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The Cambrian-Ordovician siliciclastic platform of the Balcarce Formation (Tandilia System, Argentina): Facies, trace fossils, palaeoenvironments and sequence stratigraphy

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ABSTRACT

The Lower Palaeozoic sedimentary cover of the Tandilia (Balcarce Formation) is made up of thick quartz arenite beds together with kaolinitic claystones and thin fine-grained conglomerates. The Balcarce Formation was formed in the nearshore and inner shelf environments of a tide-dominated and storm influenced open platform. It shows many features suggesting tidal sedimentation. Coarse-grained facies were formed by sand bar migration and accretion. Heterolithic packages are interpreted as interbar (swale) deposits. Subordinated HCS sandstones indicate storm events. The recognition of thick progradational clinoforms allows to confirm that the Balcarce sea was open to the south, as suggested years ago through palaeocurrent interpretation. The great abundance and variety of trace fossils is among the most outstanding characteristics of this unit. The ichnotaxa that have been recognised so far are: *Ancorichnus ancorichnus*, *Arthrophycus alleghaniensis*, *Arthrophycus* isp., *Bergaueria* isp., *Cochlichnus* isp., *Conostichus* isp., *Cruziana furcifera*, *Cruziana* isp., *Daedalus labeckei*, *Didymaulichnus lyelli*, *Didymaulichnus* isp., *Diplichnites* isp., *Diplocraterion* isp., *Herradurichnus scagliai*, ?*Monocraterion* isp., *Monomorphichnus* isp., *Palaeophycus alternatus*, *Palaeophycus tubularis*, *Palaeophycus* isp., *Phycodes* aff. *pedum*, *Phycodes* isp., *Plagiogmus* isp., *Planolites* isp., *Rusophycus* isp., *Scolicia* isp. and *Teichichnus* isp. Trace fossils have traditionally been used to assign the Balcarce Formation to the Lower Ordovician, due to the presence of *Cruziana furcifera*. However, *Plagiogmus* is typical of Cambrian successions world-wide.

KEYWORDS **Cambrian-Ordovician. Quartz arenites. Shallow marine. Trace fossils. Tandilia System. Argentina.**

INTRODUCTION

The Tandilia System contains a Lower Palaeozoic quartz arenite sequence, without body fossils, but bearing an abundant variety of trace fossils, most of which can be attributed to the activities of trilobites. Attention has been paid to many of these since the first investigations by Borrello (1966) and the following papers by Aceñolaza (1978), Alfaro (1981), Regalía and Herrera (1981), Zalba et al. (1982), Cingolani et al. (1985), del Valle (1987a, b), Poiré and del Valle (1994, 1996) and Poiré (1998).

On the contrary, and as pointed out by Poiré et. al. (1984), these Palaeozoic deposits, with abundant trace fossils, rest on siliciclastic and carbonate Precambrian sedimentary sequences, bearing a low number and variety of trace fossils.

The purpose of this paper is to summarise the knowledge available on these Lower Palaeozoic rocks, to show the progress that has lately been made on this subject, and to discuss the significance of these trace fossils in relation to the age of this sedimentary sequence.

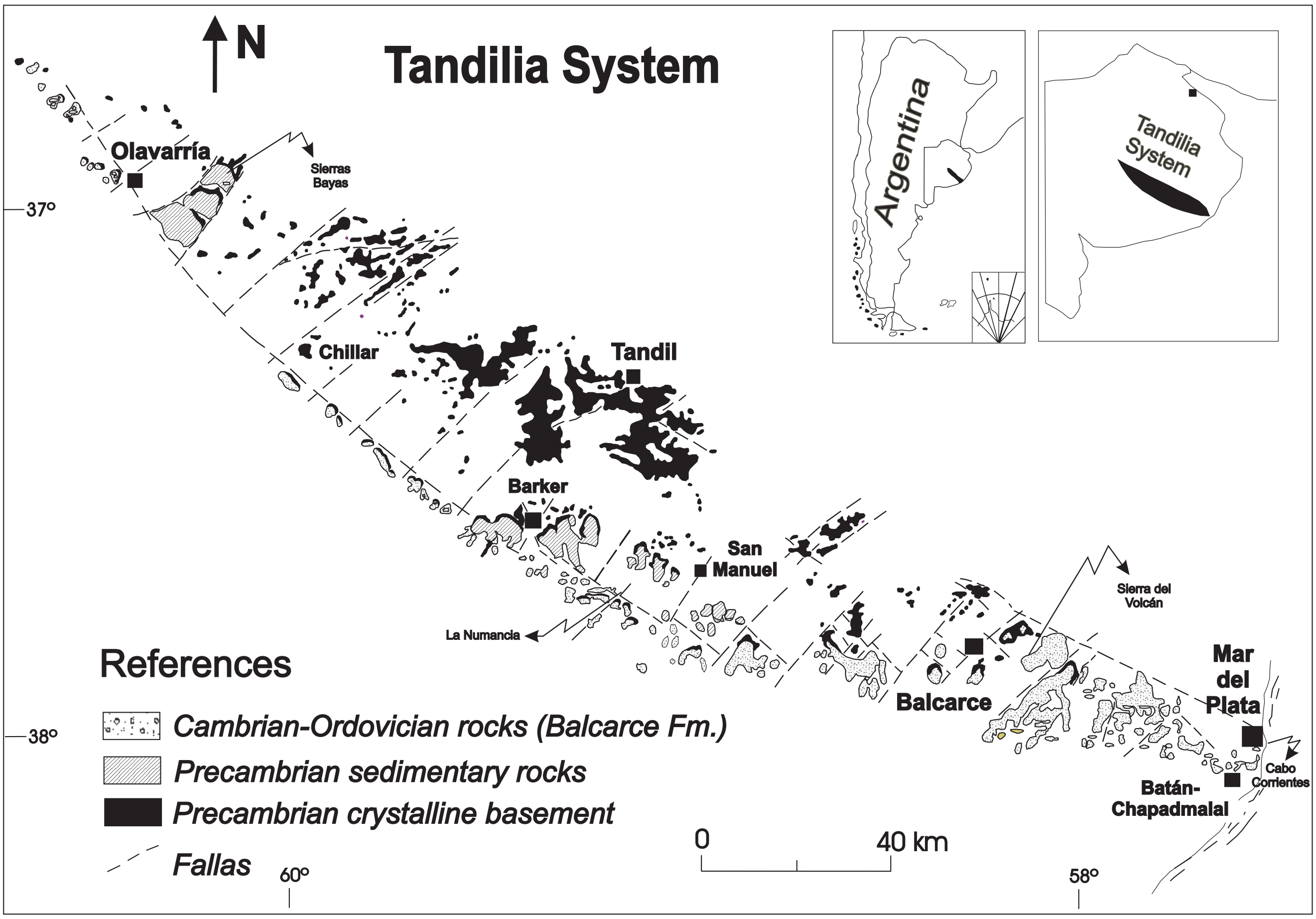

FIGURE 1 | **Geological map of the Tandilia System.**

GEOLOGICAL SETTING

The Tandilia System is an orographic belt located in the Province of Buenos Aires, between latitudes 36º 30´ - 38º 10´ South and longitudes 57º 30´ - 61º West (Fig. 1). Its maximum length is 350 km in the NW-SE direction. The hills are composed of an igneous metamorphic basement and a Precambrian and Lower Palaeozoic sedimentary cover, which displays horizontal to subhorizontal bedding (<12º).

The Precambrian sedimentary succession lies in the north-western part, around Olavarría and Barker-San Manuel region (Fig. 1), whereas the Lower Palaeozoic crops out in two areas: a western belt of the range and mainly towards the south-east (Balcarce-Mar del Plata area, Fig. 1). These deposits lie on a crystalline basement (Buenos Aires Complex, Marchese and Di Paola, 1975), which is over 2000 Ma old and is composed of granitoids, migmatites, ectinites, mylonites, amphibolites and basic dykes.

Many authors have contributed to the knowledge of the Tandilia sedimentary succession (Iñiguez et al., 1989). The stratigraphic scheme proposed by Dalla Salda and Iñiguez (1979) and modified by Poiré (1987; 1993) for the Precambrian units is given in this synthesis (Fig. 1 and Table 1). Likewise, the sequential arrangement composed of three Riphean sequences, a Riphean-Vendian sequence and a final Ordovician sequence (Iñiguez et al., 1989) is also considered.

From the lithostratigraphic standpoint (Table 1) the Precambrian sedimentary successions comprise: a) the Villa Mónica Formation (Poiré, 1993) and its equivalent La Juanita Formation, b) the Cerro Largo Formation (Poiré, 1993), and c) the Loma Negra Formation (Borrello, 1966), all of these being constituents of the Sierras Bayas Group (Dalla Salda and Iñiguez, 1979; Poiré, 1993), and d) the Cerro Negro Formation (Iñiguez and Zalba, 1974) and its equivalent Las Aguilas Formation (Zalba, 1978). The Lower Palaeozoic succession is known as the Balcarce Formation (Dalla Salda and Íñiguez, 1979).

These lithostratigraphic units were grouped by Spalletti et al. (1996) into five depositional sequences (Table 1):

TABLE 1 **Stratigraphy of the Tandilia System.**

ERAS PERIODS	STRATIGRAPHIC UNITS						DEPOSITIONAL SEQUENCES
	NW REGION		CENTRAL REGION		SE REGION		
ORDOVICIAN-CAMBRIAN	Balcarce Fm.		Balcarce Fm.		Balcarce Fm.		Batán Sequence (V)
LATE PROTEROZOIC	Cerro Negro Fm.		Las Águilas Fm.		Sierra del Volcán Diamictites	Punta Mogotes Fm.	La Providencia Sequence (IV)
	Sierras Bayas Group	Loma Negra Fm.	Sierras Bayas Group	Loma Negra Fm.			Villa Fortabat Sequence (III)
		Cerro Largo Fm.		Cerro Largo Fm.			Malegni Sequence (II)
		Villa Mónica Fm.		La Juanita Fm.			Tofoletti Sequence (I)
EARLY-MIDDLE PROTEROZOIC	Buenos Aires Complex						

the Tofoletti (I), Malegni (II) and Villa Fortabat (III) sequences are Riphean, the La Providencia sequence (IV) is Riphean-Vendian and the Batán sequence (V) is Cambrian-Ordovician. Andreis and Zalba (1998) named these sequences A1, A2, B, C and D, respectively, in the Chillar-San Manuel area.

Between the crystalline basement and the sedimentary cover, arkosic and quartz-kaolinitic saprolites indicate palaeoweathering surfaces (Zalba et al., 1992). The presence of diamictites between the crystalline basement and the Balcarce Formation is a peculiar feature reported in the Sierra del Volcán (Spalletti and del Valle,1984).

These units bear biogenic sedimentary structures (trace fossils and stromatolites) as the only evidence of biocoenosis in the Precambrian and Lower Palaeozoic seas of this region. Precambrian stromatolites are located in the Villa Mónica Formation, where they are arranged in biostromes and bioherms dated between 800 and 900 Ma (Poiré, 1987, 1993). In the Precambrian units, trace fossils are scarce and show a poor ichnodiversity. *Palaeophycus* isp. and *Didymaulichnus* isp. have been described in the Cerro Largo Formation (Poiré et al., 1984), while *Helminthopsis* isp. and probable medusa resting traces have been found in the Loma Negra Formation. *Skolithos* isp. has recently been registered in the lower part of the Cerro Negro Formation.

UPPER PRECAMBRIAN SEDIMENTARY ROCKS

The Upper Precambrian sedimentary cover of Tandilia in Sierras Bayas (close to Olavarría, Fig. 1) is a 167 m thick succession (Sierras Bayas Group, Table 1) composed of three depositional sequences separated by regional unconformities (Poiré, 1987, 1993).

The oldest depositional sequence (Tofoletti, 52 m thick) shows two sedimentary facies associations: a) quartz-arkosic arenites at the base and b) dolostones and shales at the top. The former is composed of shallow marine siliciclastic rocks (conglomerates, quartz and arkosic sandstones, diamictites and shales), and the latter is characterised by shallow marine stromatolitic dolostones and shales. This sequence has been dated at 800-900 Ma.

The second depositional sequence (Malegni, 75 m thick) consists of a basal succession composed of chert breccia, fine-stratified glauconitic shales and fine-grained sandstones, followed by cross-bedded quartz arenites which are in turn covered by siltstones and claystones. This sequence represents a shallowing upward succession from subtidal nearshore to intertidal flat deposits. An age of between 700-800 Ma has been determined from Rb/Sr dating (Bonhomme and Cingolani, 1980).

The youngest Riphean depositional sequence (Villa Fortabat) is a 40 m thick unit composed almost exclusively of red and black micritic limestones, originated by suspension fall-out in open marine ramp and lagoonal environments.

On top of the Sierras Bayas Group a regional unconformity is recognised (Barrio et al., 1991). This surface has been related with a sea-level drop. Meteoric dissolution of the carbonatic sediments is interpreted as a karstic surface on which residual clays and brecciated chert accumulated.

The Riphean-Vendian Cerro Negro Formation (La Providencia Depositional Sequence) appears on top of the above described unconformity. It is a more than 100 m thick unit characterized by claystones and heterolithic fine-grained sandstone –claystone interbeds, mainly formed in upper to lower intertidal flats.

Radiometric dating (680 Ma) and the presence of acritarchs have allowed to suggest a Vendian age for this unit (Cingolani et al., 1991).

LOWER PALAEOZOIC SEDIMENTARY ROCKS

Facies and Depositional Systems

The Lower Palaeozoic siliciclastic succession is known as Balcarce Formation (Batán Depositional Sequence, Table 1). This unit has been studied by del Valle (1987a). It overlies the crystalline basement or the former sedimentary units (Cerro Negro Formation, Las Aguilas Formation, Sierra del Volcán Diamictites and Punta Mogotes Formation).

The Balcarce Formation (100 m thick) is composed of white quartz arenites and granule-conglomerates with subordinate levels of mudstones (kaolinitic-rich clays) and quartz pebble-conglomerates (Fig. 2). The geometry of the sandstone beds is sheet-like; most sedimentary bodies are bound by convex-upward surfaces, although some wide channel-like features are also present. Planar and tangential cross-stratifications are the dominant structures within sandstone bedsets (Fig. 2), and large-scale sigmoidal bodies are common in most sections. Sheet-like and lenticular sandstone-mudstone interbeds are commonly intercalated among sandstone beds. Trace fossils are abundant at the top surface of the sandstones in sandstone-mudstone interbeds. The quarries all around Batán and Chapadmalal towns (Fig. 1) allow to depict the stratigraphic architecture of the Balcarce Formation. Based on their contrasting geometry, two main groups can be defined in this siliciclastic succession (Fig. 3): one group is characterized by a subhorizontal stacking pattern (aggradational geometry) and the other shows very well developed depositional clinoforms (progradational geometry). The observational facies of the Balcarce Formation as well as the inferred transport mechanisms and type of deposits are listed in Table 2.

Diagnostic criteria to recognise tidal processes in fair weather and storm events have been summarized in Table 3. Tidal processes are inferred from the features of cross-bedded sandstone facies (bars) and heterolithic (wavy and lenticular) facies (swales). Large to medium scale laterally persistent bodies of cross-bedded sandstones, exhibit rhythmic lateral variations in the thickness of foresets and in clay content due to spring and neap tide alternation. Clay drapes covering foresets and other sedimentation surfaces, herringbone cross-bedding, opposite palaeocurrent trends in successive sedimentary bodies and reactivation surfaces also suggest tidal deposition. The migration and accretion of bidimensional sand bars seem to be controlled by highly asymmetrical time-velocity tidal currents. Subordinated, high-energy storm episodes are suggested by hummocky cross-bedded sandstones, sheet conglomerates armouring previous tidal sand bodies, and heavy mineral concentrations in the wavy sandstone laminae of heterolithic facies.

An epicontinental shallow marine open shelf is inferred for the Cambrian-Early Ordovician in the Tandilia basin. Most sedimentary facies were developed in the nearshore and inner shelf environments of a tide-dominated and storm influenced platform.

Depositional geometry. Sequence subdivision and palaeogeographic interpretation

The Balcarce Formation has been defined as a dominantly sandy group whose strata are arranged subhorizontally or dipping very slightly to the south (Teruggi et al., 1958, 1962; Teruggi and Kilmurray, 1975, 1980). Both in the outcrops of the range and coastal areas, and in the face of various quarries, these successions show an aggradational stacking. However, in an abandoned quarry of the Batán region (Fig. 1) groups of beds of about 20 m thick are arranged in depositional clinoforms (Mitchum, 1977), showing toplap and downlap stratigraphic relations (Fig. 3).

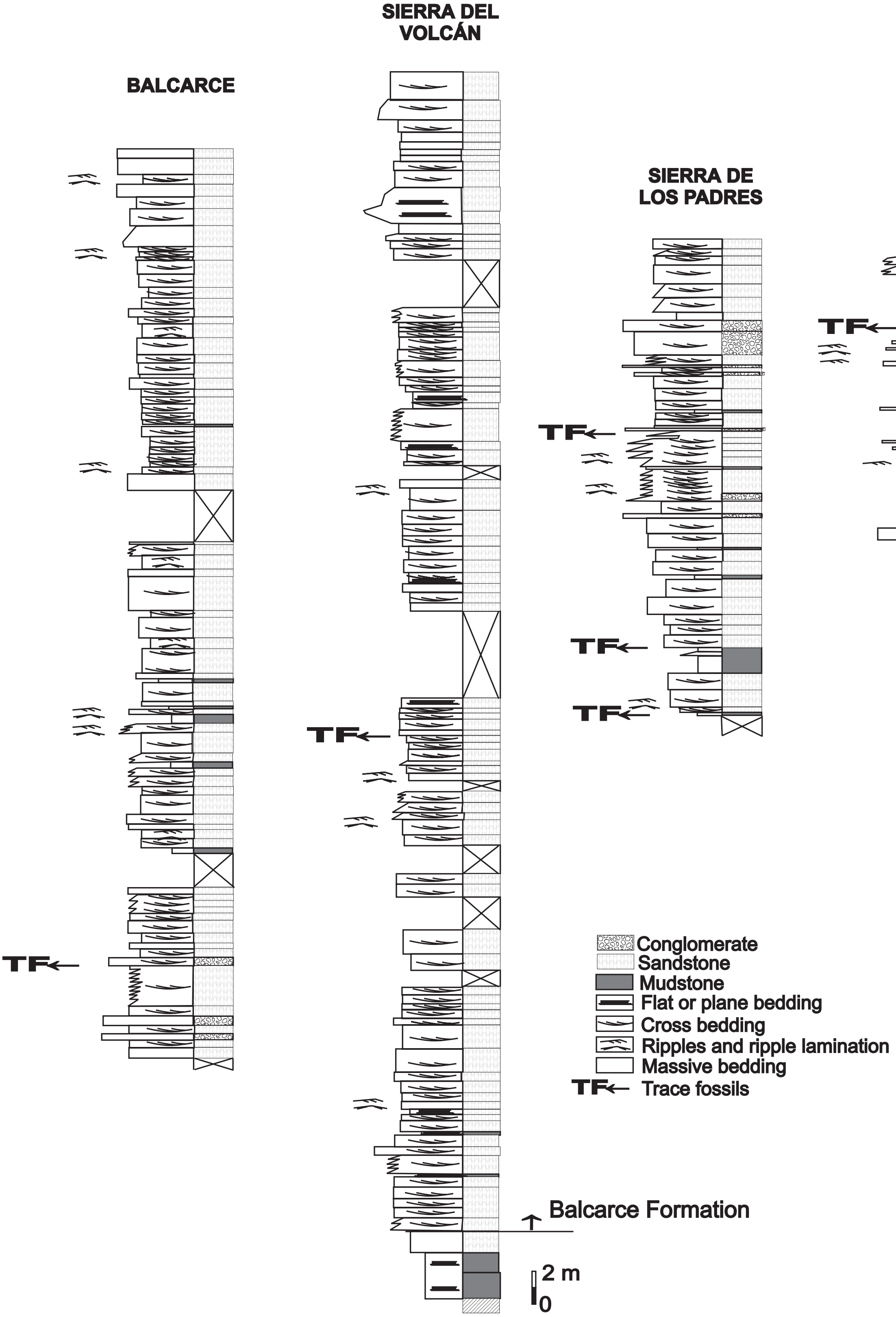

FIGURE 2 **Logs of the Balcarce Formation showing facies stacking at different localities of the eastern sector of Tandilia (modified from del Valle, 1987a).**

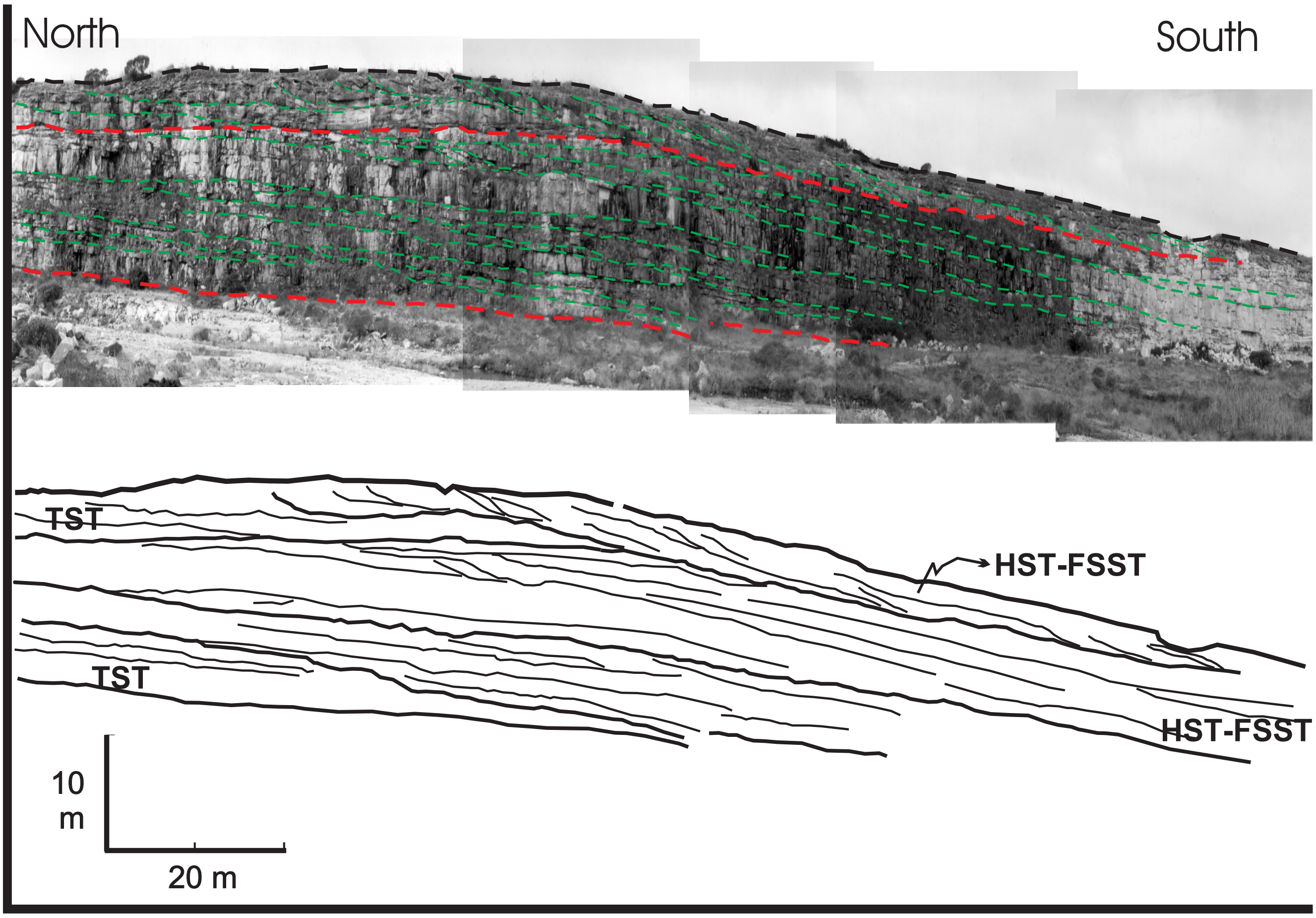

FIGURE 3 **Depositional clinoforms of the Balcarce Formation in the Batán-Chapadmalal region. TST: transgressive system tract. HST + FSST: highstand and falling stage system tracts.**

Internally, the clinoforms are composed of various sedimentary facies (Table 2; Del Valle, 1987a; Íñiguez et al., 1989), such as sandstones with planar and tangential cross-stratification, heterolithic packages, in which alternating groups of mudstones and fine rippled sandstones are associated with crossbedded sandstones, and fine conglomerates with normal gradation. The clinoforms are characterized by two architectural elements (facies associations, Spalletti and del Valle, 1990) that alternate both vertically and laterally, according to the direction of progradation. One of these elements, composed of amalgamated sandstone beds, represents subtidal bars formed by the migration of successive sand waves. The other, with greater participation of heterolithic deposits, has been assigned to interbar areas and was deposited at slightly greater depths. The base of this latter architectural element, located immediately above the tidal sand waves, represents a transgressive surface.

In the Balcarce Formation, the depositional clinoforms show a quite limited development. Clinoforms are much more typical of systems that show platform break or a slope area, whereas in the platform environment itself they are poorly developed. Even if this can be taken as one of the reasons for the poor development of the clinoforms in the studied unit, it should be taken into account that in shallow coastal areas the slope increases significantly. In sand-dominated shallow marine systems, such as that of the Balcarce Formation, the coastal slope can reach values of 2° to 3° (Cant, 1991; Walker and Plint, 1992). This causes the profile transverse to the coast to be concave upwards. In the stratigraphic record, the equilibrium profile may remain preserved (Helland-Hansen and Martinsen, 1996; Hampson, 2000) as sloped depositional geometries or clinoforms.

The poor development of clinoforms in the Balcarce Formation is probably related to the orientation of geological exposures and to its relationship with the position of the basin axis. As reported by Poulsen et al. (1998), the progradational clinoforms are more evident in the sections which are perpendicular to the basin axis. Unlike most quarries in the area, the wall where these stratal geometries are preserved has a dominant north-

TABLE 2 **Main sedimentary facies of the Balcarce Formation (modified from Spalletti and Poiré, 2000; based on del Valle, 1987b, 1990; Iñiguez et al., 1989; Spalletti and del Valle, 1989; Spalletti et al., 1996).**

FACIES	TEXTURE	SEDIMENTARY STRUCTURES	SANDSTONE BODY GEOMETRY	SCALE	MECANISM OF TRANSPORT	TYPE OF DEPOSIT
PSe	Coarse grained sand to granule gravel	Planar and tangential cross-stratification. Reactivation surfaces, mud drapes. Foresets with normal grading	Grouped sets, concave-convex geometry. Less common concave-plane (palaeo-channels)	Bed thickness between 0.3 and 1.5 m. Rarely more than 2 m thick	Low-regime tractional currents: mega-ripples	Subtidal and intertidal sand bars. Tidal currents
PShcs	Sandy	Hummocky cross stratification (HCS)	Domed-shaped bodies, Low relief	Bed thickness between 0.3 and 0.5 m	Oscillatory currents, orbital flows	Subtidal storm wave deposits
Hf	Heterolithic	Flaser	Tabular	Bed thickness less than 1.5 m	Alternation between tractional currents (dominant) and fall-out processes	Lower-middle intertidal flat
Hw	Heterolithic	Wavy	Tabular	Bed thickness less than 1.5 m	Alternation between tractional currents and fall-out processes	Intermediate Intertidal flat
Hl	Heterolithic	Lenticular	Tabular	Bed thickness less than 1.5 m	Alternation between tractional currents and fall-out processes (dominant)	Upper intertidal flat
He	Heterolithic	Alternation of mud and cross-laminated sand with cross-stratified sands	Tabular	Usually thin bedded, but thicker than the other heterolithic facies	Minor tidal bars	Lower intertidal flat
Cm	Fine to medium-grained gravel	Massive. Ripples on top, up to 15 cm long and high relief. Sharp base, sometimes ondulated	Sheet-like	Bed thickness less than 0.3 m	Shallow storm waves	Subtidal to intertidal
Cg	Fine to medium grained gravel	Normal grading	Tabular, scoured base. Gradational top to sands	Bed thickness less than 0.3 m	Post-storm deposits or begining of subtidal bars	Sandy subtidal flat

TABLE 3 **Diagnostics criteria for tidal and storm sedimentation in the Balcarce Formation.**

BALCARCE FORMATION

Diagnostic criteria for tidal sedimentation

* Large to medium-scale laterally persistent bodies of cross-bedded sandstones.

* Sigmoidal bundles.

* Bounding or reactivation surfaces.

* Variations in the thickness of foresets in sigmoidal units.

* Alternation of cross-bedded and current-ripple laminated sets.

* Heterolithic sequences: wavy and lenticular bedded sections.

* Mud drapes covering foresets and sandstone bedding surfaces.

* Lateral neap-spring tide sequences in cross-stratified units.

* Herringbone cross-stratification.

* Opposite palaeocurrent trends in successive sedimentary bodies.

Diagnostic criteria for storm sedimentation

* Sheet clast-supported conglomerates armouring sand bar deposits.

* Conglomerate intercalations in fine-grained heterolithic sequences.

* Heavy mineral concentrations on the bedding surfaces of ripple-bedded sandstones.

* Hummocky cross-bedded sandstones.

* Thin wave rippled sandstones intercalated in pelite-rich successions.

south orientation, and the progradation directions of the depositional system have a clear arrangement from north to south.

From the interpretation standpoint, clinoforms show the advance or progradation of the depositional systems towards the centre of the basin. The stratigraphic interval in which these progradational stratal arrangements appear represents a period in which accommodation is considerably reduced or clastic contribution is increased from the source (Galloway, 1989; Nummedal et al., 1993; Emery and Myers, 1996). The fairly uniform lithological characteristics of the Balcarce Formation in its aggradational and progradational sections suggests that clinoforms are strongly conditioned by a decrease of accommodation space availability.

Classic sequence stratigraphic schemes (Posamentier et al., 1988; Posamentier and Vail, 1988) show that clinoforms are among the most typical stratal arrangements of latest lowstand (lowstand wedges), latest highstand and shelf margin systems tracts. However, detailed studies on sequence stratigraphy of shallow marine deposits have led to the conclusion that these progradational arrangements are much more typical of the latest highstand (HST) and the falling stage (FSST) systems tracts (Plint and Nummedal, 2000), thus showing the decrease of accommodation caused by a progressive drop in relative sea-level (Fig. 3).

The internal anatomy of the clinoforms of the Balcarce Formation clearly shows that controls on sedimentation failed to remain uniform as progradation occurred. The interdigitation of interbar heterolithic deposits and subtidal sand bar deposits within this falling stage systems tract suggests that the shallow marine system was affected by higher order oscillations in relative sea level.

The progradation to the south of the above described clinoforms confirms that the basin margin for the deposits of the Balcarce Formation was located to the north of the Tandilia region (Teruggi, 1964; Dalla Salda and Íñiguez, 1979).

TRACE FOSSILS

The Balcarce Formation contains a large quantity of trace fossils and a much higher ichnodiversity in comparison with the Precambrian sedimentary succession of Tandilia, in which a few traces of *Didymaulichnus* isp., *Helminthopsis* isp., *Palaeophycus* isp., *Skolithos* isp. and probable medusa resting imprints have been identified (Poiré et al., 1984; Spalletti and Poiré, 2000).

The first findings of trace fossils in the Balcarce Formation were reported by Hauthal (1896) and Nágera (1919, 1926), but it was Borrello (1966) who first studied and described a large trace fossil collection taken from different outcrops and quarries of this stratigraphic unit. Aceñolaza (1978) revised the subject and gave a modernized approach to the study of trace fossils from Tandilia, together with other Lower Palaeozoic ichnofossils of Argentina. Later studies were carried out by Alfaro (1981), Regalía and Herrera (1981), Zalba et al. (1982), Cingolani et al. (1985), del Valle (1987a and b), Poiré and del Valle (1994, 1996) and Poiré (1998).

After revising the already published material thoroughly and taking into account recent discoveries made by the authors, the following up-dated list of trace fossils and their brief descriptions are presented.

Ancorichnus HEINBERG, 1974
Figure 4
Irregular meandering burrows which consist of cylindrical tubes with thick, perimetral lining and meniscated backfilling. Reference: *Ancorichnus ancorichnus*, Poiré (1998).

Arthrophycus HALL, 1852
Figures 4 and 5C, 5D, 5E and 5F

Bundles of annulated ribbon-like burrows, simple or branched, flat, commonly bilobates with median longitudinal depression (Fig. 6E) and strong, regularly spaced transverse ridges. References: *Arthrophycus alleghaniensis,* Borrello (1966), Alfaro (1981), Cingolani et al. (1985), del Valle (1987b); *Arthrophycus* isp., Alfaro (1981).

Bergaueria PRANTL, 1946
Figure 4

Plug-shaped, vertical, cylindrical to hemispherical burrows on the sole of sandstones beds. Reference: *Bergaueria* isp., Cingolani et al. (1985).

Cochlichnus HITHCOCK, 1858
Figure 4

Regularly meandering, parallel to the stratification, unbranched burrows. Reference: *Cochlichnus* isp., del Valle (1987b).

Conostichus LESQUEREUX, 1876
Figure 4

Plug-shaped, subconical burrows orientated perpendicular to the bedding and with rounded central depression in the basal end. Reference: *Conostichus* isp., Cingolani et al. (1985).

Cruziana D'ORBIGNY, 1842
Figures 4 and 5E, 7A, 7B, 7C and 7D

Bilobed furrows on the sole of sandstone beds with scratches clearly defined. Scratches may vary from fine (Fig. 7D) to coarse (Figs. 7A, 7B) and from comb-like (Fig. 7A) to V-markings (Figs. 7C, 7D). References: *Cruziana bonaerensis*, Borrello (1966); *Cruziana furcifera*, Borrello, (1966), Alfaro (1981), Cingolani et al. (1985); *Cruziana* isp., Borrello (1966), Alfaro (1981).

Daedalus ROUAULT, 1850
Figures 4 and 5B

Lying down J-shaped, perpendicular to bedding, spreiten structures (Fig. 5B); some thin spreiten-tubes show annulations. Reference: *Daedalus labeckei*, Poiré and del Valle (1996).

Didymaulichnus YOUNG, 1972
Figures 4, 6B and 6D

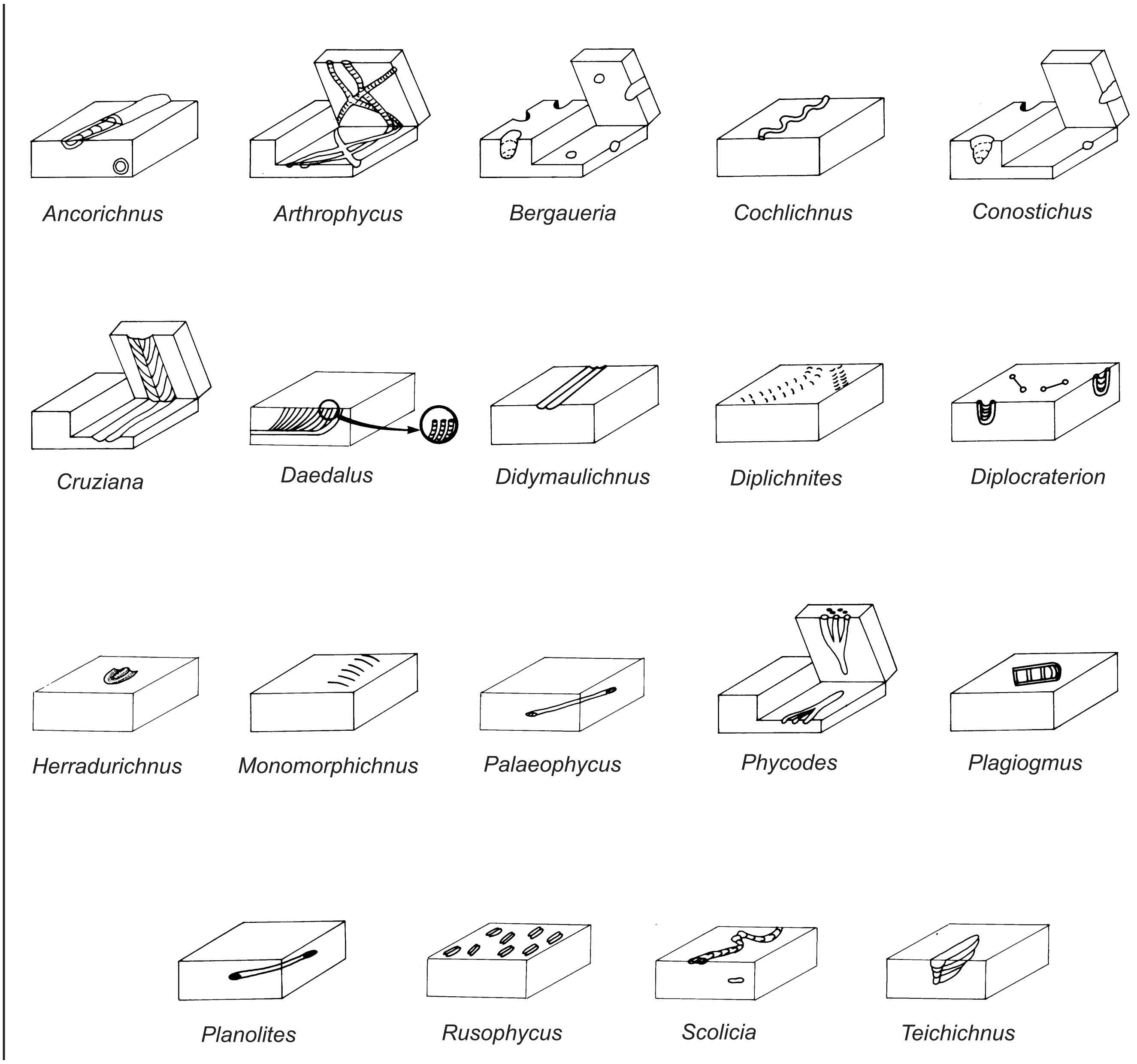

FIGURE 4 **Diagrams of the most typical trace fossils from the Balcarce Formation.**

Elongated, straight to gently curved, smooth, parallel to bedding, bilobate furrows preserved as negative epireliefs (Fig. 6D) or positive hyporeliefs (Fig. 6B). References*:* *Didymaulichnus lyelli*, Cingolani et al. (1985); *Didymaulichnus* isp., Borrello (1966), Zalba et al. (1982), del Valle (1987b), Poiré (1998).

Diplichnites DAWSON, 1873
Figures 4, 7G and 7H

Two parallel series of comb-like ridges preserved on a fine-grained sandstone sole (Figs. 7G, 7H). Reference: *Diplichnites* isp., this paper for Los Pinos quarry, Balcarce.

Diplocraterion TORREL, 1870
Figures 4 and 6H

U-shaped, perpendicular to bedding, burrows containing spreiten between the vertical tubes. The burrows are usually seen at their intersections with the upper surface of the sandstone beds (Fig. 6H). They appear as dumbell-shaped burrows, consisting of paired circular openings of the vertical burrows, joined by a slit-shaped area of disturbed sediments corresponding to the spreiten. References: *Diplocraterion* isp., Borrello (1966), and this paper for Parque San Martín, Mar del Plata, and Dazeo quarry, Batán.

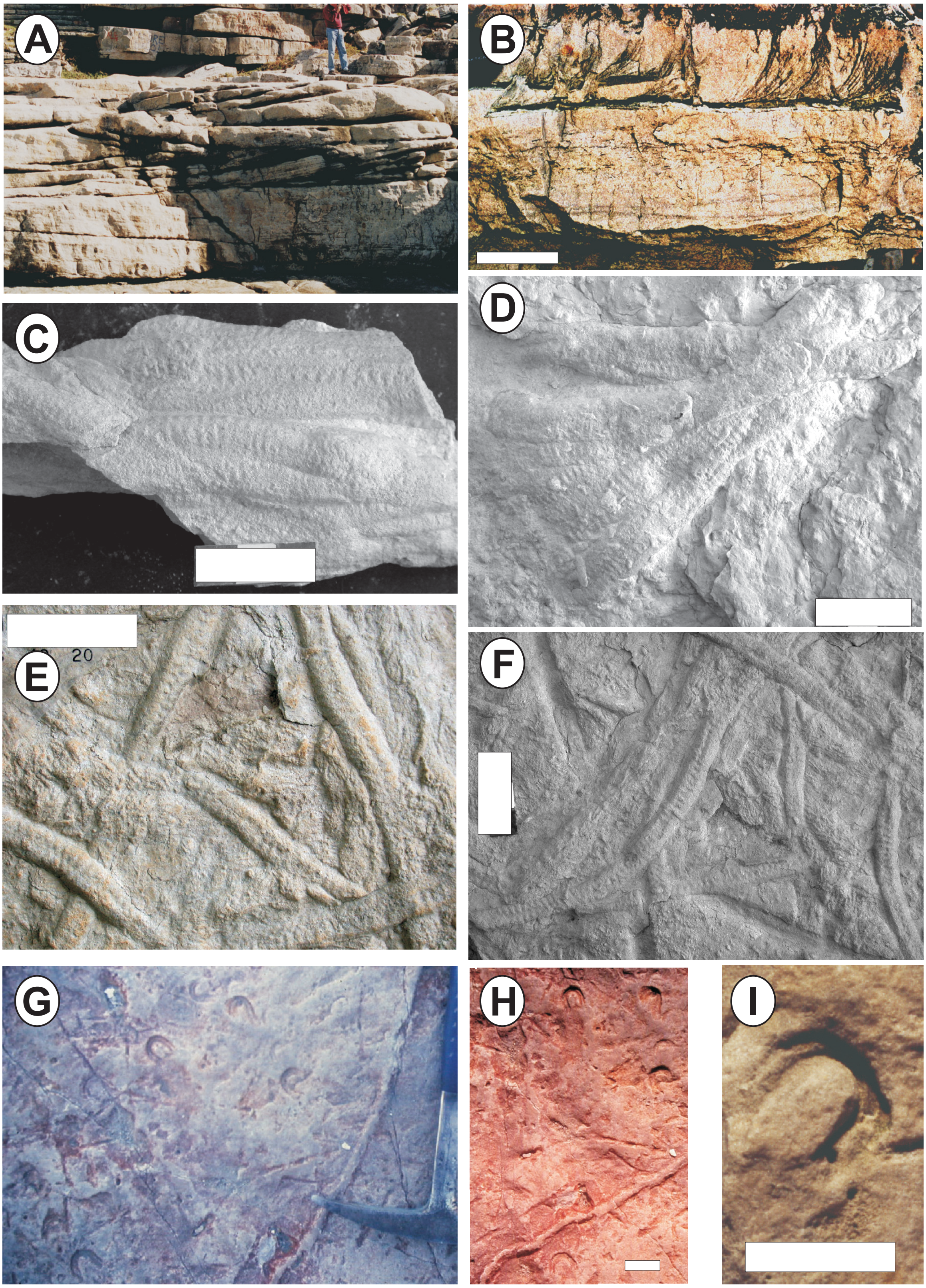

FIGURE 5 | **A: Cross-bedded quartz arenites of the Balcarce Formation. B: *Daedalus labeckei* from Cabo Corrientes, Mar del Plata (white bar= 10 cm). C/F: *Arthrophycus alleghaniensis*, San Ramón Quarry, (white bar= 3 cm), associated with *Cruziana furcifera* (E). G/I: *Herradurichnus scagliai* (white bar= 3 cm), associated with thick strings of *Scolicia* isp., Cabo Corrientes, Mar del Plata.**

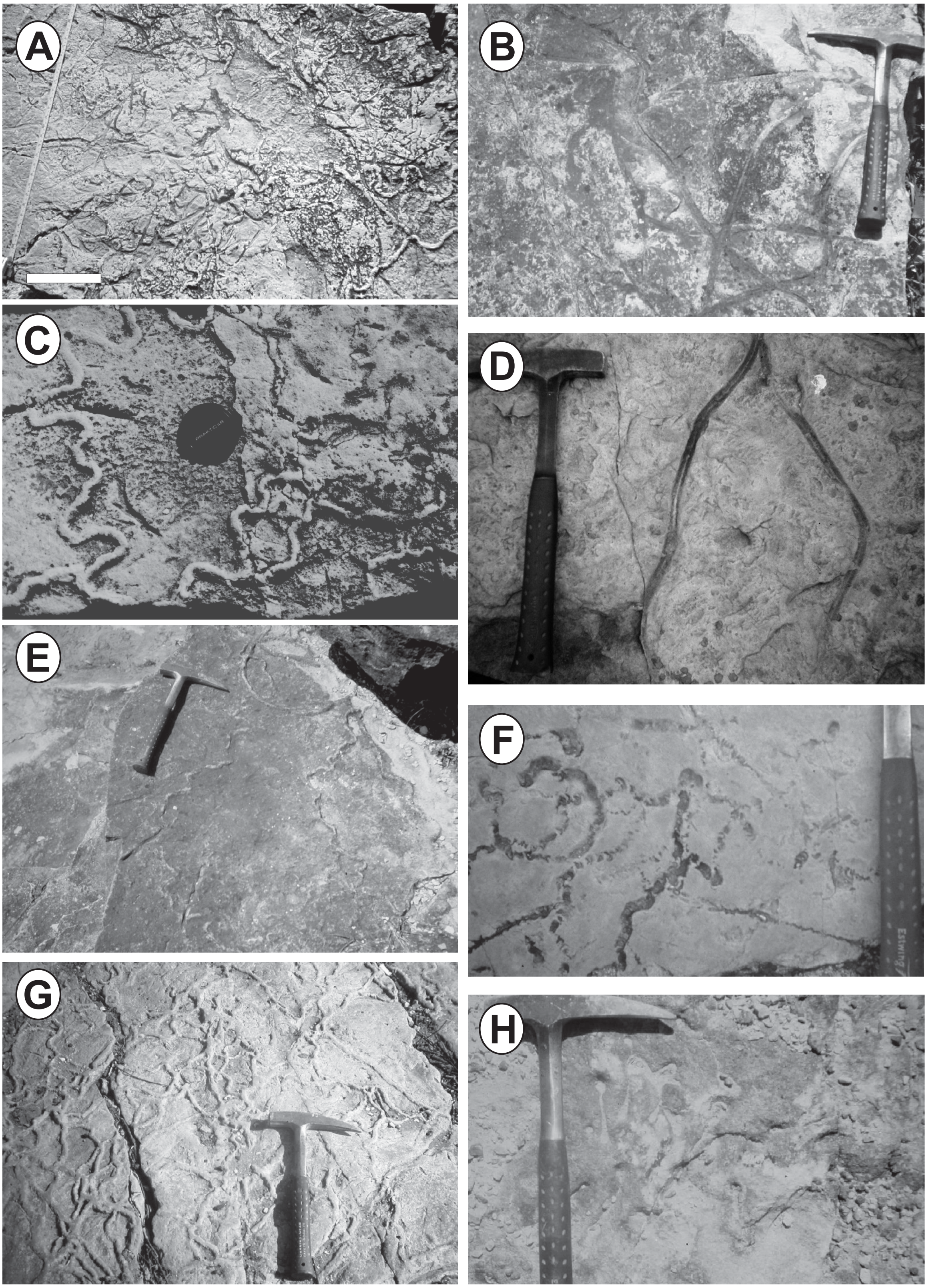

FIGURE 6 **A, C and E: Thick strings of *Scolicia* in top beds showing an irregular meandering pattern, Cabo Corrientes, Mar del Plata (white bar= 10 cm). B and D: *Didymaulichnus* isp. from both (B) La Verónica Quarry, Chillar and (D) Gutiérrez Quarry, Batán. F: *Scolicia* isp. showing its back-filling, Cabo Corrientes, Mar del Plata. G: Top bed with very high degree of bioturbation with thick strings of *Scolicia* isp., Cabo Corrientes, Mar del Plata. H: *Diplocraterion* isp. from Dazeo Quarry, Batán.**

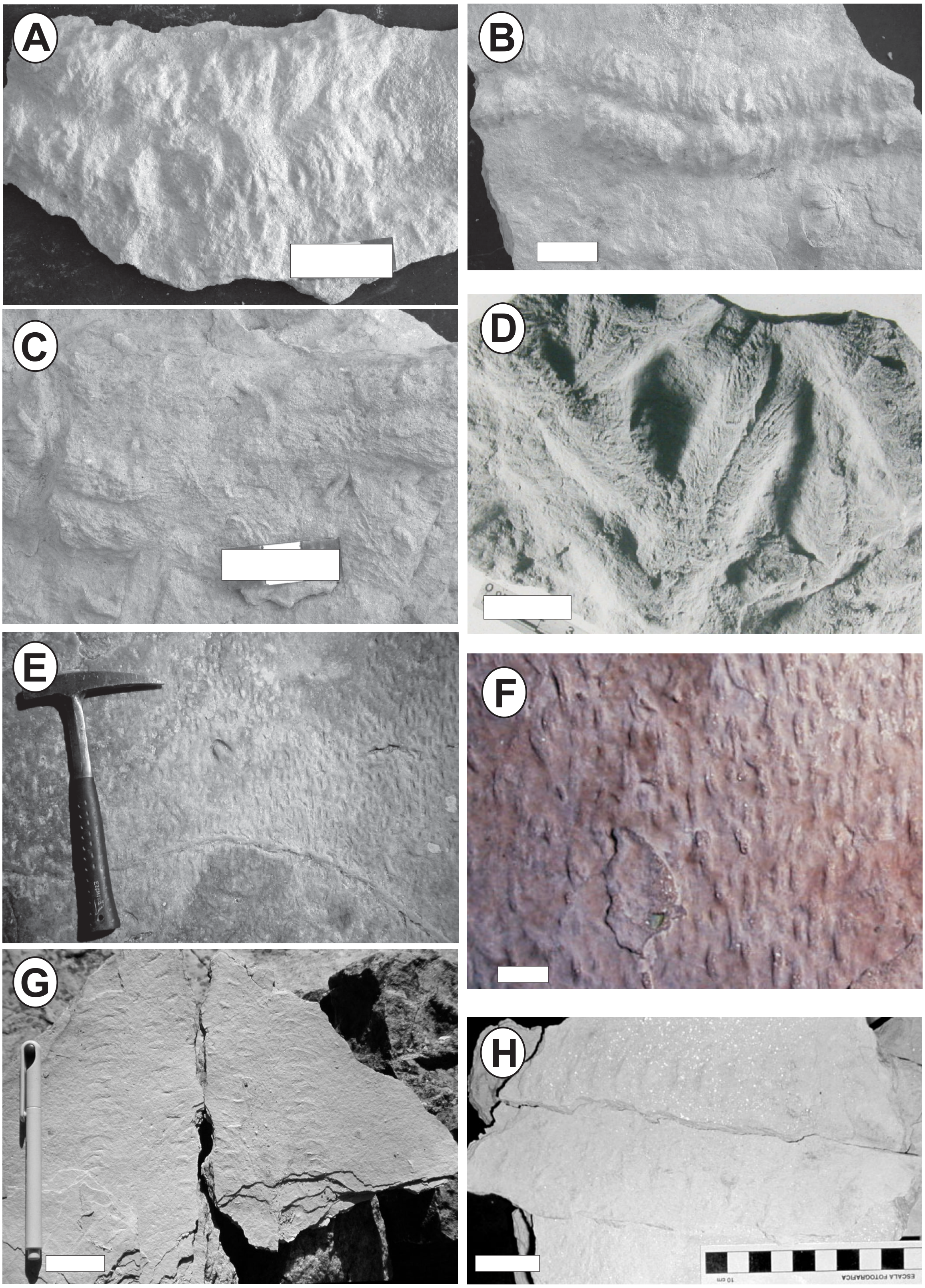

FIGURE 7 **A/B: *Cruziana* isp. from San Ramón Quarry, Almacén La Numancia (white bar= 3 cm). C: *Cruziana furcifera*, San Ramón Quarry (white bar= 3 cm). D: *Cruziana furcifera*, Licenciado Matienzo (white bar= 3 cm). E: *Scolicia* isp. and *Herradurichnus scagliai* superimposed to a top bed with extremely high density of *Rusophycus* isp., Cabo Corrientes, Mar del Plata. F: Close up of *Rusophycus* isp. (white bar= 3 cm). G/H: *Diplichnites* isp., Los Pinos Qarry, Balcarce.**

Herradurichnus POIRÉ and DEL VALLE, 1996
Figures 4, 5G, 5H and 5I

Horseshoe-shaped, parallel to bedding, bilobate furrows (Figs. 5G, 5I) with a thin middle ridge (Fig. 5I). References: *Herradurichnus scagliai*, Borrello (1966), Poiré and del Valle (1996).

Monocraterion TORREL, 1870
Figure 4

Funnel-shaped, perpendicular to bedding, burrows perforated centrally by a sand infilled tube which continue downwards. Reference: ?*Monocraterion* isp., Cingolani et al. (1985).

Monomorphichnus CRIMES, 1970
Figure 4

Set of single, straight, parallel ridges preserved on a sandstone sole. References: *Monomorphichnus* isp., Cingolani et al. (1985) and this paper for new material from Cabo Corrientes, Mar del Plata.

Palaeophycus HALL, 1847
Figure 4

Straight to slightly sinuous, cylindrical, horizontal, simple tubes in which the sediment is typically of the same lithology and texture as the host rock. References: *Palaeophycus alternatus*, Cingolani et al. (1985); *Palaeophycus tubularis*, Borrello (1966), Cingolani et al. (1985), del Valle (1987b); *Palaeophycus* isp., Borrello (1966), Poiré and del Valle (1996).

Phycodes RICHTER, 1850
Figure 4

Bundle structure in a wall-like construction consisting of a sand infilled, horizontal, main tube from which thinner, annulated tubes are continue up-wards into the sandstone. References: *Phycodes* aff. *pedum*, Regalía and Herrera (1981); *Phycodes* isp., this paper for Dazeo quarry (Batán-Chapadmalal) and San Ramón quarry (La Numancia).

Plagiogmus ROEDEL, 1929
Figure 4

Flat tape-shaped, parallel to bedding, furrow, crossed by transverse ridges, which ends in a longitudinal string; it is preserved as a positive feature on the sole of the sandstone bed. Reference: *Plagiogmus* isp., del Valle (1987b).

Planolites NICHOLSON, 1873
Figure 4

Straight to sinuous, subcylindrical, smooth-walled, simple tubes in which the structureless fill is different from the host stratum. References: *Planolites* isp.; Cingolani et al. (1985) and this paper for new material found in Dazeo quarry, Batán.

Rusophycus HALL, 1852
Figures 4, 7E and 7F

Short to elongated, bilobed, coffee bean-like furrows with median crest and transverse ridges (Fig. 7F); they are sometimes strongly orientated (Figs. 7E, 7F). References: *Rusophycus* isp., Borrello (1966), Poiré and del Valle (1996).

Scolicia DE QUATREFAGES, 1849
Figures 4, 6A, 6C, 6E, 6F, 6G and 8

Irregular meandering, horizontal, subcylindrical, bilobated, chevron-like infilled, ribbon-like burrows (Figs. 6A, 6C), which form large circles (up to 2 m of diameter, Fig. 6E). Ribbon tubes show a very regular diameter (2 cm) and may be some meters long. The lower and upper sides of the burrow are bilobated, and they are meniscated in longitudinal section (Fig. 6F). Many authors have questioned the wide use of the *Scolicia* taxonomy and suggest that this ichnogenus must be reviewed. Smith and Crimes (1983) have given some diagnostic criteria in order to clarify the systematic classification of *Scolicia*, *Subphyllochorda* and *Taphrhelminthopsis* but apparently they are not enough. For instance, the Balcarce Formation *Scolicia* specimens show some features typical of other ichnogenus, but all of them suggest a *Scolicia* assignation. They are irregular meanders like *Helminthopsis*, sometimes regular meanders like *Cochlichnus*, bilobated in the lower side like *Dydimaulichnus* (Fig. 8A) and meniscate in the longitudinal section like *Taeinidium* (Figs. 6F, 8C). All these features plus upper bilobated surface (Fig. 8A) suggest the use of the name Scolicia. References: *Scolicia* isp., Poiré and del Valle (1996) and Poiré (1998).

Teichichnus SEILACHER, 1965
Figure 4

Series of horizontal, vertically stacked, sand infilled tubes forming a wall-like spreiten structure, preserved as full relief. Reference: *Teichichnus* isp., Poiré and del Valle (1996).

RELATIONSHIP BETWEEN TRACE FOSSILS, FACIES AND SEDIMENTARY ENVIRONMENTS

Del Valle (1987a, b) and Poiré and del Valle (1994, 1996) have attempted to correlate sedimentary facies and trace fossil associations in the Balcarce Formation.

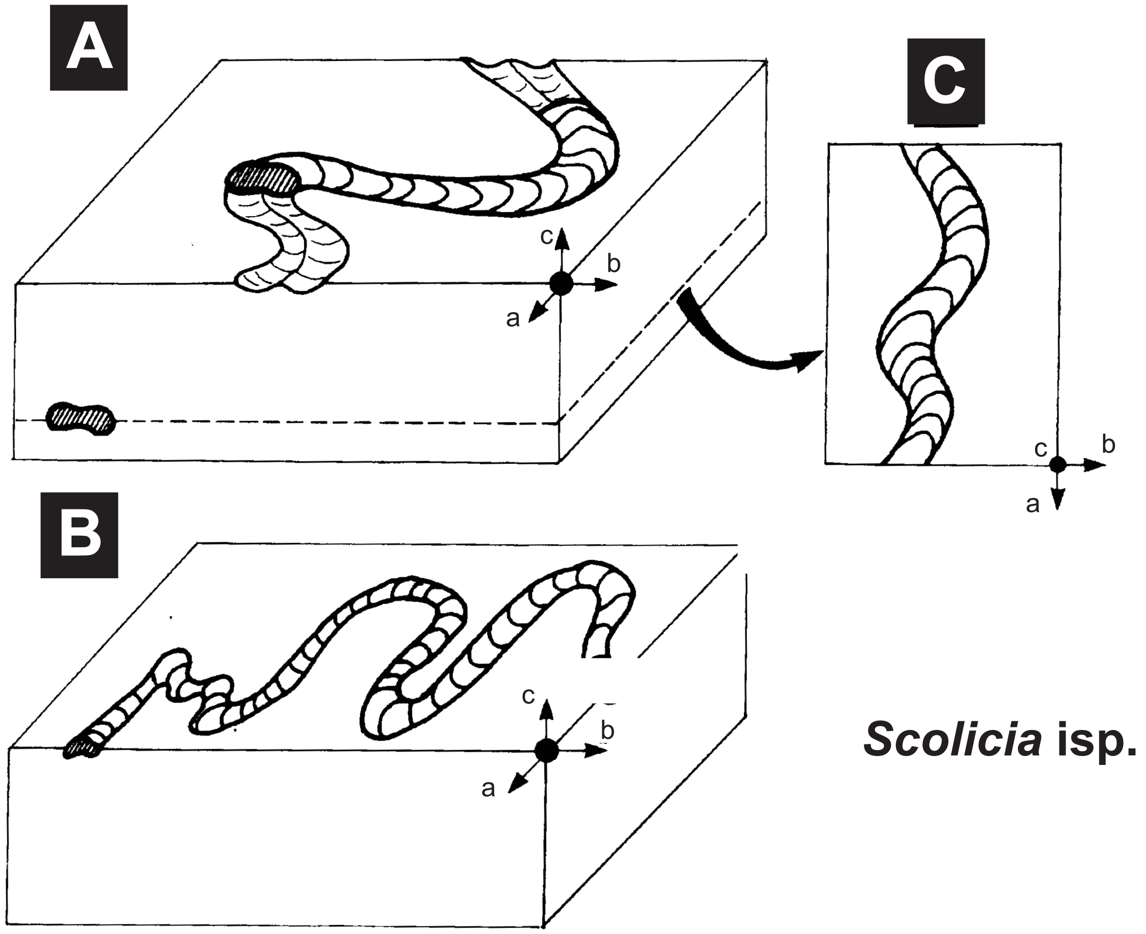

FIGURE 8 **Block diagrams of *Scolicia* isp. showing some features typical of other ichnogenus, but all of them suggesting a *Scolicia* assignation. A: bilobate negative epirelief resembling *Dydimaulichnus*. However, the bilobate upper relief is indicative of *Scolicia*. B: meandering-like pattern resembling *Helminthopsis* and *Cochlichnus*. C: meniscate infill in longitudinal section, like *Taeinidium* (from Poiré and del Valle, 1996).**

In Cabo Corrientes (Fig. 1) the relationship between facies and ichnofossils is clearly shown (Poiré and del Valle, 1994, 1996). This section (Fig. 9) is composed of four ichnolithological associations:

Pebble sandstone facies (PSe.1) with progradational reactivation surfaces and no evidence of bioturbation.

Cross-bedded sandstone facies (PSe.2) characterized by tabular and lenticular sand bodies with rare *Palaeophycus* isp.

Wavy bedded heterolithic facies (Hw) bearing *Daedalus labeckei, Herradurichnus scagliai, Rusophycus* isp., *Scolicia* isp. and *Teichichnus* isp., and

Sandy heterolithic facies (Hf) with *Herradurichnus scagliai* and *Scolicia* isp.

Sandy sedimentary facies (PSe.1 and PSe.2, Fig. 9) were interpreted as central bar deposits, sandy heterolithic facies (Hf) represent bar margin environments, and wavy bedded heterolithic facies (Hw) were formed in interbar areas as the result of suspension sedimentation combined with subordinated subcritical tractive currents. A subtidal open marine shelf is suggested for the whole Cabo Corrientes sedimentary succession.

Ethologically, two principal trace fossil assemblages were recognized by Poiré and del Valle (1994). Both assemblages may be interpreted in terms of specific colonising events. The first assemblage consists of *Rusophycus* isp. and *Herradurichnus scagliai*. These furrows formed at the water-sediment interface. The resting traces *Rusophyus* isp. are located in interbar facies Hw. *Rusophycus* isp. shows a strong rheotaxis, suggesting that

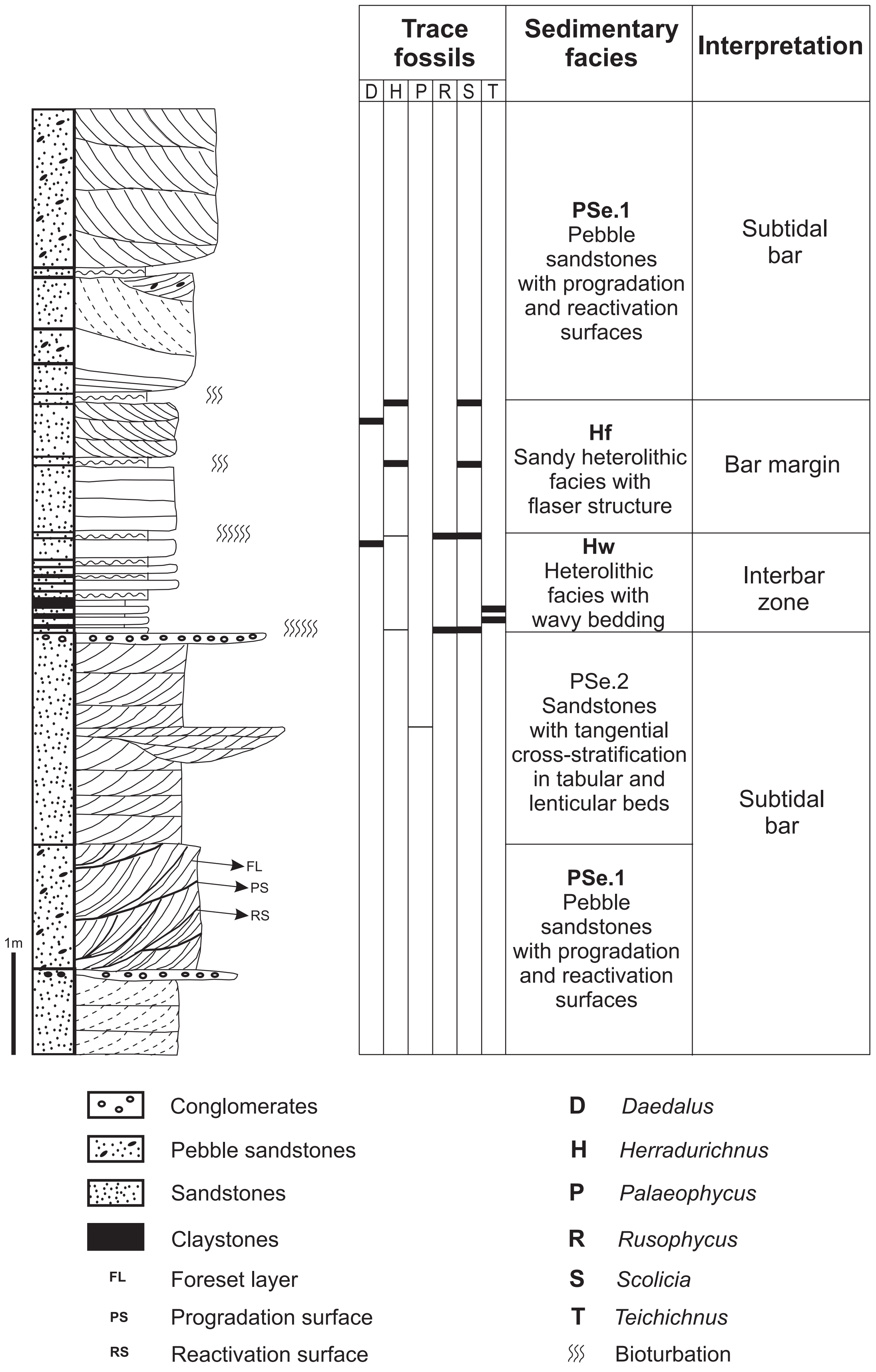

FIGURE 9 | **Cabo Corrientes log of the Balcarce Formation showing the relationship between facies and trace fossils.**

tracemaking organisms were closely related to weak subtidal currents. The common association of *Herradurichnus scagliai* with facies Hf suggests that trace-making organisms lived principally in bar margin areas.

The second trace fossil assemblage is composed of *Daedalus labeckei, Scolicia* isp. and *Teichichnus* isp., These trace fossils are post-depositional burrows formed a few centimetres below the sea floor by sediment feeding organisms that require nutrient supply from organic rich muds. The three ichnogenera are related to interbar (Hw) facies, and two of them (*Daedalus* and *Scolicia*) also appear in bar margin facies (Hf)(Fig. 9). Therefore, *Teichichnus* trace-making organisms seem to be more closely influenced by water depth and sea floor topography, while this is not the case with *Daedalus* and *Scolicia* makers.

Poiré and del Valle (1994) have considered that sandy sedimentary facies (PSe.1 y PSe.2) were not colonized by trace makers. Sand bars are usually a very important habitat for suspension feeding organisms which produce the *Skolithos* ichnofacies. According to Voosler and Pemberton (1988) these organisms are opportunistic faunas that colonise shallow marine (coastal) sand bars. Thus, the lack of *Skolithos* in the Cabo Corrientes section could be associated with a deeper location of the subtidal sand bars.

The palaeoenvironmental history of bioturbation in this section of the Balcarce Formation began with synsedimentary ichnofossil development in heterolithic interbar and bar margin deposits. These deposits were later buried by vertical accretion of subtidal sand waves. Coevally, mud feeding organisms took available nutrients from the buried wavy bedded heterolithic facies and reworked these previously formed deposits. As this intra-sedimentary process occurred, at the water-sediment interface of interbar and bar margin areas organisms produced a new assemblage of syndepositational traces.

AGE OF THE BALCARCE FORMATION

It is difficult to determine the precise age of the Balcarce Formation. Through radiometric dating (680 Ma) and the presence of acritarchs the underlying Cerro Negro Formation has been dated in the Vendian (Cingolani et al., 1991). The upper boundary of the Balcarce Formation is sustained by an intrusive diabase body dated around 450 Ma and 498 Ma (Rapela et al., 1974). Consequently, the Balcarce Formation has to be assigned to the Cambrian-Ordovician lapse.

During the seventies and eighties, *Cruziana* has been considered a useful biostratigraphic indicator (Seilacher, 1970; Crimes, 1975). Based on this concept, the presence of *Cruziana furcifera* (Figs. 5E, 7C, 7D) has been one of the most substantial elements to suggest an Ordovician age for the Balcarce Formation. Nevertheless, Marwood and Pemberton (1990) have seriously questioned the validity of *Cruziana* as a biostratigraphic marker, since these authors have identified *Cruziana furcifera* in the Lower Cambrian of Alberta (Canada). Therefore, the records of this ichnospecies could be extended at least from the Lower Cambrian to the Lower-Middle Ordovician. On the other hand, the presence of *Plagiogmus* isp. reported by del Valle (1987b) in the Balcarce Formation would strongly indicate a Cambrian age according to Glaessner (1969) and Crimes (1975).

In the measured sections of the Balcarce Formation *Cruziana furcifera* is usually associated with *Arthrophycus alleghaniensis*, *Didymaulichnus* isp., *Monomorphichnus* isp. and *Phycodes* isp., and *Plagiogmus* is co-occurrent with *Arthrophycus alleghaniensis*, *Didymaulichnus* isp. and *Palaeophycus tubularis*. Therefore *Cruziana furcifera* and *Plagiogmus* do not appear together in the same stratigraphic levels. This trace fossil information together with the available stratigraphic and geochronologic data suggest that the Balcarce Formation can be considered either Cambrian and/or Ordovician. Future and more detailed ichnological studies and their comparison with other quartz sandstone sequences, without body fossils but rich in trace fossils, from this Gondwana region (i.e. the Lower Palaeozoic successions from South Africa and Malvinas Islands) could contribute to establish a more accurate age for the Balcarce Formation.

CONCLUSIONS

A tide-dominated and storm influenced open platform is suggested for the deposition of the Balcarce Formation. Most facies were formed by highly asymmetrical time-velocity tidal currents. Cross-bedded quartz arenites and fine-grained conglomerates are interpreted as nearshore and inner shelf tidal sand bars. Interbar deposits are represented by heterolithic packages. Subordinated HCS sandstones suggest storm events. The identification of progradational clinoforms oriented to the south in the Balcarce Formation allow the source areas of the basin to be located towards the north. Besides, the shallow marine sand bars of the Balcarce Formation were formed by tidal currents oriented parallel to the coast line.

A summary of the ichnologic knowledge about the Balcarce Formation is given in this paper. The following trace fossils have been identified: *Ancorichnus ancorichnus*, *Arthrophycus alleghaniensis*, *Arthrophycus* isp., *Bergaueria* isp., *Cochlichnus* isp., *Conostichus* isp., *Cruziana furcifera*, *Cruziana* isp., *Daedalus labeckei*, *Didymaulichnus lyelli*, *Didymaulichnus* isp., *Diplichnites* isp., *Diplocraterion* isp., *Herradurichnus scagliai*, ?*Monocraterion* isp., *Monomorphichnus* isp., *Palaeophycus alternatus*, *Palaeophycus tubularis*, *Palaeophycus* isp., *Phycodes* aff. *pedum*, *Phycodes* isp., *Plagiogmus* isp., *Planolites* isp., *Rusophycus* isp., *Scolicia* isp. and *Teichichnus* isp.

The trace fossil assemblage shows that the succession belongs to the Lower Palaeozoic. Even if *Cruziana furcifera* has been used to suggest an Ordovician age, the presence of *Plagiogmus* isp. is a strong Cambrian indicator. Therefore, the Balcarce Formation is, so far, assigned to the Cambrian-Ordovician.

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