947) (Fig. 5D), *Theriosynoecum barrancalensis minor* (Musacchio et al., 1990) and *Mandelstamia* sp. (Fig. 8). The genus *Penthesilenula* Rossetti and Martens, 1998 (Darwinuloidea, Darwinulidae) comprises two species groups: the *incae*-group and the *africana*-group. *Penthesilenula sarytirmenensis* is a large-sized darwinulid (more than 0.900 mm in length), with an elongate carapace and with the posterior part broadly enlarged and nearly straight, the left valve overlapping the right one along the entire periphery and the external surface smooth. A pointed caudal internal tooth in the left valve (which characterizes the *incae*-group) is not visible in the studied carapaces. The species has been described from the Middle Jurassic of the Mangishlaka Peninsula, ex USSR (Mandelstam, 1947) and also was recognized from the Middle and Late Jurassic of several localities in China (Li, 1985; Zheng, 1995; among others) and south-eastern India (Govindan, 1975). In Argentina, Musacchio et al. (1990) and Musacchio (2001) recognized

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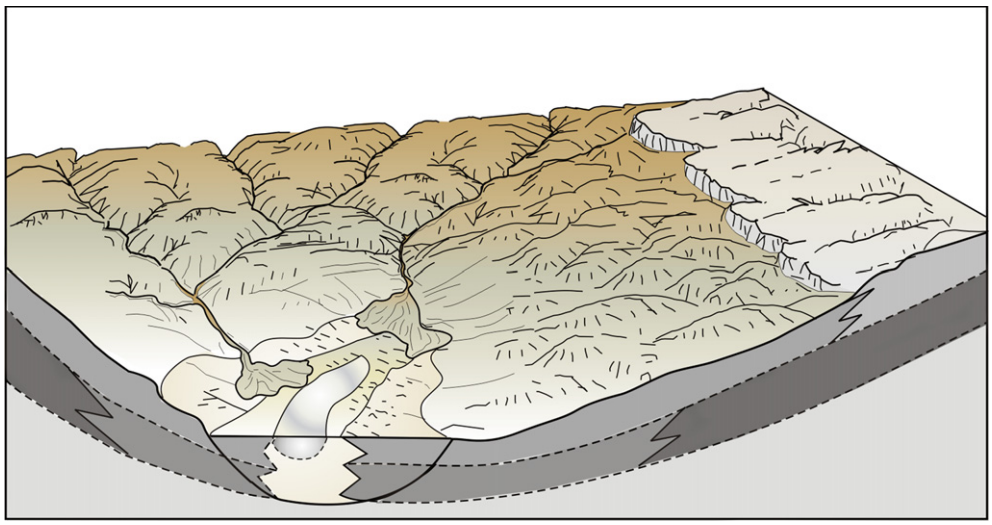

Fig. 6. Block diagram of the "Estancia La Sin Rumbo" locality. In the first plane, the position of the lake. The surrounding of the lake represents the silting of the basin (without scale).

it from the Late Jurassic of "Estratos de Almada", El Barrancal (near to Paso de Indios) and El Capricho (near to Cerro Cóndor), Chubut Province. *Theriosynoecum barrancalensis minor* (Cytheroidea, Limnocytheridae) is large in size (0.800–0.900 mm in length), dimorphic, subrectangular in lateral view, with obliquely rounded anterior margin, very compressed anterior peripheral area and truncated posterior margin; subtriangular to pyrifom in dorsal view. Lateral surface reticulate, with numerous diminute papillae and with longitudinal striae along the ventral area. It presents a conspicuous anterior subcentral sulcus and a less deep second sulcus in front of it. This species is recognized from the Late Jurassic of "Estratos de Almada", El Barrancal (near to Paso de Indios) and El Capricho (near Cerro Cóndor), Chubut Province, Argentina (Musacchio et al., 1990; Musacchio, 2001). The genus *Mandelstamia* Ljubimova (1955) (Cytheroidea) is known from the Late Jurassic of Europe, ex USSR and southwestern Asia. *Mandelstamia* sp. (often as moulds) is elongate oval in lateral view, with straight dorsal margin, feeble anterior subcentral sulcus and lateral surface covered with small tubercles. Musacchio (2001) mentioned *Mandelstamia* in Late Jurassic sediments from a locality near to Gan Gan (Chubut Province).

Populations of *Penthesilenula sarytirmenensis* and *Theriosynoecum barrancalensis minor* comprise large numbers of adults and of juvenile instars corresponding to the early ontogeny of the species.

4.1.4. Mollusks

The mentions of mollusks from the Cañadón Asfalto Formation are those of Volkheimer (in Tasch and Volkheimer, 1970, p. 19) and Martínez et al. (2007). The first authors note the gastropod *Potamolithus* and the bivalve *Palaeomutela* from some beds of the Las Chacritas Member, while the second group mentions the bivalves cf. *Diplodon*, Sphaeridae and Corbiculidae of the Las Chacritas Member and cf. *Diplodon* and the gastropod "*Viviparus*" of the Puesto Almada Member.

In the studied section, cf. *Diplodon* and a large indeterminant gastropod are found (Fig. 5F,J). Specimens are small, preserved as moulds, without signs of fractures. Valves are of rather uniform size, dissarticulated, mostly parallel to the stratification surface, with random orientation, forming concentrations (one or two beds about 1 cm thick). Since they are moulds, abrasion cannot be properly evaluated but it seems not to have been important enough to leave some evidence. It is difficult to establish the proportion of convexity of valves up or down, because the moulds suffered some compression. According to the visualization or not of growth bands, there are present both modalities.

The bivalves are comparable to *Diplodon*, based on overall morphology; but lack important characters such as the hinge, umbonal sculpture, or muscle scars, obligate to be cautious with the identification. Shape and size are very homoplasic characters in the Unionoida (Parodiz and Bonetto, 1963; Graf, 2001), and there is a high intraspecific variation of shell shape (e.g. Ortmann, 1920).

4.2. Age

Age is based on lithostratigraphic correlation, biostratigraphic evaluation of the invertebrate record and radiometric dating.

1) *Lithostratigraphic correlation* with well-dated sections outcropping in nearby areas within the same depocenter Cerro Cóndor

The lithology and sedimentary characteristics of the studied section are comparable to those of the type section of the Puesto Almada Member of the Cañadón Asfalto Formation, illustrated in Fig. 7, taking into account that the type locality corresponds to a more central position in the depocenter, with a major participation of fine grained sediments deposited in deeper areas of the lake, while the "Estancia La Sin Rumbo" area represents a marginal facies with prevailing tuffites and tuffs (Fig. 3).

2) *Biostratigraphic evaluation of the invertebrate record registered in the studied section* (Fig. 8).

The spinicaudatan association of Euestheriidae and Eosestheriidae (from the Las Chacritas Member) support a Middle to Late Jurassic age for the bearing levels. In change, the association of *Congestheriella rauhuti* (Afrograptidae), *Pseudestherites* sp. (Anthronestheriidae), and Fushunograptidae (from the Puesto Almada Member) indicates a Late Jurassic (or even somewhat younger) age for the bearing sequence. The spinicaudatan fauna from this locality reports the probable presence of a new genus and species of the Family Fushunograptidae, which resembles the genus *Qinghaiestheria*. Fushunograptids (*Qinghaiestheria sichuanensis* Chen and Shen, *Q. chuanzhongensis* Chen and Shen, *Q. suboblonga* Chen and Shen and *Orthestheria* sp.) are secondary components of the typical Late Jurassic "*Eosestheriopsis dianzhongensis* fauna" of

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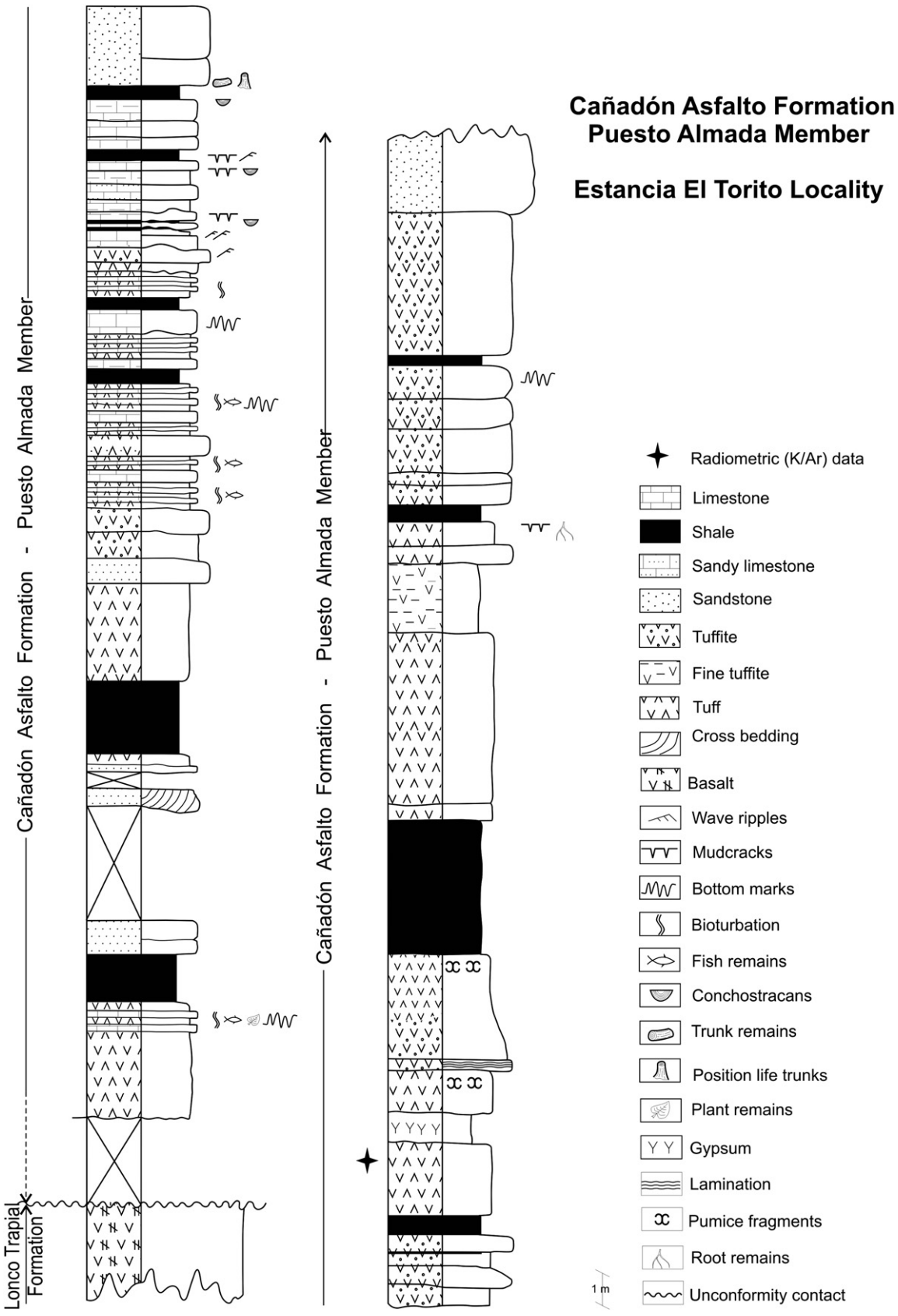

Fig. 7. Columnar section of the Puesto Almada Member at the type locality (Estancia El Torito).

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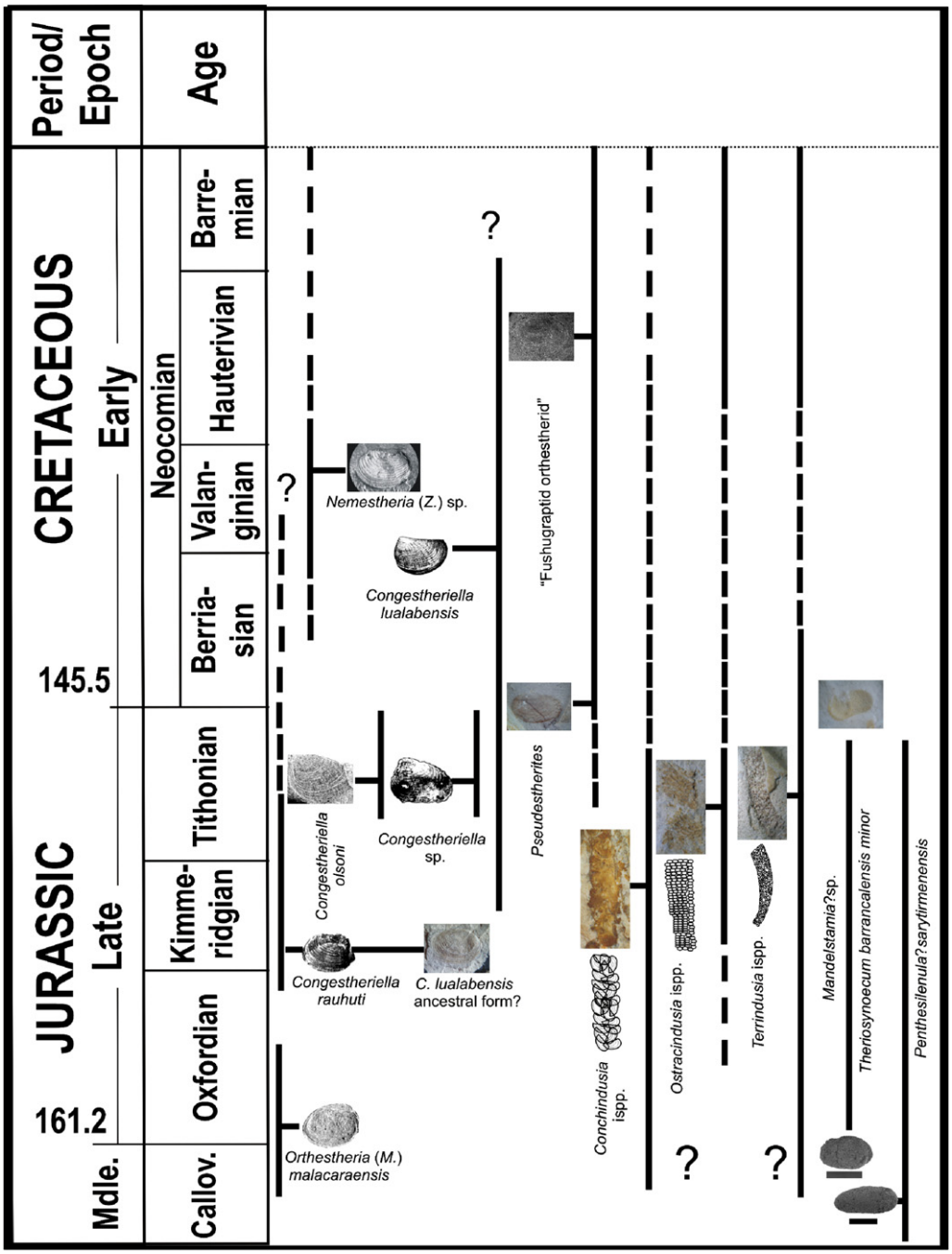

Fig. 8. Range chart showing the stratigraphic distribution of the spinicaudatan species (and others related from northern South America and Africa), caddisfly case ichnogenera and ostracod species from the Middle-Upper Jurassic from Patagonia, Argentina. Spinicaudatan: *Orthestheria (Migransia) malacaraensis* from the La Matilde Formation (Deseado Massif, Argentina), *Congestheriella lualabensis* ancestral form and *Nemestheria (Zhestheria)* sp. from the Cañadón Calcáreo Formation (Extraandean Patagonia, Argentina); *Congestheriella olsoni* from La Quinta Formation (Venezuela); *Congestheriella* sp. from the Barro Basin (Brazil), *Congestheriella rauhuti* from Cañadón Asfalto and Cañadón Calcáreo formations (Extraandean Patagonia, Argentina), *Pseudestherites* spp. from other stratigraphic units from Extraandean Patagonia (Argentina); Fushunograptidae ("orthestherid") from the Cañadón Asfalto Formation (Extraandean Patagonia, Argentina) and *Congestheriella lualabensis* from the Stanleyville Series (Central Africa). Caddisfly cases: *Conchindusia*, *Ostracindusia* and *Terrindusia* ichnogenera from the Cañadón Asfalto (Extraandean Patagonia, Argentina) and La Matilde formations (Deseado Massif, Argentina) including the distribution of other known species of the world. Ostracods: *Penthesilenula sarytirmenensis*, *Theriosynoecum barrancalensis minor* and *Mandelstamia* sp.

the middle Jehol biota from Asia (Chen, 1999; Chen et al., 2007; Li, 2004; Li et al., 2007). *Qinghaiestheria* was originally recorded from the Hongshuigou Formation (Mangya, Qinghai) and also occurs in the Penglaizhen Formation (Sichuan Basin, southwestern China). Both are considered to be of Late Oxfordian in age. It is approaching to *Polygrapta biaroensis* Defretin-Lefranc (ascribed to *Migransia* by Chen and Shen, 1977) from the Upper Jurassic Stanleyville Series (Congo Basin, Africa) in its shape, growth line with serrated structure and radial lirae. The Hongshuigou Formation yields *Sinoestheria*, which strongly resembles *Palaeolimnadiopsis lombardi* Defretin-Lefranc (Stanleyville Series), in its large and thin carapace, recurved postero-dorsal margin, large polygonal reticulation and stout growth line with a row of tubercles. The Stanleyville Series is dated as Kimmeridgian in age (Defretin-Lefranc, 1967).

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The two ostracod species of the studied section belong to the *Theriosynoecum barrancalensis* Zone of Late Jurassic age (Musacchio, 1989, 2001; corresponding to Megasequence II: mature hemigraben, Figari, 2005). This ostracod zone, originally named *Bisulcocypris barrancalensis*, is herein renamed *Theriosynoecum barrancalensis*. The genus *Bisulcocypris* Pinto and Sanguinetti is currently referred to as a junior synonym of *Theriosynoecum* Branson (see Do Carmo et al., 2004 and references herein).

Due to the uncertain identification of the bivalves (cf. *Diplodon* sp.) they are not useful for biostratigraphic considerations. Anyway, the known fossil record does not contradict the proposed age. The genus is known at least since the Middle Jurassic in Argentina (La Matilde Formation; Morton and Herbst, 2001), and is recorded also in the Late Jurassic-Early Cretaceous Tacuarembó Formation of Uruguay (Martínez et al., 1993; Perea et al., 2009). The considerations about the uncertainty of the identification taking into account only overall shape must be applied also in these last cases. In North America, is recorded in the Triassic (Good, 1989 and references).

Finally, the spinicaudatan genus *Qinghaiestheria* was recovered from the Penglaizhen and Hongshuigou formations (Late Jurassic, China), also the last formation yields a Palaeolimnadiopseids spinicaudatan. In addition, similar associations are recorded in the Stanleyville Series (Kimmeridgian, Late Jurassic, Africa) and the La Matilde Formation (Callovian-Oxfordian, Middle to Late Jurassic) from Patagonia Argentina. In the Puesto Almada Member (at the Estancia Fossati locality) is recorded an undescribed species of the Family Palaeolimnadioseidae. Also, the previous data offer new evidence for the paleontological and paleobiogeographical spinicaudatan relationships between central Africa and South America (ASA province) as suggested by Gallego and Martins-Neto (2006) and Gallego et al. (2010).

This assemblage allows us to compare our association with the "*Eosestheriopsis dianzhongensis* fauna" (Chen et al., 2007; Li, 2004) and the other fauna mentioned above that support a Late Jurassic age for the bearing levels (Puesto Almada Member, Cañadón Asfalto Formation).

The range chart (Fig. 8) shows the distribution of the spinicaudatans and related forms, adding the range of the three ichnogenera of the caddisfly fossil cases and the ostracod species from the Puesto Almada Member (Cañadón Asfalto Formation). All data of the chronologic distribution support an Oxfordian - Tithonian age for this Member.

3) *Radiometric dating* (K/Ar) based on studies of idiomorphic biotites of volcanic tuffs.

Radiometric dating (K/Ar) of biotites from a thin layer of volcanic tuffs (Age: 147.1 ± 3.3 Ma from the upper part of the Puesto Almada Member at its type locality indicates a Tithonian age (Koukharsky, M. in Cabaleri et al., 2010a). The new U/Pb age (161 ± 3 Ma) in zircons present in tuffites of the Puesto Almada Member from the locality "Estancia La Sin Rumbo" suggests that the sedimentation began during the Oxfordian (Cabaleri et al., 2010b).

5. Paleoenvironmental model

The studied profile shows a simple environmental evolution, exemplified by deposits of tuffs and tuffites dissected by channelled tuffitic sandstones. The sedimentary regime of the basin was modified by an important pyroclastic supply. The pyroclastic deposits are the product of ash fall and input of this fluvially reworked material into the water body. The lithologic character indicates that the pyroclastic material (Tiercelin, 1991) may have been deposited in marginal areas of the Cerro Cóndor paleolake and represents a gradual silting of the depocenter (Fig. 6). The facies pattern is reflected by the presence of water levels which register a cycle of expansion (or high lake level) and contraction of the lake (Fig. 3). The major episode of expansion is documented in the basal 10 m of the section, interrupted by brief episodes of contraction, with the characteristic systems of mud-cracks. Expansion is represented by levels of tuffites and channelled tuffitic sandstones, produced by transport during the input of water in the marginal areas. These conditions are demonstrated by the presence of sediments reworked by waves of low energy (Platt and Wright, 1991) and the presence of bottom marks which indicate soft currents. The input of water is produced by tractive currents and the input of sediments by small streams (creeks). The fine grained levels of claystones would indicate crevasse splays on the marginal areas, temporarily exposed and later covered by littoral facies. In the lower hemicycle (expansion) can be observed rare horizontal borings (*Scoyenia* ichnofacies) in tuffitic levels. Zhang et al. (1998) observed that these borings are originated during the low level of the lake, but they are preserved during the moments of flooding and expansion of the water body under conditions of low energy, characteristic for marginal lacustrine facies.

The contraction is prevailing in the upper 35 m of the section and is interrupted by brief episodes of expansion. During the contraction the water level begins to be reduced by increasing aridity and silting, due to the high pyroclastic supply, which produced the filling of the lake. The change to dry climatic conditions is indicated by desiccation of the marginal areas and the development of a system of mud-cracks, which are frequent in the levels of fine grained sediments, previously remobilized by soft waves. It can be deduced that the climate is modifying gradually towards dryer conditions in the upper parts of the section.

The spinicaudatans are the most abundant (freshwater) invertebrate group recorded in the Cañadón Asfalto Formation, as well as in the La Matilde Formation (Middle to Late Jurassic of the Deseado Massif). They inhabit small and temporary water bodies and littoral areas of lakes, with freshwater to brackish water conditions and water temperatures from 13° to 25 °C. They can survive under extreme values as 1° or 41 °C and pH conditions from neutral to alkaline. The record of spinicaudatans is shared by both stratigraphic units of the Cañadón Asfalto Formation (Las Chacritas and Puesto Almada members). These taxa differ in morphologic features of the carapace, but mainly in their dimensions, probably related to an environmental (ecologic) control. The fauna of the Las Chacritas Member, composed by Eustheriidae and Eosestheriidae, is characterized by large spinicaudatans with multiple and wide spaced growth lines, which correspond with large-deep perennial water bodies, where those populations could develop. The absence of fish records in this sequence implies the minor predator-prey pressure supported by the spinicaudatan assemblage. On the other hand, the fushunograptid from the "Estancia La Sin Rumbo" locality with one of the smallest carapace sizes in the Cañadón Asfalto fauna, probably shows a response to the high fish diversity recorded in other coetaneous levels of this formation (Bordas, 1942; Bocchino, 1967; López-Arbarello et al., 2002; López-Arbarello, 2004). Nevertheless, another possibility is that this carapace size may be related to a shallow ephemeral and marginal water body, occasionally with high energy impact as suggests the sedimentologic analysis. The dry climatic conditions indicated by the presence of mud-cracks are also supported by the co-occurrence with a great number of small spinicaudatans in these levels, which suggest a mass mortality event (Fig. 4F).

The taphonomic evidence indicates that the caddisfly cases are autochthonous. They originated in a shallow marginal lake system of the upper Cañadón Asfalto Formation (Puesto Almada Member), under warm and semiarid environmental conditions. In this context

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it is interesting to mention the observation of Jarzembowski (1995) of the uncommon presence of the caddisflies in the Wealden of England, consistent with a warm climate and some salinity. At the "Estancia La Sin Rumbo" locality, both ichnogenera *Conchindusia* and *Ostracindusia* are preserved together with ostracods and spinicaudatan valves used by them for constructing their cases.

Penthesilenula and *Theriosynoecum* are typical fresh water ostracods. Recent *Penthesilenula* have been found in a wide range of aquatic environments, but including semi-terrestrial and terrestrial habitats. The type species *P. incae* is bottom-dweller, especially abundant in coarse-grained sediments rich in organic matter. It has also been found in shallow hot springs, pools and channels in largely dry lakes, rich in algae and of 10–20 cm depth, at the southern Altiplano in Perú, Bolivia and Argentina (Rossetti et al., 1996; Laprida et al., 2006). Other living species of *Penthesilenula* have been recovered from both saturated and unsaturated terrestrial habitats, such as leaf litter in forests (Pinto et al., 2004). These characteristics agree with the low diversity of the association and the fact that the percentage of the total individuals made up by the two most abundant species (*P. sarytirmenensis* and *T. barrancalensis minor*) reaches near 90% of the total of specimens, which characterizes freshwater associations (Whatley, 1983). The presence in both species of large numbers of adults and of juvenile instars well back into the ontogeny of the species can be interpreted as the product of a low energy regime, typified (in modern analogues) by Histogram of Type A of Whatley (1983). The studied microfauna is mainly composed of carapaces (articulated valves). It is argued that, if high percentages of adult specimens are articulated, these have not been subject to any great amount of post-mortem transportation (which is valid in our study of the Cañadón Asfalto Formation) or this indicates rapid burial before biologic activity and/or tissue decay which can bring about disarticulation. However, the fact that certain species have been encountered as carapaces and others as valves, as demonstrated by Whatley (1988) may be due to biologic and morphologic reasons of the species in question rather than taphonomic ones. Also, there exists the strong possibility that the adductor muscles (which close the valves) of some species contract on death while in others they relax. Darwinulids, as many freshwater species, reproduce by parthenogenesis. They are brooders (eggs and the first two or three instars are retained in the carapace). For that reason it is important how tightly the valves can close. They have marginal structures such as internal teeth (in the left valve in *Penthesilenula*) which prevent them from closing too much and thus crushing eggs and juveniles and the brood pouch becomes obscured (Martens et al., 2002). However, closing valves must be safe enough to prevent them from opening which would cause the death of the animal and progeny.

Unionoids are fresh water bivalves, and ideally live with intermediate current velocities, where the fine fraction of sediment is present but water is clean and well oxygenated, pH slightly basic, substrate stable, and depth up to 7–10 m (Good, 2004 and references; C. Clavijo pers. com., 2009). They are shallow infaunal filter feeders and fish must be present in the habitat for hosting their parasitic glochidia. In Mesozoic times they may have been depredated by lungfish.

Taphonomical data (rather thin concentrations with size sorting, dissarticulation, not fragmentation nor abrasion, random orientation, presence of stable and instable positions), plus the sedimentological evidence of currents discussed above, indicate that the valve concentrations represent a death assemblage, deposited by currents of moderate energy not far from where the bivalves lived, and in a relative short time spam after their death.

The stressing conditions of this marginal lacustrine area would be also suggested by the total absence of fish remains in contrast to the records of the Puesto Almada Member in other localities as "Estancia El Torito", "Puesto Limonao", "Cañadón Los Chivos" and "Sierra de la Manea", where the environmental conditions of the paleolake were adequate for the survival of an abundant fish fauna. These conditions include availability of nutrients, suitable pH, relatively constant water temperatures throughout the day and year and sufficient water depth in order to avoid extreme oscillations of water temperature.

In the Upper Jurassic Penglaizhen Formation (China), Li (2004) reported an association of the fushunograptid spinicaudatan *Qinghaiestheria* with the freshwater-brackish ostracods (darwinuloids and *Damonella*). Li (2004) mentioned other occurrences of spinicaudatans (*Euestheria*, *Neopolygrapta*, and *Dendrostracus*) with fresh to brackish water taxa (freshwater gastropods *Viviparus* and *Valvata*, bivalve *Unio*, freshwater-brackish bivalve *Neomiodon*) in the Middle Jurassic Great Estuarine Group (Kildonnan Member, Lealt Shale Formation, Scotland), inhabiting lagoonal waters yielding relative palaeosalinities of 0–4‰. All of the mentioned spinicaudatans share the presence of small punctae in their growth bands, which are useful for osmoregulation when the salinity of the water changes. This morphological feature allowed Li (2004) to propose that possible *Qinghaiestheria* and associated invertebrate could survive in freshwater-brackish environmental conditions.

6. Conclusions

At "Estancia La Sin Rumbo" locality, 41 km north of the Cerro Cóndor village, a 45 m thick sequence of yellowish tuffs and tuffites of the Puesto Almada Member of the Cañadón Asfalto Formation crops out. Corresponding to the Megasequence II (mature hemigraben) of Figari et al. (1992) and Figari (2005), it rests on the volcanic Lonco Trapial Formation of early Middle Jurassic age. The section shows a cyclic expansion-contraction of the lake basin. The expansion hemicycle is represented in the lower half of the section and includes eight episodes of contraction. The hemicycle of contraction includes episodes of expansion, which are more frequent in the upper part of the profile. Contraction is shown by the predominance of volcanic tuffs, deposited in the context of the silting of the Cerro Cóndor Depocenter. The tuffites of the upper part of the section contain several levels bearing spinicaudatans, ostracods, mollusks (bivalves) and larval stages of the first records of fossil Trichoptera cases in the Cañadón Asfalto Formation. The fossils mentioned lived in small bodies of water during the periods of expansion of the lake, when a major input of water to the basin was indicated by the presence of thin levels of fossiliferous tuffites. The dry climatic condition is indicated by the occurrence of great numbers of spinicaudatans preserved in levels with mud-cracks, suggesting several local mortality events, and also by the smallest size of carapaces of the spinicaudatan specimens. The fauna from "Estancia La Sin Rumbo" locality (spinicaudatan fushunograptid, ostracods, and caddishfly cases) adding the stressed warm and dry climatic situation probably could suggest that the conditions of the Puesto Almada Member lake are varying from fresh to brackish water. Also, freshwater conditions are indicated by the distributions of ostracods, reaching the two most abundant species: *Penthesilenula sarytirmenensis* and *Theriosynoecum barrancalensis minor*, nearly 90% of the total of specimens. Taphonomic data of unionoid bivalves plus sedimentologic evidence of currents, indicate that the valve concentrations represent a death assemblage, deposited by currents of moderate energy not far from where the bivalves lived, and in a relatively short time span after their death. The taphonomic evidence suggests that the caddisfly cases are autochthonous and that they lived in marginal environments of the lake system.

The record of the spinicaudatan fushunograptid, adding others from the Puesto Almada Member (as *Congestheriella rauhuti*) and

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a new U/Pb age (161 ± 3 Ma) in zircons present in tuffites support a Late Jurassic age (Oxfordian to Tithonian) for this Member of the Cañadón Asfalto Formation. The caddisfly cases of the ichnogenera *Conchindusia* and *Terrindusia* are shared by two Middle-Upper Jurassic formations of Patagonia: the Cañadón Asfalto Fm. and the La Matilde Fm. Both units also share other fossil invertebrates as the spinicaudatans (Fushunograptidae and Palaeolimnadiopseidae), bivalve mollusks ("*Diplodon*", Corbiculidae and Sphaeridae, *Diplodon simplex* and *D. matildensis*), gastropods, ostracods (Darwinulidae) and insect body fossils (Order Coleoptera and Hemiptera). The shared record of fossil invertebrates between the Cañadón Asfalto and the La Matilde formations suggests not only a coetaneous time of deposition, but also similar environmental conditions.

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