TRACE FOSSILS OF THE GLACIAL TO POSTGLACIAL TRANSITION IN THE EL IMPERIAL FORMATION (UPPER CARBONIFEROUS), SAN RAFAEL BASIN, ARGENTINA

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ABSTRACT: This paper reports the first ichnologic investigation in the San Rafael Basin, carried out in the glacial to postglacial transition, recorded in the El Imperial Formation at the Rio Atuel canyon. Following previous published stratigraphic schemes, three units were recognized in the field, but the upper one is ichnologically sterile and not studied in this paper. The lower unit shows evidence of glacial influence but lacks marine indicators and was deposited in a shallow paleovalley. Almost exclusively, the ichnofossils include locomotion traces produced by arthropods (*Diplichnites* and *Diplopodichnus*) or molluscs (*Archaeonassa*). Palynomorphs are terrestrial and show evidence of intense transport and deterioration. The middle unit contains a more varied range of ethologic categories: pascichnia (e.g., *Mermia, Gordia, Cochlichnus*), repichnia (e.g., *Paganzichnus, Diplopodichnus, Didymaulichnus, Diplichnites, Undichna*), and fodinichnia (e.g., *Treptichnus*) documented in transgressive deposits that record the glacial retreat and early postglacial interval. Many previous detailed studies carried out in contemporary successions of the basins of western Argentina have been the object of intense debate about the marine or nonmarine nature of these successions. In the middle unit, ichnofossils occur together with palynomorphs that show degradation and pyritization and contain scarce acritarchs suggesting brackish-water rather than fresh-water conditions in a fjord depositional system.

INTRODUCTION

Ichnologic studies supply information about interaction of living animals and substrate and are useful for exploring the influence of physical parameters on living communities. The original ichnofacies scheme (Seilacher, 1967) was based on bathymetric control in the marine realm; transitional and terrestrial environments were not extensively considered. More recently, several studies have pointed out the complexity of terrestrial environments. New ichnofacies have progressively been defined, whilst new lines of ichnologic research are being opened (see McIlroy, 2004, for discussion). However, postglacial fjords and marine engulfments of Quaternary and older glaciated times have received little attention.

The Gondwanan supercontinent was affected by a glacial episode that peaked during the Late Carboniferous (Visser, 1997). Basins containing glacial and glacial-retreat sequences occur in all southern-hemisphere continents. The glacial event was diachronous, spanning mainly the Late Carboniferous in western Gondwanan basins and the Early Permian to the east. In Argentina, such late Paleozoic basins occur all across the country. There are numerous ichnologic publications on the Argentinean glacially influenced successions (e.g., Aceñolaza and Buatois, 1991; Buatois and Mángano, 1993a, 1995, 2003; Pazos, 2000, 2002a, 2002b; Buatois and del Papa, 2003). However, the question of whether fresh water or diluted marine waters prevailed during glacial to postglacial transitions is far from completely solved, due to the scarcity of integrated approaches and reliable paleogeographic reconstructions. The San Rafael Basin of west-central Argentina (Fig. 1A) is crucial to any attempt to resolve the debate because it is considered an example of marine embayment and presents a relatively simple paleogeography, containing open marine facies to the west (Espejo, 1990). No integrated facies-ichnologic analysis has previously been conducted in this basin. This paper presents the first ichnologic record for the basin at the

Rio Atuel canyon locality (Fig. 1B), where the El Imperial Formation records the glacial to postglacial transition, in superbly exposed sections. This paper introduces evidence to elucidate the marine versus nonmarine dilemma of the ichnologic record in glacial to postglacial transitions. The database includes: (a) ichnologic content with ichnotaxonomic assignment; (b) stratigraphic location of ichnofossils and paleoenvironmental interpretation; (c) palynologic analysis, including taphonomic features of the palynomorphs, and (d) a discussion about previous paleoenvironmental interpretations and pyritization as a marine indicator.

GEOLOGIC SETTING

The San Rafael Basin is an elongated foreland basin with a NW–SE axis developed in the late Paleozoic (Andreis and Archangelsky, 1996). The early depositional history includes the glacial record and postglacial deltaic and fluvial depositional systems fed mainly with clastic debris eroded from lower Paleozoic units or igneous–metamorphic fragments sourced from the east (Espejo, 1990). During the Permian, the paleocurrent pattern from the east reversed to the west, indicating a magmatic-arc influence, also recorded in an enormous thickness of volcaniclastic deposits and fluvial and eolian intercalations (Andreis and Archangelsky, 1996). At the Rio Atuel canyon the El Imperial Formation unconformably overlies a basement composed of Devonian submarine-fan deposits (La Horqueta Formation, Fig. 2). The El Imperial Formation here is Late Carboniferous to Early Permian in age (García, 1996; Andreis and Archangelsky, 1996). The formation is unconformably overlain mainly by volcanic and pyroclastic deposits of the Permian Cochicó Group (Kleiman, 1998). The basin experienced contemporary sedimentation and tectonic deformation, particularly during Permian times as a result of the eastern migration of the magmatic arc (Espejo et al., 1996).
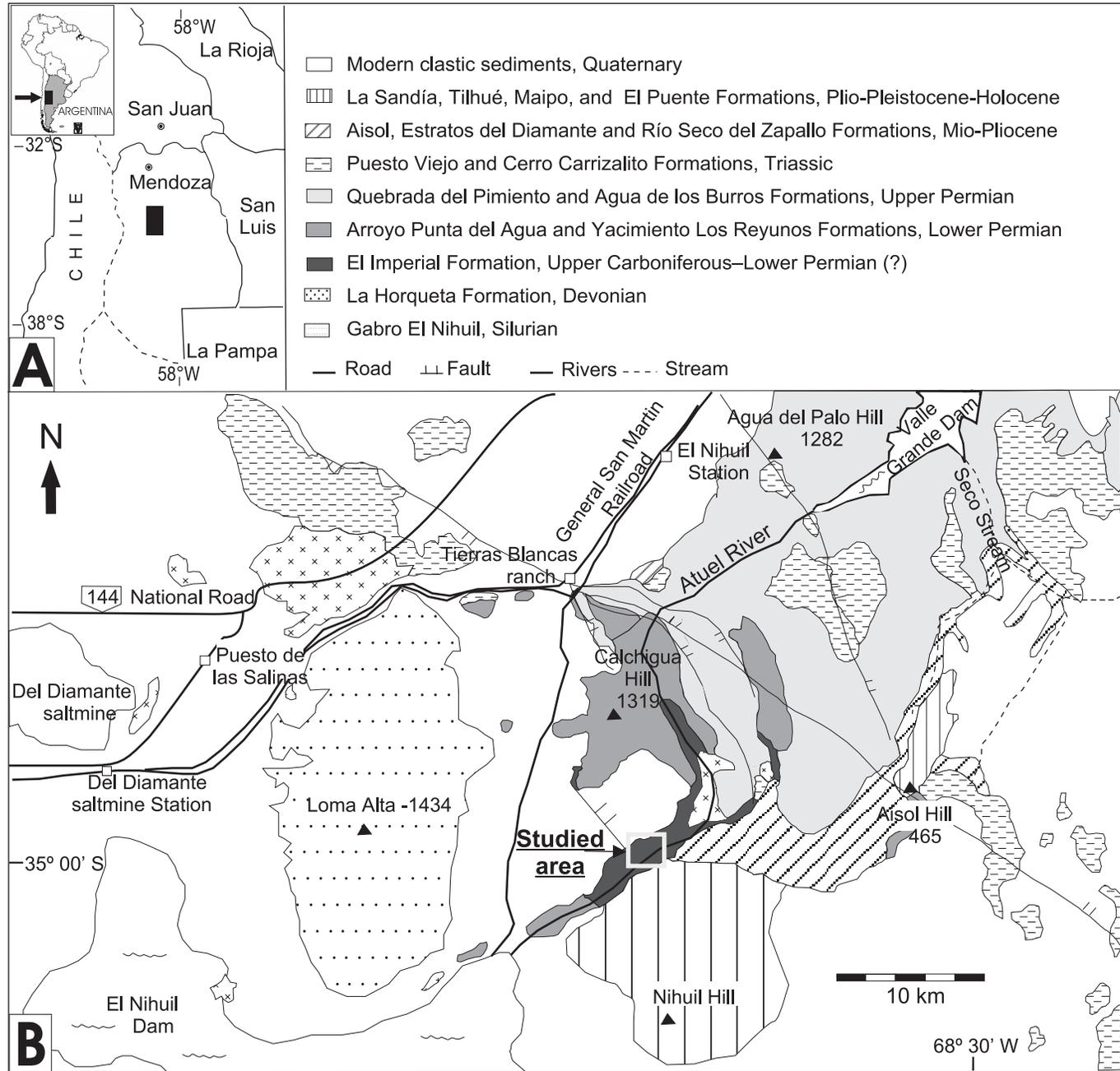
Fig. 1.—**A)** Geographic location of the studied area. **B)** Geologic map showing the studied area at the Atuel River canyon, San Rafael Basin, Mendoza province (modified from Kleiman, 1998).

Stratigraphic Units

The stratigraphic subdivision of the El Imperial Formation was carried out by Arias and Azcuy (1986) and Espejo (1990) and is followed in this paper. They recognized three stratigraphic units distinguishable in the field by lithology, lithofacies dominance, and paleoenvironmental differentiation (Fig. 2). In particular, Espejo (1990) identified variations in grain size and thickness above the surface that separates each stratigraphic unit, suggesting allocyclic controls, probably glacially related. Our

field observations introduce new data and confirm the importance of the surfaces suggested by Espejo (1990), but we disagree with the paleoenvironmental interpretation previously proposed for the lower unit.

The lower unit was previously interpreted as deep-water facies, turbidite-like, developed on a highly irregular remnant topography produced by uplift and erosion related to the Chanic Orogeny (Espejo et al., 1996). The middle unit records the Gondwanan glaciation, the postglacial transgression, and a final shallowing cycle with deltaic and fluvial deposits. The upper unit
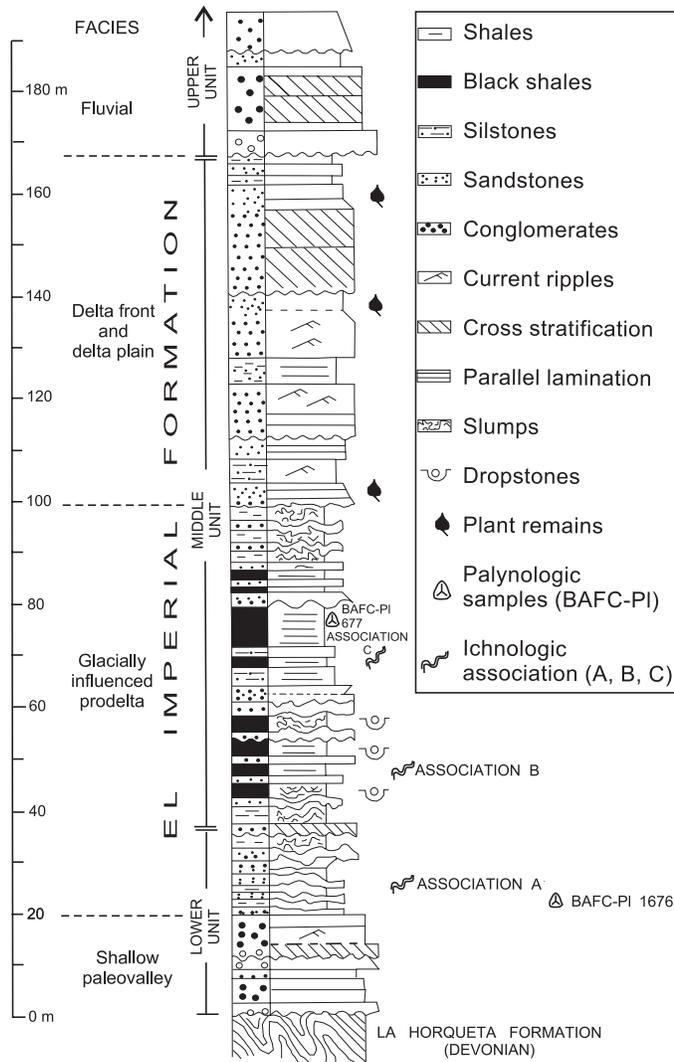
FIG. 2.—Stratigraphic column and facies of the El Imperial Formation (modified from Arias and Azcuy, 1986).

is continental and includes different types of fluvial systems (Arias and Azcuy, 1986; Espejo, 1990). New sedimentologic features, particularly geometry of the deposits and sedimentary structures, are incorporated in the analysis of the three stratigraphic units.

Lower Unit.—

*Description.—*This unit is approximately 40 m thick and is composed of shales with subordinate siltstones and fine sandstone beds. The basal contact is particularly well exposed in the western side of the Atuel River (km 13) for a distance of 1 km. The succession coarsens upward, but no thickening-upward trend is visible. Shales are mainly gray to black, are laminated to massive, and are less commonly bioturbated. Sandstones are paler and contain different types of sedimentary structures, dominated by poorly defined parallel lamination and massive beds. Sandstone thicknesses vary from 0.1 to 0.6 m and exceptionally 1 m. The thickest beds are dominated by climbing-ripple lamination. The basal contact is commonly sharp or sometimes loaded. Ripples

are strongly asymmetric and exhibit moderate to high angles of climbing. Some beds exhibit offshooting and more symmetric profiles, particularly stratigraphically higher in the unit. Trace fossils are restricted to some shales and siltstones.

*Interpretation.—*Arias and Azcuy (1986) interpreted this unit as a deep-sea fan filling paleorelief sculpted during the Chanic Orogeny. However, the water was not necessarily deep; turbidite-like beds have previously been recorded in other late Paleozoic basins interpreted as affected by glacial conditions, in both shallow and deep depositional settings (e.g., López Gamundí and Martínez, 2000; Pazos, 2000). Here, symmetric ripple lamination indicates wave action and deposition above storm wave base.

A highly variable paleotopography with abrupt lateral changes in thickness as suggested by Arias and Azcuy (1986) has been confirmed. Espejo (1990) interpreted this unit as deltaic in origin. A shallow paleovalley connected with a glaciated area situated to the east is a likely interpretation taking into account that glacial facies were observed, but not yet described, in the field. More detailed field investigation is being carried out to suggest a more accurate interpretation of this unit.

Middle Unit.—

*Description.—*This unit commences with a 30 m interval containing coarse-grained sandstone and scarce conglomerates, amalgamated in places, deposited in sharp contact over the lower unit. Sandstone beds are yellowish and brownish and exhibit erosional or loaded bases and thickness up to 1.5 m. Convolute lamination is common, and massive to graded bedding is dominant downward in the unit; trough cross-stratification is more common upward. Conglomerates show both matrix-supported and clast-supported fabrics, and they are composed of pebbles, cobbles, and boulders of varied composition including sedimentary and metamorphic rock fragments and subordinate granite clasts.

The succession continues with decimetric sandstone beds showing parallel lamination and tabular-planar cross stratification that in a short stratigraphic interval pass into deformed and slumped sandstones with folding and intense synsedimentary deformation. This interval has been mentioned in other works (e.g., Arias and Azcuy, 1986; Espejo, 1990) as a diagnostic stratigraphic interval in the succession. Matrix-supported green-gray diamictites, mainly pebbly sandstone and pebbly mudstone types containing granite blocks, are followed by gray shales with outsized clasts showing impact structures and intercalations of fine-grained sandstones with asymmetric to almost completely symmetric ripples. Stratigraphically upward the succession thins and shows a fining trend where shales turn from gray to black and sandstones are less common. The fining-upward interval is rich in ichnofossils and contains abundant record of locomotion and grazing traces. The lower part of the middle unit ends with several meters of black shales containing starved ripples and trace fossils together with scarce marine palynomorphs (sample 1677).

The upper part of the middle unit begins with a thickening- and coarsening-upward succession composed of turbidite-like sandstones with shales that stratigraphically upward change to gray and brownish colors, respectively. Fine-grained sandstones show tool marks; normal grading and climbing-ripple lamination are very common. Thicknesses vary from 5 up to 130 cm. The sequence continues with fine-grained to medium-grained sandstones and mudstones and intervals with coarse conglomerates (Espejo, 1990), followed by cross-stratified sandstones.

*Interpretation.—*The lower part of the middle unit contains deposits considered to be the prototype of glaciomarine sedimen-

tation in the area, mainly on the basis of herringbone stratification (e.g., Espejo, 1990). However, structures described by Espejo (1990, fig. 13) show a unidirectional paleocurrent pattern and lack the features of true herringbone structure. Herringbone only indicates tidal action. Thus, a marine environment based on that illustrated sedimentary structure alone is a misinterpretation. Moreover, diamictites contain features that indicate subaqueous deposition but they provide no information on salinity. Ripples are asymmetric or slightly asymmetric, indicating some wave influence and relative shallowness. Subaerial exposure features are lacking, and the depositional setting is a permanently sub-aqueous realm that sporadically received an enormous amount of glacially related debris, previously deposited in unstable areas and redeposited as slumped beds or subaqueous debris flows, currently described as diamictites in the literature.

It is important to point out that some beds may be interpreted as primary gravitationally reworked "tillites" probably in proxi-mal proglacial areas. Extrabasinal dropstones as well as boulders immersed in the pebbly sandstone beds are composed mainly of granitic and metamorphic lithologies rather than sedimentary rocks, evidencing a distant source (Pampean Ranges) rather than local basement. This suggests, in addition, that local tectonic activity was not involved in the source of debris and creation of accumulation space for this unit of the El Imperial Formation. The thinning- and fining-upward trend is similar to the glacial to postglacial transition recorded in the Guandacol Formation of the neighboring Paganzo Basin (e.g., Pazos, 2000, 2002a) and in the Loma de los Morteritos Formation of the Frontal Cordillera (Folguera et al., 2004) and indicates the increase in the accommo-dation space during the marine postglacial transgression. The most plausible interpretation is a fjord similar to the model of Kneller et al. (2004) for glacially related Carboniferous deposits of the western areas of the Paganzo Basin.

The upper part of the middle unit has been interpreted as deltaic, fluvial, and fan-deltaic (Arias and Azcuy, 1986; Espejo, 1990).

Upper Unit.—

The upper unit was interpreted as fluvial and lacustrine by Espejo (1990) and Espejo et al. (1996). In particular, pebble con-glomerates at the base of the upper unit (see Fig. 2) have been interpreted as part of a fan-delta system probably related to glacially controlled sea-level changes (Espejo, 1990), but the relationship of the glacial control with the magmatic arc remains obscure.

ICHNOLOGY

Systematic Ichnology

Archaeonassa fossulata *(Fenton and Fenton).—*

Irregularly curved traces preserved as concave epirelief, com-prising a median groove flanked by rounded or externally flat-

tened ridges. Width ranges from 0.8 to 1.1 cm. Ridge width varies between 0.2 and 0.4 cm, and relief is 0.1 cm or almost absent (Fig. 3A). Traces are very short, 5.5 cm, and not very well preserved. Overcrossing is absent, and the median groove is in part deep, having a very well developed or flattened "V" shape.

Archaeonassa is a very simple trace originally recorded from the Middle Cambrian Mont White Formation (British Columbia, Canada) by Fenton and Fenton (1937). The type material was reviewed by Yochelson and Fedonkin (1997). Material analyzed by Buckman (1994) presents ornamentation in the groove and ridges and, according to Melchor et al. (2003), should be removed from this ichnogenus. Buatois and Mángano (2002) recorded several specimens of *Archaeonassa* in Stephanian floodplain de-posits of the Tupe Formation in the Paganzo Basin (Argentina). Other possible late Paleozoic records originally assigned to *Scolicia* isp. from Africa were excluded from that ichnogenus by Pazos (2002b) and are now considered examples of *Archaeonassa* (cf. Melchor et al., 2003).

This ichnogenus is considered an endichnial subsurficial bur-row (Yochelson and Fedonkin, 1997) excavated immediately be-low the water–sediment contact, or a surficial grazing trail (Buckman, 1994; Buatois and Mángano, 2002). Possible tracemakers in nonmarine environments are annelids and molluscs (Buatois and Mángano, 2002) and also molluscs, either gastropods or bivalves, in marine and brackish environments (Buckman, 1994). In our case, no evidence of marine influence has been recognized, and freshwater molluscs are the most probable tracemaker. Ma-terial: two specimens collected in slab A (CPBA-20163).

Cochlichnus anguineus *(Hitchcock).—*

Sinusoidal, horizontal trails (Fig. 3B) with regular to irregular sinusoids in a single specimen, preserved as convex hyporelief and exhibiting a straight or gently curved path. Width is 0.1 cm, length is 3.0 cm, and wavelength is 0.2–0.3 cm.

Cochlichnus is a very common component of Carboniferous ichnofaunas in Argentina (Buatois and Mángano, 1993a; Pazos, 2002b), but it has also been recorded in Permian (Buatois et al., 1997a) or Triassic (Melchor et al., 2003) ichnofaunas. Carbonifer-ous examples occur in lacustrine and delta-plain facies (Buatois and Mángano, 1993a; Zavala et al., 1993; Pazos, 2002b), and Permian and Triassic examples are known in floodplain and lacustrine facies (Buatois et al., 1997a; Buatois and del Papa, 2003; Melchor, 2004).

Candidate producers for *Cochlichnus* are worms, worm-like animals, nematodes, insect larvae (dipteran), agnatha, and leeches (Tasch, 1968; Gluszek, 1995; Metz, 1987; Buatois et al., 1997a). Pazos (2002b) recorded *Cochlichnus antarticus* (Tasch, 1968), dis-tinguishable from *C. anguineus* by the lateral imprints, suggesting an arthropod rather than a nematode as a possible tracemaker. Populations of small and large traces in nonmarine successions have been attributed to different growth stages (Buatois et al., 1997a) or different producers (Melchor et al., 2003). In our mate-rial, specimens are very small, and transitions to winding traces suggest grazing rather than mere locomotion.

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Fɪɢ. 3 (opposite page).—Trace fossils from the El Imperial Formation at the Rio Atuel Canyon locality. **A)** *Archaeonassa fossulata,* concave epirelief. **B)** *Cochlichnus anguineus,* convex hyporelief. **C)** *Didymaulichnus lyelli,* concave epirelief. **D)** *Diplichnites gouldi,* convex hyporelief. **E)** *Diplopodichnus biformis,* concave epirelief. **F)** *Diplopodichnus biformis,* convex hyporelief. **G)** *Diplopodichnus biformis,* with lateral traces, concave epirelief. **H)** *Gordia marina,* convex hyporelief. **I)** *Helminthoidichnites tenuis,* convex hyporelief. **J)** *Mermia carickensis,* convex hyporelief. **K)** *Paganzichnus carboniferus* convex hyporelief. **L)** *Treptichnus pollardi,* concave epirelief. **M)** *Treptichnus pollardi,* concave epirelief. **N)** *Undichna* isp, convex hyporelief. **O)** Arthropod trackway, concave epirelief. Scale in millimeters, coin radius 5 mm.
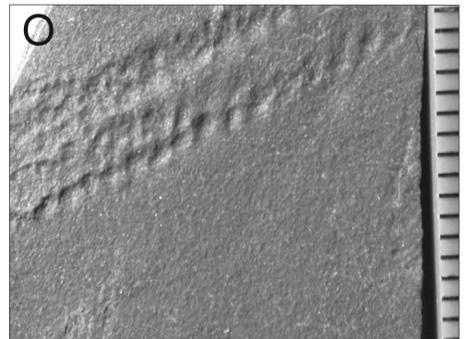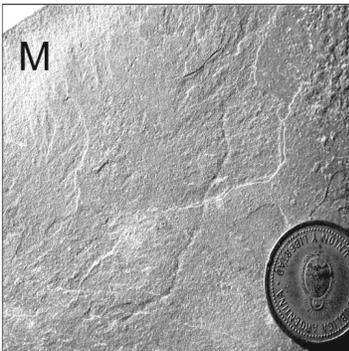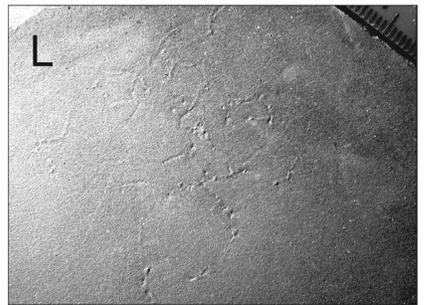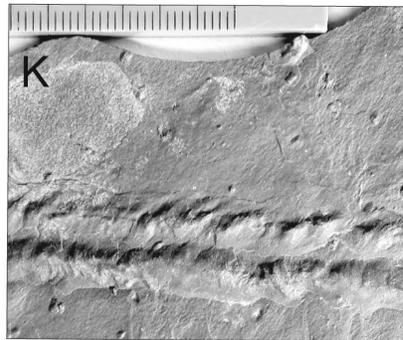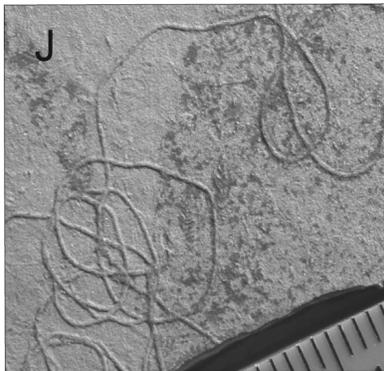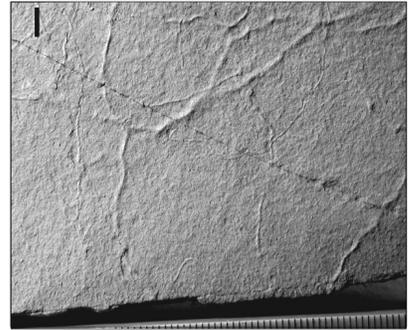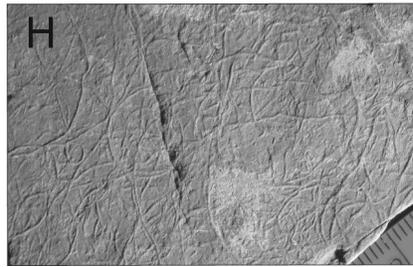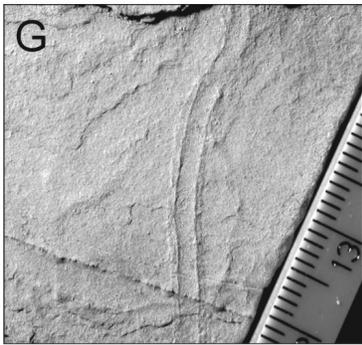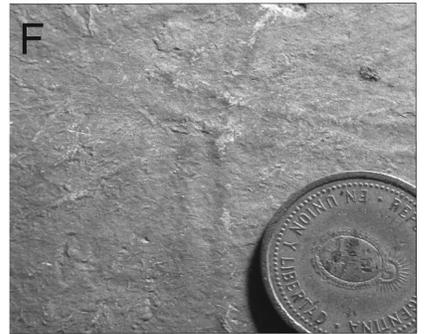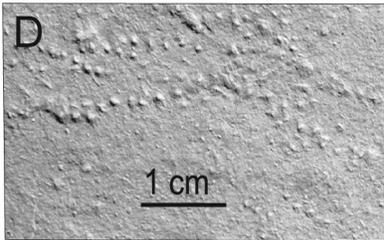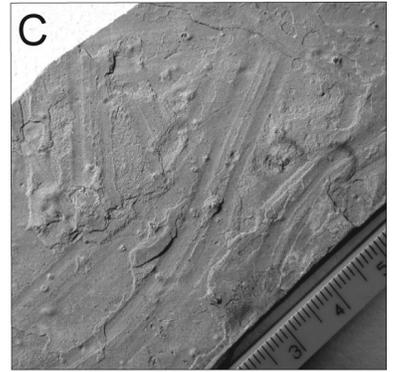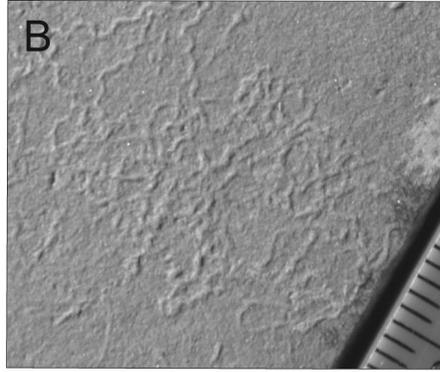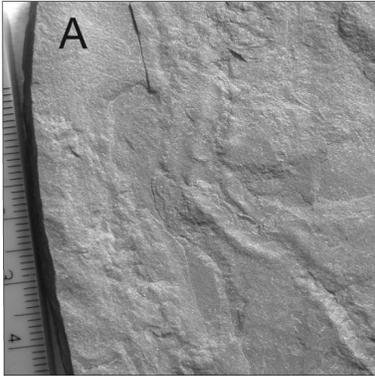
Lithofacies indicates fully submerged substrates above wave base in a marine-influenced environment. This scenario was probably more suitable for worms and worm-like animals than insect larvae. Material: one slab (A) with several specimens (20170).

Didymaulichnus lyelli *(Rouault).*—

Very simple, bilobate structures with marginal smooth lobes and a central furrow (Fig. 3C) sometimes partially preserved, with straight and gently curved course. Overcrossing is common, and looping is absent. Width is 0.4–0.8 cm, and the maximum length recorded is 5.3 cm; they are preserved as positive epirelief and rarely as hyporelief. This ichnogenus differs from *Gyrochorte* in the opposite relief for epichnial and hypichnial forms. The lack of scratch ornament distinguishes this ichnogenus from *Cruziana*, whilst the absence of smooth ornament distinguishes it from *Didymaulichnus alternatus*.

This ichnospecies has been interpreted as locomotion traces of gastropods, bivalves, or arthropods, and it is a common component of glacial Carboniferous ichnocoenoses in Argentina (e.g., Buatois and Mángano, 1993a; Pazos, 2000). Arthropods are the most likely tracemakers. Material: two slabs (A-B) with several specimens (20167).

Diplichnites gouldi *(Gevers).*—

Trackway with opposite symmetry, composed of two rows of small, closely spaced circular imprints arranged in a compound trackway (Fig. 3D). The number of imprints is not clearly displayed but is less than 10. The trackway is straight, and several segments can be differentiated. External width is 0.4 cm, and trackway course can be traced for up to 5.3 cm. Set overlap is 0.3–0.4 cm, and stride is 0.9–1.0 cm. Some very short trackways and isolated elongated imprints complete the different forms preserved as positive hyporeliefs.

This ichnospecies presents a pattern similar to the trackways described by Buatois et al. (1998a) as *Diplichnites gouldi* type B; it differs in size from Silurian material of Australia (Trewin and McNamara, 1995) and from the Lower Old Red Sandstone in Wales (Morrissey and Braddy, 2004). The number of imprints suggests an arthropod with fewer legs than myriapods, which use more legs in locomotion (see Manton, 1977). Material: one slab (A) with one specimen and several parts (20171).

Diplopodichnus biformis *(Brady).*—

Trackways consist of two rows of parallel epichnial grooves, or hypichnial ridges (Figs. 3E–G). The grooves are elongated and disposed perpendicular to the trace axis. Specimens with epichnial grooves are smaller than others with hypichnial ridges. Epichnial specimens are 0.3–0.4 cm width, and hypichnial forms are 0.7–0.9 cm wide and 3.0–12 cm long.

Diplopodichnus has been interpreted as a locomotion trace of arthropods, probably millipedes and myriapod-like animals. It is a common trace in nonmarine facies from Ordovician to Permian and less commonly recorded in marginal marine (estuarine) facies (Buatois et al., 1998a). The relationship between *Diplichnites* and *Diplopodichnus* has been taxonomically discussed in detail by Buatois et al. (1998b). Taking into account that no slabs contain both ichnogenera, some *Diplopodichnus biformis* lacking lateral traces look like undertrack preservations of the more complete specimens, although transition between *Diplichnites* and *Diplopodichnus* has not been recognized. Material: several slabs (A–H) with numerous specimens (20165).

Gordia marina *(Emmons).*—

Simple, fine, irregular trails that may cross themselves (Fig. 3H); width is less than 0.1 cm, and length is very difficult to measure due to overcrossing. Preservation is as hypichnial ridges in siltstones.

Gordia is distinguishable from other grazing traces by self-crossing and constitutes a common trace in lacustrine or fjord depositional systems in glaciated Carboniferous basins (Buatois and Mángano, 1993b; Pazos, 2000; Buatois and del Papa, 2003). It is also known from the Neoproterozoic and may be assigned to vermiform organisms (e.g., Vidal et al., 1994). Material: Two slabs (A–B) with several specimens (20169).

Helminthoidichnites tenuis *(Fitch).*—

Simple, unbranched, straight or gently curved, horizontal trails preserved as epichnial grooves or less common hypichnial ridges (Fig. 3I). Width is 0.05–0.1 cm, and maximum length (field specimens) is 5.5 cm.

Helminthoidichnites has been reported from Carboniferous (e.g., Buatois and Mángano, 1993b, 2003; Pazos, 2002b), Permian (Buatois and Mángano, 2002), and Triassic (Melchor et al., 2003) successions in Argentina and from Tertiary fluvial deposits of Switzerland (Uchman et al., 2004). Usually it is interpreted as a grazing trace produced by nematodes or insect larvae (Buatois et al., 1997b). Material: two slabs (A–B) with several specimens (20174).

Mermia carickensis *(Smith).*—

Very thin, sinuous, and intensely looped trails (Fig. 3J). Individual specimens are difficult to distinguish due to self-crossing. Preserved as hypichnial ridges or more rarely as epichnial grooves. *Mermia carickensis* is a grazing trace known from nonmarine facies and the archetypal trace of the *Mermia* ichnofacies (Buatois and Mángano, 1995). This ichnogenus has previously been recorded in Carboniferous successions of Argentina (Buatois and Mángano, 1993a, 2003; Pazos 2002b) and in the Old Red Sandstone of Scotland (Pollard and Walker, 1984). Nematodes are the most likely producers of this ichnofossil (Buatois and Mángano, 1993a). Material: two slabs (A-B) with several specimens (20168).

Paganzichnus carboniferus *(Pazos).*—

Trackway composed of two rows of elongated closely spaced imprints resembling rice grains disposed oblique to the middle line (Fig. 3K). Distance between them is variable, and overlapping is common. Width is 0.9 cm and length is 5.3 cm. Buatois and Mángano (2003) considered *Paganzichnus* (Pazos, 2000) to be an invalid ichnogenus and the ichnospecies as a variant of ichnogenus *Maculichna* (Anderson, 1977). We accept that *Paganzichnus* probably could be a junior synonym of another ichnogenus, particularly an arthropod trackway, but taking into account ichnotaxabases (cf. Trewin, 1994), *Maculichna* is not a suitable ichnogenus for relocating *Paganzichnus*. An emendation of *Maculichna* is needed before allowing the inclusion of trackways like *P. carboniferus* and possibly other material. *Paganzichnus* may have been produced by an arthropod with undifferentiated locomotory appendages, such as myriapod-like animals. Material: two slabs (A–B) with specimens (20170).

Treptichnus pollardi *(Buatois and Mángano).*—

Epichnial thin grooves, 0.1 cm wide, composed of straight, zig-zag, and curved segments joined by small oval pits (Figs. 3L,

M). Maximum length is 4.5 cm. *T. pollardi* has previously been reported from Carboniferous successions (Buatois and Mángano, 1993a, 1993b), Triassic deltaic facies (Melchor, 2004), and Tertiary fluvial deposits (Uchman et al., 2004). *T. pollardi* has been interpreted as a fodinichnion (deposit feeder) of vermiform organisms (Buatois and Mángano, 1993b). Material: Four slabs (A–D) with several specimens (20164).

Undichna *isp. (Anderson).*—

Sinusoidal trail preserved as convex hyporelief or concave epirelief. The material is very fragmentary (Fig. 3N), and it does not allow any ichnospecific assignment. However, out-of-phase traces are a feature of *U. britannica* (Higgs, 1988), while slab B contains single sinusoidal traces that characterize *U. unisulca* (de Gibert et al., 1999). *Undichna* is a trail of a swimming fish (Anderson, 1976; Higgs, 1988; Trewin, 2000) and a very common trace fossil in upper Paleozoic glacially influenced sediments (e.g., Buatois and Mángano, 1993a; Trewin et al., 2002). Preservation could be favored in lacustrine shales, but the trace fossil is not solely indicative of nonmarine facies, as suggested by de Gibert et al. (1999). Material: two slabs (A-B) with two specimens (20173).

Open Nomenclature: "Arthropod Trackways".—

Two rows having closely spaced imprints of oval or circular shape (Fig. 3O). Each row contains external and internal imprints arranged in a poorly defined form, with highly variable organization (20166A). The other specimen (20166B) presents less differentiated imprints but arranged in two rows like the first one. Width is 0.4 cm to 0.6 cm, and length is 2.1 cm to 5.0 cm, and both are preserved as negative epirelief in black shales. Ichnotaxonomy of arthropod trackways is a matter of debate regarding proliferation of ichnogenera based on inappropriate material (see Trewin, 1994; Braddy, 1995). Therefore, this fragmentary material is retained in open nomenclature. These trackways are similar to the arthropod trackways reported from the Carboniferous of Chile that were assigned to a new ichnogenus named *Lirquenichnus* (Bandel and Quinzio-Sinn, 1999). However, the diagnosis of *Lirquenichnus* is very poor, and it deserves a more detailed ichnotaxonomic treatment. Material: two small slabs (A-B) with two specimens (20166).

Trace-Fossil Associations

Association A.—

This association is recorded in the lowermost part of the lower unit of the El Imperial Formation. Traces assigned to the ichnogenera *Diplichnites* and *Diplopodichnus* are much more common than *Archaeonassa fossulata* and unnamed arthropod trackways. *Diplichnites gouldi* and *Diplopodichnus biformis* occur in light-colored siltstones, and *Archaeonassa* and unnamed arthropod trackways are present in dark shales containing palynomorphs of the sample BAFC-Pl 1676.

Association B.—

Documented in the glacial-retreat deposits of the middle unit, this association occurs particularly in the interval with dropstones and fine-grained diamictites. The association is dominated by *Diplopodichnus biformis*, feeding and grazing traces (*Treptichnus pollardi*, *Helminthoidichnites tenuis*), arthropod trackways (*Paganzichnus carboniferus*), and minor fish traces (*Undichna* isp.). Just 2 m stratigraphically upward, the succession becomes more

fine grained, with abundant dropstones, and the ichnologic record is there dominated by grazers (*Gordia marina, Mermia carickensis, and Cochlichnus anguineus*).

Association C.—

Association C is present in black shales with scarce or no dropstones. It is composed exclusively of *Didymaulichnus lyelli* and *Diplopodichnus biformis*. The levels with *Didymaulichnus* include intensely bioturbated beds that also yielded a diverse palynomorph assemblage with scarce marine acritarchs (sample BAFC-Pl 1677).

PALYNOLOGY

Two dark gray shale samples of the lower and middle units of the El Imperial Formation yielded two assemblages (Fig. 2). The twenty-four palynomorph species identified (di Pasquo 2004, unpublished data) have been described fully in previous papers on Late Carboniferous assemblages of Argentina.

Sample BAFC-Pl 1676 contains poorly preserved spores, scarce pollen grains, and phytoclasts such as tracheids and a few cuticles amongst other nonstructured debris. Many specimens were difficult to determine beyond generic level because of their dark color and the cracked and biodegraded nature of the exines. The only recognizable species were assigned to *Brevitriletes*? *cornutus*, *Horriditriletes? curvibaculosus,* and *Cristatisporites* spp. No phytoplanktonic elements, either marine or continental, were found.

Sample BAFC-Pl 1677 yielded poorly preserved palynomorphs. Most of them are dark, cracked, and degraded and show euhedral pyrite voids (Fig. 4). The phytoclastic fraction constitutes 60% of the phytoclast / miospore assemblage represented by tracheids, cuticles, and other debris (Fig. 4D). The other 40% corresponds to the miospore group, which is dominated by lycophyte spores represented by several species of *Cristatisporites* and *Vallatisporites* (Fig. 4A, B), unrecognizable spores, others of pteridophytic affinity (e.g., *Punctatisporites, Laevigatosporites,* Fig. 4F), scarce monosaccate pollen grains (e.g., *Potonieisporites* spp., *Plicatipollenites* spp., Fig. 4E, H), and rare acritarchs (*Gorgonisphaeridium* sp., Fig. 4G).

Based on the comparison of spore assemblages (achieved to species level) with others previously published for the Upper Carboniferous to Lower Permian succession of the San Rafael Basin (e.g., García, 1995, 1996), sample BAFC-Pl 1676 can similarly be stratigraphically located with respect to the association documented by García (1996, BAFC-Pl 785).

Sample BAFC-Pl 1677 contains palynomorphs not mentioned by García (1995, 1996), including the acritarch *Gorgonisphaeridium* sp. Recently, Césari and Gutiérrez (2001) referred such assemblages to an integrated biostratigraphic scheme of late Paleozoic basins being attributed to the *Raistrickia densa–Convolutispora muriornata* (DM) Biozone. In particular, the assemblages of San Rafael Basin were included in the Sub-Biozone B, suggesting a late Moscovian–Kasimovian age, on the basis of the presence of several spores such as *Cristatisporites scabiosus* and *C. stellatus* and the dominance of monosaccate pollen grains.

Paleoecologic and Taphonomic Implications

The dominance of lycophyte spores in BAFC-Pl 1677 suggests that most of the assemblage was derived from nearby lakes or peats. Poor preservation of monosaccate pollen grains (related to Cordaitales and Coniferales) and most miospore specimens have suffered mechanical damage, such as cracking (Fig. 4A, B) and breaking of spore exines (Fig. 4F, H), attributed to fluvial trans-
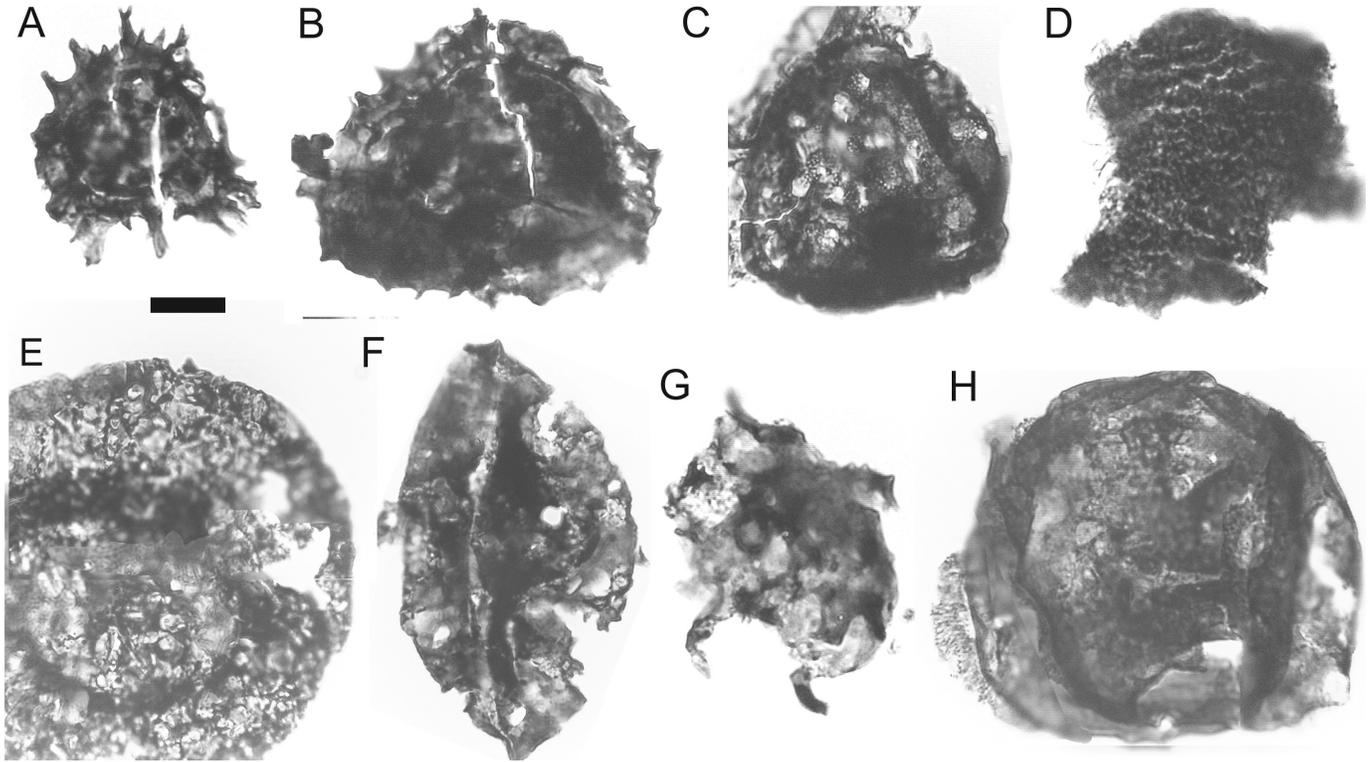
Fɪɢ. 4.—Palynomorphs from the El Imperial Formation at the Rio Atuel Canyon locality. **A)** *Cristatisporites inconstans*, BAFC-Pl 1677(1) EF Y47/1 with cracking. **B)** *Cristatisporites scabiosus*, BAFC-Pl 1677(1) EF P60/1 with cracking. **C)** Central body monosaccate pollen with pyrite, BAFC-Pl 1677(1) EF C28/1. **D)** Unstructured phytoclast with filaments (bacterial or fungal sheath?), BAFC-Pl 1677(1) EF Z36/0. **E)** *Potonieisporites novicus*, BAFC-Pl 1677(1) EF V29/4. **F)** *Laevigatosporites vulgaris*, BAFC-Pl 1677(1) EF Y48 with broken exines. **G)** *Gorgonisphaeridium* sp., BAFC-Pl 1677(1) O31/2. **H)** *Potonieisporites neglectus* (central body), BAFC-Pl 1677(1) EF H58/0 with broken exines. Scale bar: Figs. D, G – 1 cm = 10 μm (x1000). Figs. A, B, C, E, H – 1 cm = 15 μm (x 750). Fig. F – 1 cm = 20 μm (x 500). EF = England Finder coordinates.

portation and desiccation in temporary depositional sites prior to final deposition (Campbell, 1999). This damage probably favored the biologic degradation of the exines by bacterial and fungal activity (Fig. 4D, E, F, H) including the formation of euhedral pyrite within miospore exines and tissue debris (Fig. 4C, E, F, H). Equant pyrite in palynomorph forms during early diagenesis before compaction, typically in marine waters under anoxic bottom conditions (Canfield and Raiswell, 1991). Sawlowicz (2003) indicates that the morphology of pyrite is strongly dependent on the sulfate saturation level and the rate of formation of crystals; euhedral pyrite may form slowly at low saturation levels. On the other hand, the small size of the crystals (less than 5 μm) could indicate their formation in an anoxic and sulfidic water column, as in the modern Black Sea (Wilkin et al., 1997).

Sawlowicz (2003) also mentioned that in strictly anoxic systems pyrite can form very quickly at low temperatures. The nearly complete dissolution of the pyrite that left only regular and irregular voids on spore exines may indicate a later change to slightly more oxygenated bottom conditions. Sample 1677 comes from a shale interval with bioturbation (*Didymaulichnus lyelli*), suggesting that pyrite oxidation may be related to oxygenation during or after bioturbation. The dissolution of the euhedral pyrite from the palynomorph walls could be caused by the activity of benthic organisms favored during seasonal increases in the oxygen content of the bottom surface (Canfield and Raiswell, 1991, p. 371).

CONTRIBUTION OF ICHNOLOGY AND PALYNOLOGY TO THE PALEOENVIRONMENTAL INTERPRETATION

In the lower unit, lack of marine palynomorphs or marine fossils suggests fresh water. Palynomorphs were transported and reflect the source rather than the sedimentation area. The ichnofossils (Association A) match more with permanently submerged fresh-water systems (e.g., Melchor et al., 2003; Morrissey and Brady, 2004) than with normal marine or brackish conditions.

The lower part of the middle unit is a glacially influenced (fjord) depositional system. The ichnofossils documented (Associations B and C) are similar to those of Carboniferous glaciated successions of Argentina (e.g., Aceñolaza and Buatois, 1991; Buatois and Mángano, 1993a, 2003; Pazos, 2000, 2002a, 2002b). The composition of Association B shows a dominance of arthropod locomotion and a replacement by grazers (nematodes). The first group is endemic in glacial deposits (Pazos, 2002b) but the second one could indicate a nonmarine (fresh-water) environment that matches with the Mermia ichnofacies (cf. Buatois and Mángano, 1995) but also may indicate a very reduced salinity according to Pazos (2002b). The paleoenvironment of Association C is related to that of Association B, considering the thinning- and fining-upward trend in the succession that exhibit a progressive replacement of siltstones by black shales and marine influence (acritarchs), but the ichnodiversity is reduced in the black shales.

Reduced salinity is to be expected in a Carboniferous glacially influenced basin with a funnel shape (e.g., fjords) because normal marine waters are pushed away by an enormous amount of fresh-water discharge from glaciated areas (Pazos, 2002b). Unfortunately, many models for brackish environments are based on temperate successions that are not glacially related, and are probably not applicable to all glacially influenced marine facies (Pazos, 2002b), where sometimes variations in sedimentation rate, turbidity, temperature, and salinity are common.

Other records almost identical in composition to that of Association C have been reported from several early postglacial deposits (e.g., Pazos, 2000, 2002a, 2002b). These deposits are a common component of postglacial units in several late Paleozoic basins of Argentina (see López Gamundí, 1997) recording the postglacial transgression after the glacial lowstand. For instance, in the Paganzo Basin this interval is very rich in organic matter and contains a euryhaline fauna documented in localities previously interpreted as lacustrine (see, Martínez, 1993; Pazos, 2000). Black shales do not necessary indicate deep waters but a geologically instantaneous transgression (López Gamundí, 1989) possibly related to cycles of third order or higher frequency (Pazos, 2002a). Several palynomorphs, including acritarchs, were reported from glacial deposits in the Late Carboniferous Tarija Basin, but they are reworked species from Devonian successions and are useless for paleoenvironmental proposals (see di Pasquo, 2003). Conversly, in the Paganzo Basin, several levels with acritarchs and marine algae (Ottone, 1991) occur in areas where Devonian rocks are not in the source area and indicate a primary origin of those elements. However, marine palynomorphs appear in a very reduced percentage, usually less that 5% (see Ottone, 1991) and were neglected in previous studies that interpreted a lacustrine origin for these successions. Ichnofossils reported from that area included arthropod trackways and grazing traces (Pazos, 2000) suggesting intervals with reduced salinity rather than pure fresh water (Pazos 2002b).

Buatois and Mángano (2003) reported from the same region a record composed of arthropod trackways and grazing traces (e.g., *Mermia*). They listed nonmarine palynomorphs, without any taphonomic information, that supported the fresh-water interpretation and severely criticized the interpretation published by Pazos (2002b). These data were later used to favor a fresh-water interpretation of the ichnofossils recorded in the glacial to postglacial fjord deposits of the Paganzo Basin (Buatois and Mángano, 2004). This controversy is also present in the interpretation of varves in the glacially influenced succession of the Rio do Sul Formation in the Parana Basin, traditionally interpreted as lacustrine but reinterpreted as brackish by Nogueira and Netto (2001). Varves is a term traditionally assumed to be indicative of a lacustrine environment, but Holocene Arctic fjords are examples of "marine" varves (see Pazos, 2002b, for discussion).

In the San Rafael Basin, particularly at the Rio Atuel canyon, the Devonian La Horqueta Formation is sterile (García, 1996), and the acritarch reported in the sample BACF- PI 1677 is not assignable to any Devonian form but resembles the forms described by Garcia (1996) several kilometers to the west, in a region considered to be the depocenter of the basin by Espejo (1990). A primary origin is a plausible explanation for their occurrence in the El Imperial Formation. Useful information usually not included in studies that combine ichnology with palynology is the taphonomy of the palynomorphs. We can now prove that a mere list of palynomorphs, without any taphonomic description, may not be sufficient to support a fresh-water origin, particularly taking into account that terrestrial palynomorphs reflect the source rather than the accumulation area. For instance, these features suggest for sample 1677 comparatively less transport and deterioration than for sample 1676 and also indicate marine waters, or at least a mixture of fresh and saline waters, considering pyritization of palynomorphs. Because pyritization is developed mainly under anoxic bottom conditions, the voids left by dissolution of the pyrite from the palynomorph walls may indicate that bioturbation occurred in oxygenated conditions after pyritization. The maximum marine influence could be located in the first levels of the black shales, more precisely where evidence of ice rafting (dropstones) or fresh-water discharge from ice or icebergs disappears.

CONCLUSIONS

The first ichnologic record for the San Rafael Basin is reported. It includes eleven ichnogenera and unnamed trackways. Ichnotaxa are: *Archaeonassa fossulata, Cochlichnus anguineus, Didymaulichnus lyelli, Diplichnites gouldi, Diplopodichnus biformis, Helminthoidichnites tenuis, Gordia marina, Mermia carickensis, Paganzichnus carboniferus, Treptichnus pollardi,* and *Undichna* isp.

The lower unit of the El Imperial Formation at the Rio Atuel canyon exhibits some features of glacial influence and abrupt lateral changes in thickness and facies. They are interpreted in terms of a very irregular paleotopography infilling a shallow paleovalley. Thus, marine elements have not been reworked and indicate marine waters. Ichnofossils are dominated by arthropod locomotion traces (Association A) represented by *Diplichnites* and *Diplopodichnus* and other components such as *Archaeonassa*, possibly produced by molluscs. Palynomorphs are nonmarine, and exhibit fluvial (?) transportation damage and lack of marine elements, indicating fresh waters.

The middle unit records the glacial episode and contains subaqueous diamictites deposited in a fjord depositional system, rather than an open glaciomarine environment as previously was suggested by Espejo (1990). Trace fossils include abundant trails and trackways (Association B) composed mainly of *Paganzichnus, Undichna,* and arthropod trackways and also by grazing traces like *Gordia, Mermia,* and *Cochlichnus,* recorded in a progressively thinning-upward succession containing abundant ice-rafted debris. A black shale interval bearing Association C, composed of *Didymaulichnus* and *Diplopodichnus,* yielded a very diverse palynologic association including acritarchs. This interval represents the marine transgression and confirms for the first time the marine influence in this area of the basin.

The pyritization process affecting the palynomorphs at this level is also described for the first time in this basin. Extensive subaqueous bacterial degradation, pyritization of continental palynomorphs, and scarce, poorly preserved acritarchs support a marginal or brackish paleoenvironment. The almost complete dissolution of the pyrite crystals that left only regular and irregular voids on spore exines may indicate a later change into slightly more oxygenated bottom conditions. This shale interval having trace fossils (exclusively *Didymaulichnus*) indicates that oxygenation is related to bioturbation in a relatively low-energy bottom with a low rate of sedimentation (decantation process), supporting a close relationship with marine waters.

ACKNOWLEDGMENTS

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