[22] Heterogeneous distribution of trace fossils across initial transgressive deposits in rift basins: an example from the Springhill Formation, Argentina

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In the Lago San Martín region (Santa Cruz Province, Argentina), the Springhill Formation (50–100 m thick) overlies the syn-rift El Quemado Complex, showing outcrops with wedge geometry. Four sedimentological sections were measured in the field, and three depositional palaeoenvironments were interpreted. The Springhill Formation starts with fluvial deposits, characterized by channel-fills and floodplains with palaeosol development, passing transitionally to a coastal plain and, finally, to marine sedimentation. The initial sandy transgressive deposits (Facies Association 9) are the main focus of this study, in which 10 ichnogenera (*Arenicolites*, *Bergaueria*, *Cylindrichnus*, *Diplocraterion*, *Macaronichnus*, *Palaeophycus*, *Planolites*, *Ophiomorpha*, *Rosselia* and *Skolithos*) are described. Two ichnoassociations (foreshore and shoreface) were defined, and their distribution was controlled by the local palaeoenvironmental conditions, mainly energy, bathymetry and grain size of sediments. A highly bioturbated surface (BI = 4) was recognized in Section 1 showing a limited occurrence and disappearing over short distances perpendicular to the palaeoshoreline. This surface shows a sharp sub-horizontal gently undulating top contact with a bioturbation thickness between 15 and 25 cm. This type of surface has limited usefulness as a key correlative surface, because it is spatially restricted in rift basins due to the tectonic activity, which creates high accommodation space rates. A more accurate characterization of the initial transgressive deposits of the Springhill Formation – which is the most important reservoir in southern Patagonia – could provide new ideas to solve problems in subsurface studies. ☐ *Ichnoassociation, lower cretaceous, rift basins, shallow marine deposits, transgressive systems tract.*

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Trace-fossil analysis constitutes an extremely important tool that complements the sedimentological background for characterizing basin fill. In sequence stratigraphy, ichnology has frequently been used to describe and generate models that can be applied worldwide (Pemberton & MacEachern 1995; Gingras *et al.* 2002; MacEachern *et al.* 2007a,b). However, the majority of those ichnological models have been developed for passive margins and foreland basins, and only a few of the existing examples are from rift basins (Malpas *et al.* 2005; Martins-Neto & Catuneanu 2010). Compared with passive margin settings (where the main control is the relative sea-level fluctuations), in rift contexts, as a consequence of rapid tectonic subsidence, 'instantaneous' accommodation space is created (Martins-Neto & Catuneanu 2010). This situation generates a relatively thin transgressive systems tract and a very well developed highstand systems tract overlying the maximum flooding surface (Martins-Neto & Catuneanu 2010). Most of the important sequence surfaces defined for passive margins can be correlated for long distances at basin scale (correlative conformities, *sensu* Mitchum *et al.* 1977). In contrast, the recognition and correlation of these kinds of surfaces in rift basins have a constrained correlation distance (Prosser 1993; Gawthorpe *et al.* 1997; Young *et al.* 2003; Jackson *et al.* 2005; Martins-Neto & Catuneanu 2010). Similarly, local changes in trace-fossil distribution can be expected for the initial transgressive systems tract.

Exceptional outcrops of the Springhill Formation from the Austral Basin, Argentina, allow the recognition of lateral variations in two ichnoassociations present in the initial deposits of a transgressive systems tract. Moreover, due to the nature of the

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exposure, this key deposit can be walked out from the shallow foreshore to the shoreface palaeoenvironments over a distance of <1 km.

The main goals of this contribution are to analyse trace-fossil variability across the initial transgressive systems tract in a wedge-shape outcrop of the Springhill Formation, to highlight the restricted, specific locations of the ichnoassociations in this kind of basins and to show the sequence stratigraphic implications of the transgressive surface in this geological setting. This study provides valuable information for a more accurate characterization of the most important reservoir in southern Patagonia, as well as showing limitations in well-log studies.

Study area and methodology

The study area is located in the Santa Cruz Province, SW Patagonia, Argentina (Fig. 1A), in the Lago San Martín locality (Fig. 1B, C), where four sedimentological profiles were measured in detail (scale 1:100) (Fig. 3). To describe the main sedimentary facies, a bed-by-bed characterization was performed, concerned with the main sedimentological aspects (lithology, composition, mechanical and biological structures, geometries, contacts, etc.), as well as a systematic sampling of rocks.

Facies analysis includes the identification of sedimentary facies characterized by a particular texture and mechanical and/or biological sedimentary structures, among other characteristics. Geometry and scale of sedimentary bodies were measured to determine the lithosome architecture (Bridge 1993). The combination of sedimentary facies and architectural analyses, together with the recognition of the interpreted fossil origin (continental vs. marine), enabled the distinction of 12 facies associations (FAs; Table 1). The excellent 3D exposures of the Springhill Formation in the study area allowed a detailed analysis of the lateral and vertical relationships of the FAs. The detailed description and interpretation of the FAs was crucial in the definition of the depositional model, which generated a more accurate

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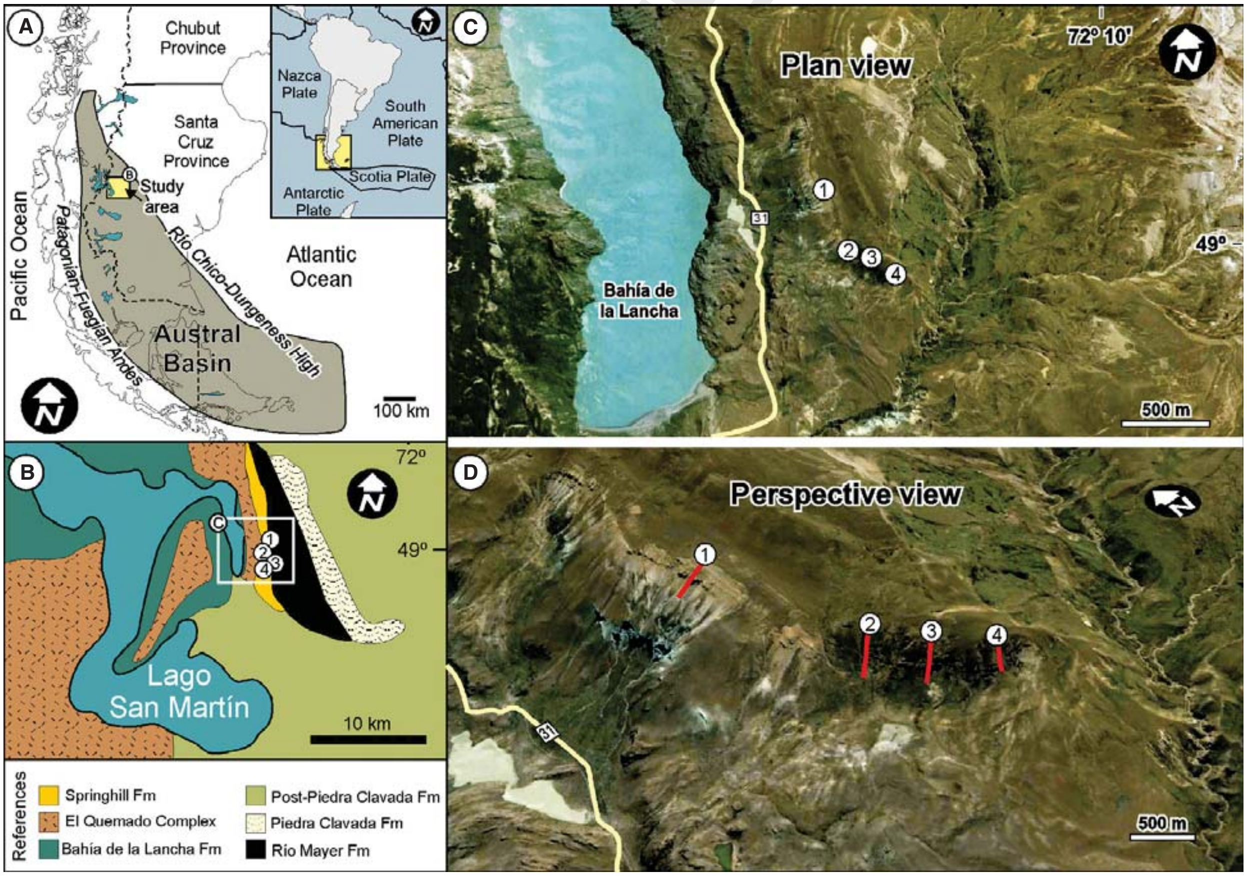

Fig. 1. Location of the Austral Basin in South America and position of the sedimentary logs in the study area. A, position of the Austral Basin in Argentina (South America). B, detailed geological map of the Lago San Martín locality and the sedimentary logs position. C, satellite image of the Bahía de la Lancha area and location of the four sedimentary sections analysed. D, perspective view of the deposits studied. 21

Table 1. Description and interpretation of the 12 facies associations identified for the Springhill Formation at the study area.

Facies Association	Lithology	Sedimentary structures	Dimensions	Geometry and bounding surfaces	Interpretation	Environment
FA 1 Tabular tuffs	Coarse to very fine-grained tuff	Massive tuffs. Silicification. *In situ* trunks	0.2–1 m thick	Tabular at outcrop scale. Base and top: sharp and horizontal	Pyroclastic deposits in floodplains	Fluvial
FA 2 Large-scale complex ribbon bodies	Granule to medium-grained sandstone. Rip-up clast conglomerate	Trough cross-bedding (30–50 cm thick and up to 4 m wide). Trunks on the channel bases	4–10 m thick; up to 250 m wide	Plano-convex lens. Base: concave-upward and erosional. Top: horizontal. Interfingered with fine-grained deposits	Relatively low-sinuosity rivers	Fluvial
FA 3 Large-scale simple ribbon bodies	Granule to coarse-grained sandstone. Rip-up clast conglomerate	Massive and trough cross-bedding (30 cm thick and up to 1 m wide). Mudclasts and trunks on the channel bases	1 m thick; up to 7 m wide	Plano-convex lens. Base: concave-upward and erosional. Top: horizontal to undulated	Small coastal channels	Fluvial
FA 4 Small-scale simple ribbon bodies	Granule to medium-grained sandstone. Rip-up clasts conglomerate	Massive. Plant remains	0.3–0.5 m thick; up to 4 m wide	Plano-convex lens. Base: concave-upward and erosional. Top: horizontal. Interfingered with heterolithic deposits	Crevasse channels	Fluvial
FA 5 Lobe-shaped bodies	Fine-grained sandstone	Massive. Horizontal to inclined lamination. Large-scale rhizoliths, mottles and iron concretions	0.3–1.2 m thick; 15 m wide	Convexo-planar lens. Base: sharp and horizontal. Top: sharp, convex-upward	Crevasse splays with paleosols development	Fluvial/ coastal plain
FA 6 Massive fine-grained deposits	Mudstone and silstone	Massive, rhizoliths, mottles, cutans, nodules, concretions and slickensides. Plant remains. Horizontal lamination	Centimetres to 5 m thick	Tabular. Base and top: horizontal, sharp to transitional	Floodplain deposits with palaeosols development	Fluvial
FA 7 Tabular coals and mudstones	Coal and mudstone	Massive, horizontal lamination towards the top. Rhizoliths, mottles, cutans and slickensides	Centimetres to 2 m thick	Tabular. Base and top: horizontal, sharp to transitional	Waterlogged palaeosols development in coastal plain	Coastal plain
FA 8 Heterolithic deposits	Mixed, fine-grained sandstone and mudstone	Flaser and wavy bedding	0.5–1.2 m thick	Tabular. Base and top: horizontal, sharp to transitional	Tidal flat/estuarine deposits	Coastal plain
FA 9 Tabular bioturbated sandstones	Coarse to medium-grained sandstone	Trough and planar cross-bedding. Horizontal to low angle planar cross-bedding. Intense bioturbation	3–5 m thick; more than 1 km wide	Tabular. Base and top: horizontal and sharp	Foreshore to middle-shoreface deposits	Marine
FA 10 Thickening- and fining-upward mixed carbonate-siliciclastic succession	Medium to fine-grained skeletal packstones and wackestones interbedded with mudstones and marls	Mainly massive. Horizontal lamination. Bioturbation. Inoceramids, pectinids, oysters, ammonites and belemnites	10–15 m thick	Tabular. Base and top: horizontal and sharp	Lower shoreface deposits	Marine
FA 11 Massive wackes and sandstones	Very coarse to medium-grained wackes and sandstones. Rip-up clast conglomerates and glauconite grains	Massive	0.1–1 m thick	Lenticular and tabular. Base: concave-upward to horizontal and sharp. Top: horizontal and sharp	Storm deposit (tempestite)	Marine
FA 12 Laminated mudstones and limestones	Mudstones and limestones	Horizontal lamination	3–15 m thick	Tabular. Base and top: horizontal and sharp	Offshore deposits	Marine

understanding of the development of the transgressive deposits of the Springhill Formation.

A bed-scale identification and description of the trace fossils was carried out in the field. The general description includes the size, the presence/absence and type of wall, kind of filling, relative abundance and cross-cutting relationships, among others characteristics. This study concentrates in qualitative trace-fossil data (presence/absence); however, some considerations about relative abundance between different sedimentary sections were made by comparison of the intensities of bioturbation. To define the intensity of bioturbation, the bioturbation index (BI) was used following the criteria of Taylor & Goldring (1993).

The Austral Basin and the Springhill Formation

The Austral Basin is located in the southernmost part of Argentina and Chile, South America (Fig. 1A). The stratigraphy of the Austral Basin in the study area is summarized in Figure 2. The geological history of the basin is characterized by three main tectonic stages (Biddle *et al.* 1986; Varela *et al.* 2012). The rift stage is represented in the study area by the El Quemado Complex (Early Jurassic to earliest Cretaceous; Pankhurst *et al.* 2000). At this initial stage, grabens and half-grabens developed and filled with volcaniclastic and volcanic rocks intercalated with some epiclastic sediments (Biddle *et al.* 1986). The thermal subsidence stage occurred subsequently once the tectonic activity had ceased and the thermal subsidence stage had begun. The Springhill Formation developed at the end of the rift stage and at the beginning of the thermal subsidence broadly overlaps the margins of the initial half-grabens. This unit is overlain by a thick deep-marine succession, characterized by alternating black mudstones and marlstones of the Río Mayer Formation, which extends to the Early Cretaceous (Richiano *et al.* 2012). Finally, the foreland stage marked by a regional change from an extensional to a shortening deformation took place since the Late Cretaceous to the Neogene (Biddle *et al.* 1986; Wilson 1991; Fildani *et al.* 2003; Fildani & Hessler 2005; Spalletti & Franzese 2007; Fosdick *et al.* 2011; Varela *et al.* 2012).

Most information about the Springhill Formation is reported from sub-surface studies, as this unit represents the most important reservoir in the Austral Basin (Thomas 1949a,b; Spalletti *et al.* 2006; Schwarz *et al.* 2011; among others). Studies concerning the sedimentology of the outcrops in this unit are scarce, especially for the study area. General sedimentological and palaeontological aspects have been published by different authors, but without any characterization of the trace-fossil content (Riccardi 1971; Kielbowicz *et al.* 1983; Arbe 1986, 2002).

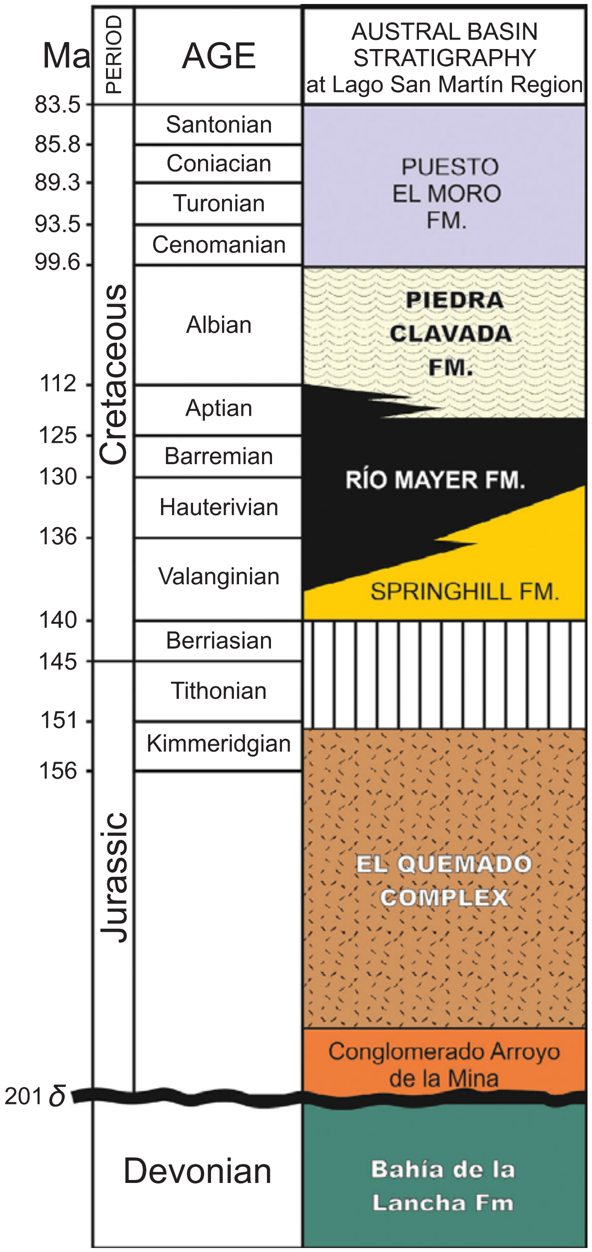

Fig. 2. Stratigraphical chart of the Austral Basin (Argentina) in the study area (Arbe 2002; Richiano *et al.* 2012; Varela *et al.* 2012). δ: discordance.

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The original description of the Springhill Formation made by Thomas (1949b) refers to a highly diverse unit ranging from coal and coaly shales to mainly sandstone bodies. This arrangement was interpreted as having developed in a nearshore to lagoonal palaeoenvironment (Thomas 1949b). Cecioni (1955) divided this unit into two different palaeoenvironments: the lower part of the unit was considered as having been deposited in continental environments, while the upper part deposited under marine conditions. The Springhill Formation represents a transgressive succession composed of fluvial, coastal plain, estuarine and open-marine siliciclastic deposits that fills grabens and half-grabens (Biddle *et al.* 1986; Arbe & Fernández Bell Fano 2002; Schwarz *et al.* 2011). Despite the importance of the Springhill Formation, few studies have carried out facies analyses as well as interpreted its depositional systems, focusing on the sub-surface at the scale of hydrocarbon reservoirs (e.g. Limeres *et al.* 2000; Schwarz *et al.* 2011). From an ichnological point of view, Buatois & Lopez Angri-[3] man (2000) and Schwarz *et al.* (2011) cited trace fossils of the *Skolithos* and *Cruziana* ichnofacies from a core description of this unit within Tierra del Fuego Province, Argentina.

Sedimentological framework

The excellent preservation of outcrops of the Springhill Formation at the Lago San Martín locality (Fig. 1) developed as the infill of the rift stage of the Austral Basin allowed to analyse sedimentological logs both perpendicular and parallel to the wedge geometry recognized in the field (Figs 1, 4). The sedimentary rocks of the Springhill Formation were grouped into 12 FAs (Table 1), which correspond to three major palaeoenvironments (Fig. 4).

Fluvial and coastal plain deposits

The fluvial FAs comprised the basal part of the Springhill Formation deposits that lie above the syn-rift deposits of El Quemado Complex (Figs 4, 5). These continental deposits include six FAs (FA 1–FA 6; Table 1) and can be divided into two intervals. The lower interval is composed of tabular tuffs (FA 1) interbedded with large-scale simple ribbon sandstone bodies (FA 3), isolated within massive fine-grained (muddy) deposits (FA 6) and associated with small-scale simple ribbon sandstone bodies and lobe-shaped sandstone bodies (FA 4 and FA 5). FA 3 is interpreted to comprise single-story [4] ribbon-shaped channel bodies (*sensu* Gibling, 2006). The occurrence of FA 3 as isolated simple sandstone bodies within FA 6 (muddy deposits) suggests sinuous channels which flowed through coastal plains [5] (cf. Martinsen *et al.* 1999); this is why FA 3 is interpreted as a system of small coastal distributary channels. The upper interval is composed of large-scale complex ribbon sandstone bodies (FA 2), laterally associated with massive fine-grained (muddy) deposits (FA 6). FA 2 bodies were probably deposited by solitary channels with low degree of lateral migration or by relatively straight channels with lateral bars and meandering thalweg (cf. Bridge 1993). FA 2 is interpreted as the deposits of relatively low-sinuosity rivers. The fluvial facies associations are interpreted as decreasing accommodation/sediment supply conditions from a system of small coastal distributary channels to relatively low-sinuosity, possibly meandering, rivers, interbedded with floodplains, crevasse splays and crevasse channels with palaeosol development (Table 1; Figs 3–5).

The coastal plain FAs are <20 m thick and correspond to the intermediate part of the Springhill Formation deposits (Figs 4, 6). These deposits include three FAs (FA 5, FA 7 and FA 8; see Table 1). The coastal plain succession began with tabular coals and mudstones (FA 7) interbedded with lobe-shaped bodies (FA 5), while towards the top, it is composed of heterolithic deposits (FA 8). The presence of hydromorphic pedological features in FA 7 indicates that palaeosol development occurred under waterlogged drained conditions. These conditions in turn favoured the preservation of organic matter and subsequent accumulation of coal. The presence of mudstone drapes in FA 5 could be related to tidal impact on fluvial discharge. The occurrence of flaser, lenticular and wavy bedding in FA 8 indicates an alternation of tractional and suspension-settling processes, which is consistent with the action of tides. The close vertical relationships between the coastal plain FAs are interpreted as a transgressive arrangement from upper to intermediate/lower tidal flats (Table 1; Figs 3, 4, 6).

Marine deposits

The marine FAs include two intervals. The lower interval is represented by tabular bioturbated sandstones (FA 9), and it constitutes the focus of this study (Table 1; Figs 4, 7). FA 9 is 3–5 m thick and is mainly composed of bioturbated (BI = 1–2) coarse- to medium-grained sandstones with trough and planar cross-bedding, and horizontal to low-angle planar cross-bedding (Fig. 7). At section 1, FA 9 is characterized by coarse-grained sandstone with horizontal to low-angle cross-bedding attributed to unidirectional flows of high-energy conditions related to foreshore environment. At sedimentary sections 2, 3 and 4, FA 9 is constituted by coarse- to medium-grained sandstones with trough and planar cross-bedding interpreted as deposited by migration of sub-tidal both straight- and sinuous-crested dunes (2D and 3D) in an upper to middle shoreface

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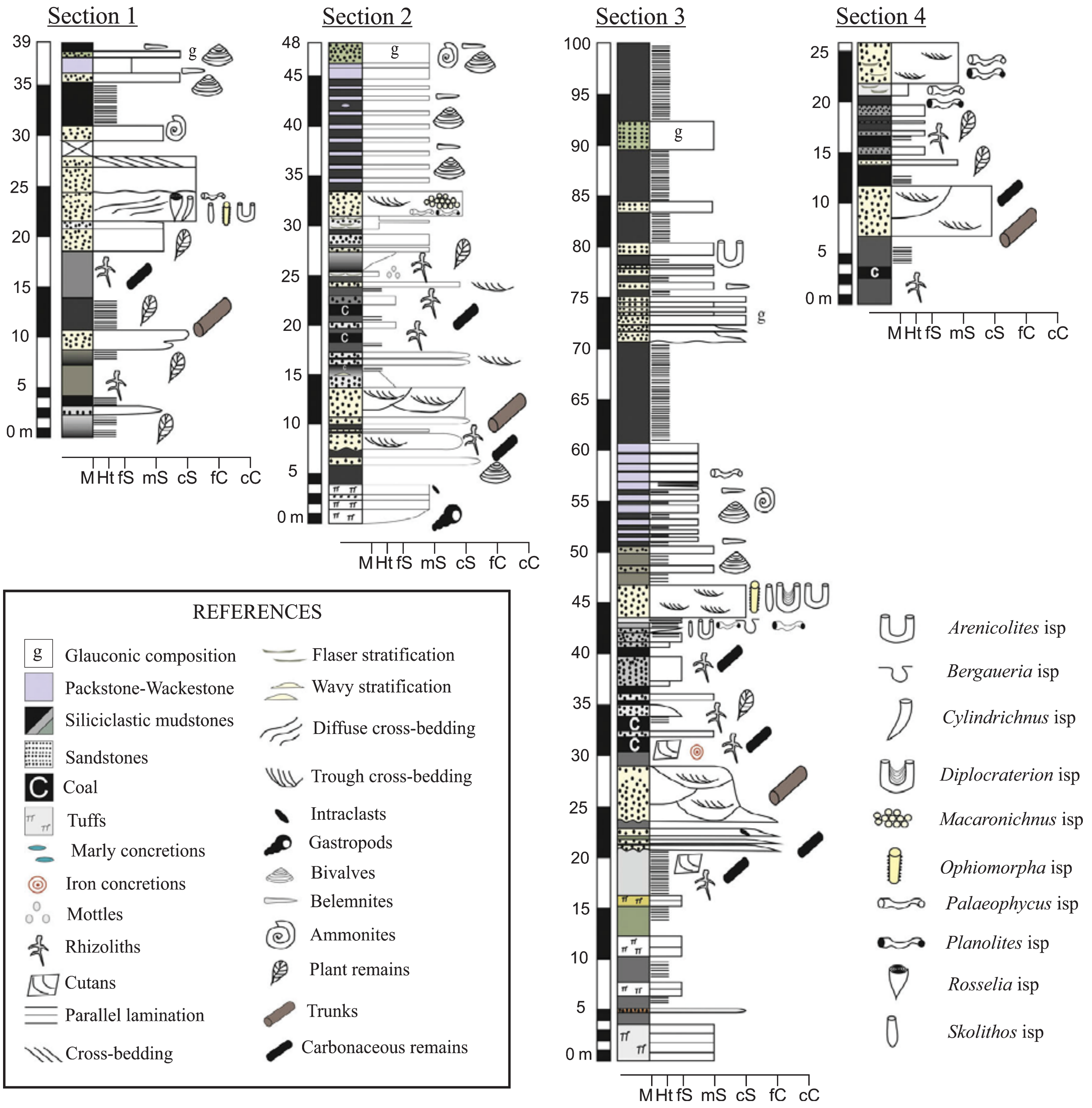

Fig. 3. Sedimentary logs from the Springhill Formation at Lago San Martín region. M: mudstone; Ht: heterolithics; fS: fine-grained sandstone; mS: medium-grained sandstone; cS: coarse-grained sandstone; fC: fine-grained conglomerate; cC: coarse-grained conglomerate (see location in Figures 1B, D).

environment. The most remarkable aspect of FA 9 at sedimentary section 1 is the intense bioturbation preserved (BI = 4) as a sharp sub-horizontal gently undulating surface with a bioturbation thickness between 15 and 25 cm (Figs 7G, 8, 9), which is not present at the rest of the sections.

The rest of the marine deposits comprise a thickening- and fining-upward mixed carbonate-siliciclastic succession (FA 10) and laminated mudstones and limestones (FA 12), interbedded with massive wackes and sandstones (FA 11). These marine FAs are interpreted as a transgressive package from foreshore to offshore, where deposits of tempestites are preserved (FA 11).

Ichnology

Trace fossils

In the basal transgressive marine deposits of the Springhill Formation (FA 9) from the four sedimen-

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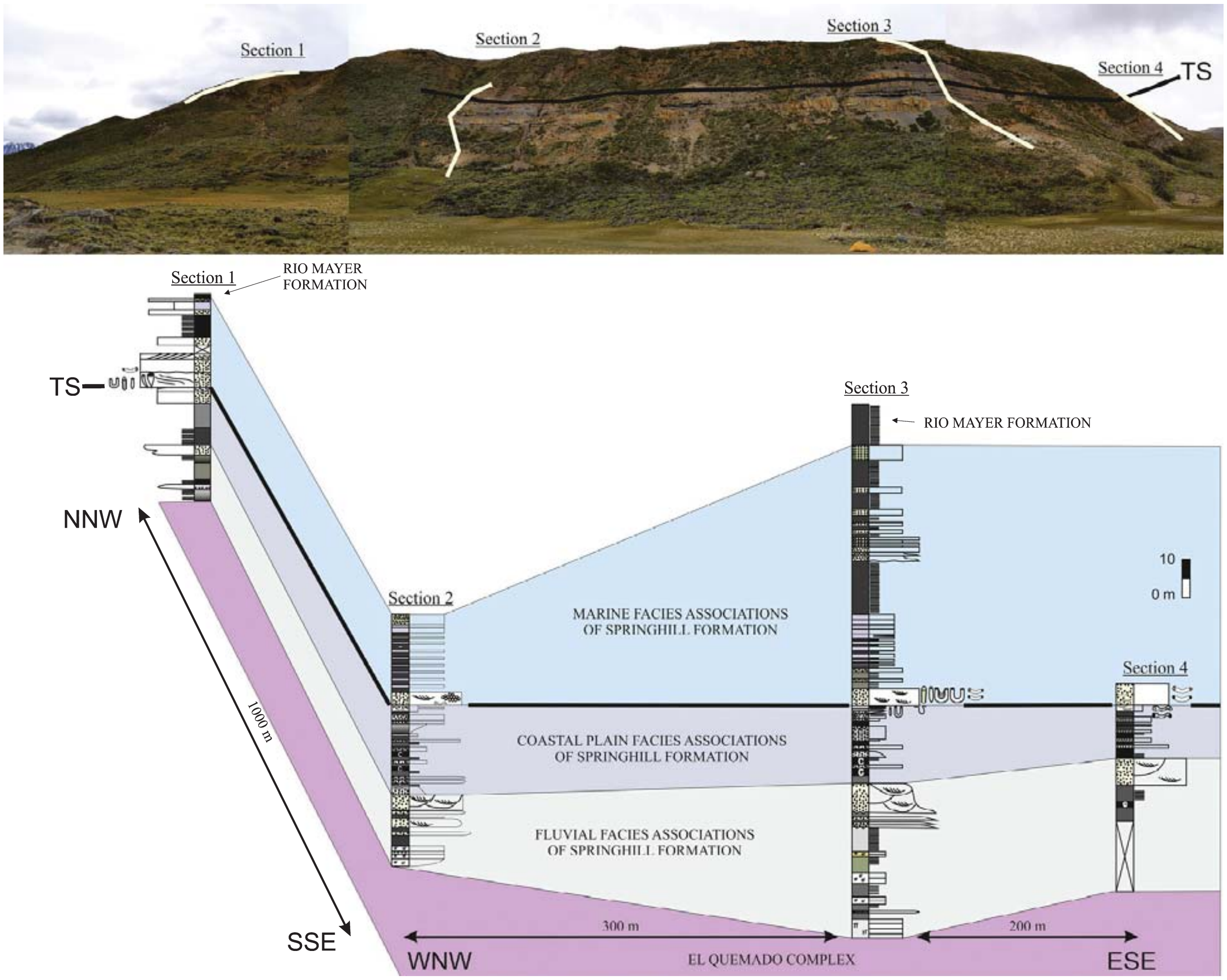

Fig. 4. Spatial distribution of the four sedimentary sections studied showing the arrangement of the three interpreted palaeoenvironments. References as in Figure 3. TS: transgressive surface.

tary sections analysed, ten ichnogenera were identified: *Arenicolites*, *Bergaueria*, *Cylindrichnus*, *Diplocraterion*, *Macaronichnus*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Rosselia* and *Skolithos* (Figs 8, 9).

Arenicolites isp. (Fig. 8A, B) is recognized as U-shaped, vertically oriented tunnels and/or as paired circular openings on the bedding surface, filled with the host sediment. Burrow diameter is about 0.5 cm and up to 5 cm in length. Ethologically, *Arenicolites* was interpreted as dwelling burrows of suspension feeders (e.g. Howard & Frey 1984; Pickerill *et al.* 1984) and produced by deposit feeders (Bromley 1996).

Bergaueria isp. (Fig. 8C) appears as vertical hemispherical burrows with smooth borders; in general, the diameter of the base is ca. 1.2–1.5 cm. The burrow fill is similar to the host rock. The ichnogenus *Bergaueria* has been interpreted as the dwelling or temporary reclusion structure of anemones, which is passively filled by sand after the death of the animal or the abandonment of the burrow (e.g. Alpert 1973; Häntzschel 1975; Pemberton *et al.* 1988; Ekdale & Lamond 2003). It is a common component of normal marine successions, but it is also recorded in marginal marine deposits and oxygen-deficient palaeoenvironments, suggesting the adaptability of their producer to different marine environmental scenarios (e.g. Dam 1990; Crimes & Crossley 1991; Buatois & Mángano 1993; Buatois *et al.* 2009; Lima & Netto 2012; Richiano *et al.* 2013).

Cylindrichnus isp. (Fig. 8D, E) occurs as isolated, cylindrical, steeply inclined burrows, in general up to 2 cm in diameter, with a maximum length of about 20 cm. Only in some specimens, a very thin dark lining was identified. The trace fossil is filled with material similar to the host rock (Fig. 8D, E). Burrows of *Cylindrichnus* are known as vertical, steeply inclined forms, characteristic of high-energy environments (Howard & Frey 1984; Frey & Howard

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Fig. 5. Fluvial deposits. A, general view of the large-scale complex ribbon bodies (FA 2) interbedded with massive fine-grained deposits (FA 6). Circled person for scale. B, detail of large-scale simple ribbon bodies (FA 3). C, picture showing the small-scale simple ribbon bodies (FA 4). Hammer: 35 cm.

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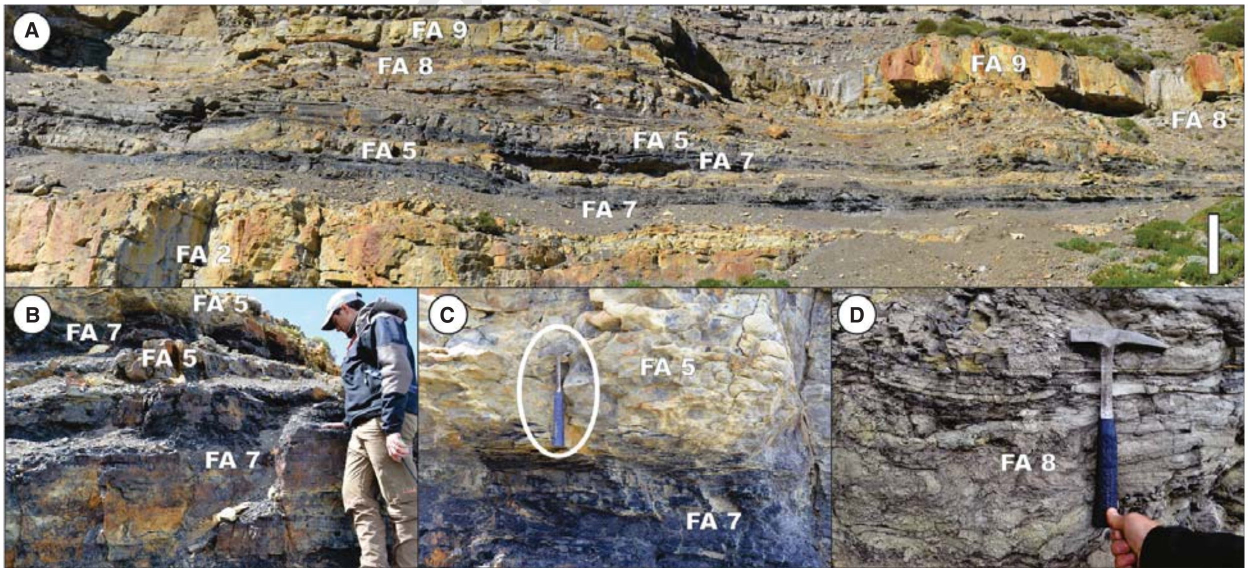

Fig. 6. Coastal plain deposits. A, general view of the coastal plain deposits showing the tabular coals and mudstones (FA 7) at the base, interbedded with lobe-shaped bodies (FA 5), and heterolithic deposits (FA 8) towards the top (scale bar = 5 m). B, C, detail of the tabular coals and the lobe-shaped bodies. D, close-up view of the heterolithic deposits. Hammer: 35 cm.

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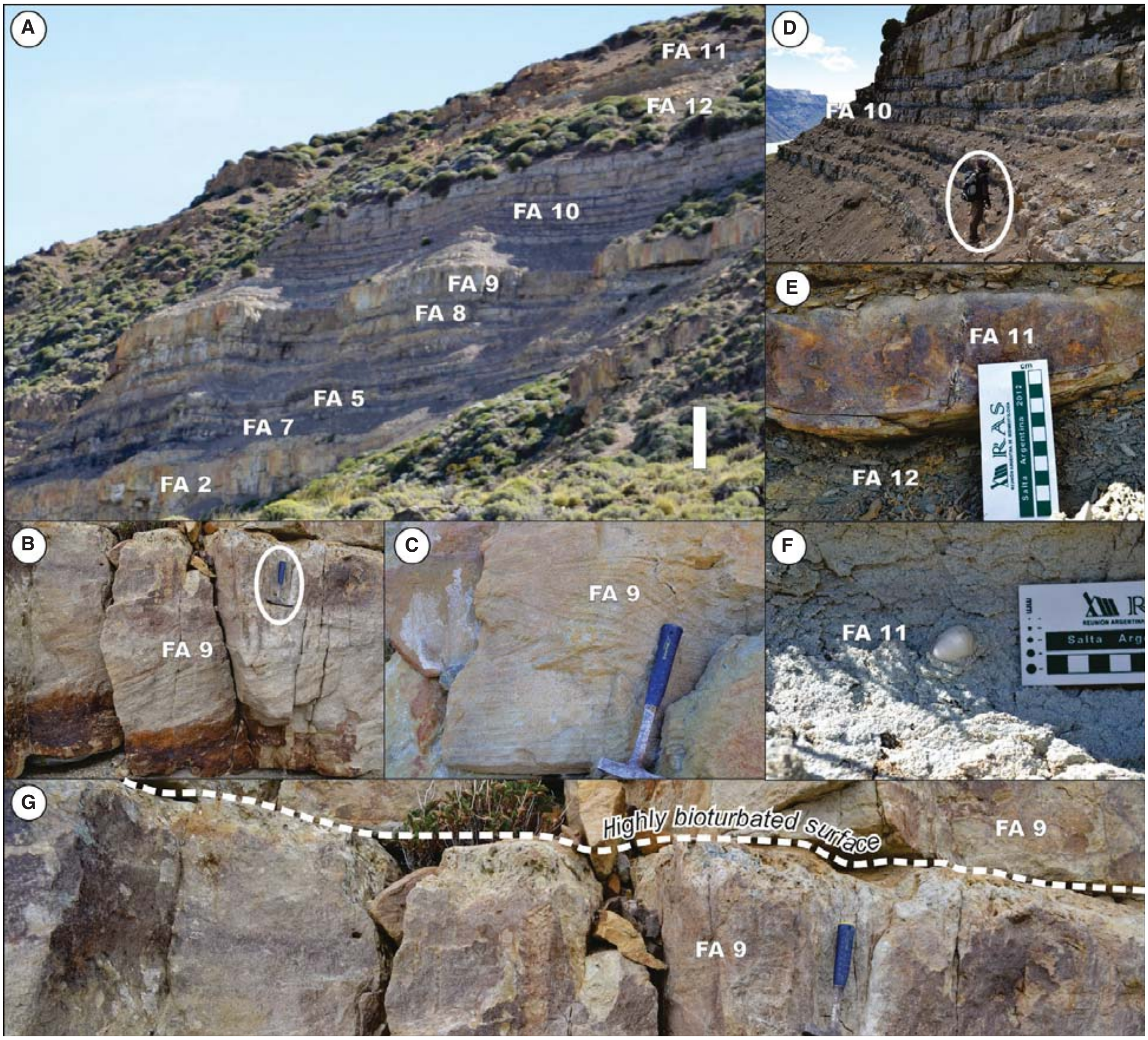

Fig. 7. Marine deposits. A, general view of the coastal plain (FAs 5, 7, 8) and marine (FAs 9, 10, 11, 12) deposits of the Springhill Formation (scale bar = 5 m). B, C, detail of the sedimentary structures present in the tabular bioturbated sandstones (FA 9). D, main arrangement of the thickening- and fining-upward mixed carbonate-siliciclastic succession (FA 10). E, F, detail of the massive wackes and sandstones (FA 11) and the laminated mudstones and limestones deposits (FA 12). G, highly bioturbated surface into the FA 9 at Sedimentary Section 1. Hammer: 35 cm.

1985; Frey 1990). On the other hand, sub-horizontal forms are cited in low-energy conditions (Fürsich 1974; Frey 1990; Rotnicka 2005).

Diplocraterion isp. (Fig. 8F) was recorded as the vertical shafts of a U-shaped burrow with spreiten. The diameter of the vertical shafts is about 0.3–0.5 cm, and they penetrate into the substrate up to 10 cm. The burrow fill is similar to the host rock. *Diplocraterion* is interpreted as a dwelling structure of suspension or detritus feeders. The tracemaker has the ability to move in a vertical direction in response to changes in the water/sediment interface as a consequence of high sedimentation rates and/or erosion events (e.g. Turner *et al.* 1981; Bromley 1996; Savrda & Nanson 2003; Seilacher 2007). *Diplocraterion* occurs in a wide variety of environmental settings, including fully marine, estuarine and deltaic deposits (McIlroy 2004, 2007; Buatois *et al.* 2005; Chakraborty & Bhattacharya 2005; Lima & Netto 2012). This situation reflects the high degree of plasticity of the trace makers of this ichnogenus to the environmental factors.

Macaronichnus isp. (Fig. 8G–I) can be observed as cylindrical tubes in an intrastratal non-branching arrangement. The traces are 0.5–1 cm in diameter, with a maximum length of 15 cm, generally parallel to the bedding plane. The recorded specimens are horizontal to gently inclined rectilinear forms

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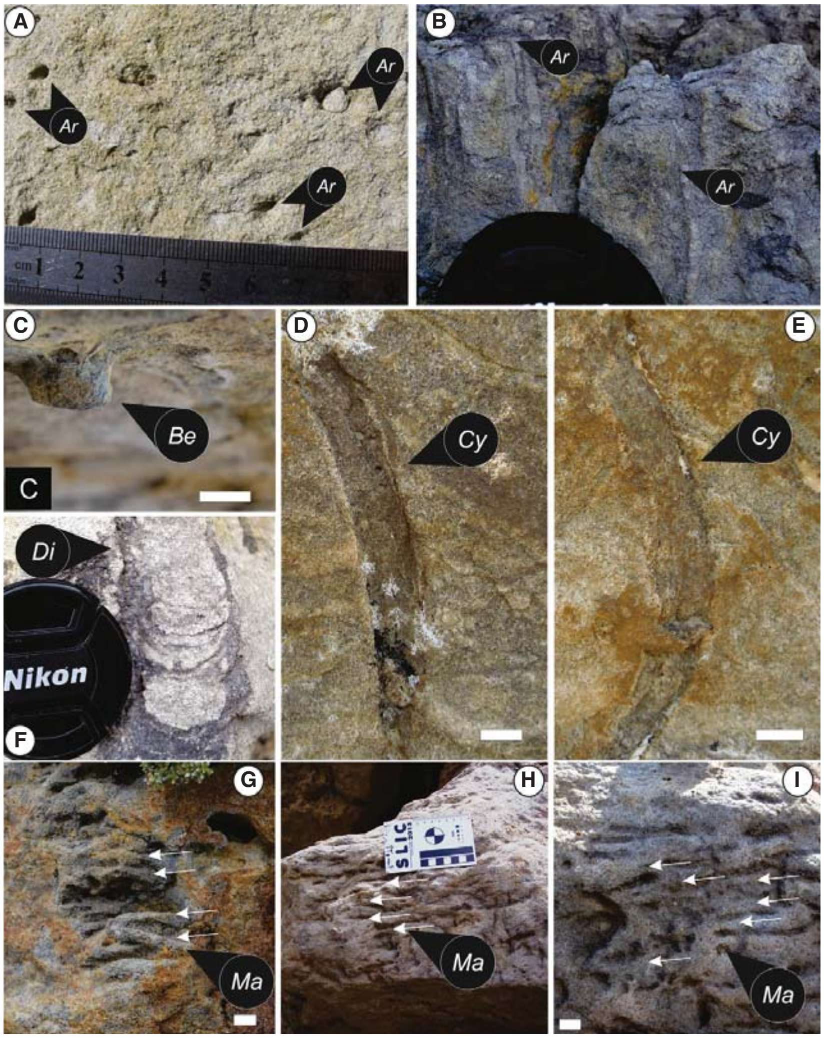

Fig. 8. Trace fossils recovered from the sandy initial transgressive deposits (FA 9) of Springhill Formation at Lago San Martín region. A, B, *Arenicolites* isp. in plain view and vertical section, respectively. C, *Bergaueria* isp. D, E, *Cylindrichnus* isp. F, *Diplocraterion* isp. G, H, I, *Macaronichnus* isp.; white arrows mark the individual tunnels. Scale bar: 1 cm; camera lens: 5.2 cm.

oriented in NW–SE direction. *Macaronichnus* usually shows a preferred orientation in dense concentrations (Seike 2007), and it is considered as an excellent indicator of ancient foreshore deposits (Clifton & Thompson 1978; Seike 2007; Mayoral *et al.* 2013; among others). The longer axes of *M. segregatis* have been interpreted as indicative of an orientation perpendicular to the palaeoshoreline (e.g. Koyama 1983; Seike 2007). Nevertheless, it has been cited in distal delta-front deposits, in wave-dominated estuaries and also commonly in upper and lower shorefaces (MacEachern & Pemberton 1992; Pemberton *et al.* 2001; Carmona *et al.* 2009; Buatois & Mangano 2011; Mayoral *et al.* 2013).

Ophiomorpha isp. (Fig. 9A, B) was recognized mainly as vertical cylindrical shafts and, to a lesser extent, as horizontal galleries with Y-shaped junctions. The diameter of the burrows ranges from 1.5 to 2.5 cm (Fig. 9A, B). This ichnogenus usually shows a wall formed by pellets, regularly spaced, 0.2–0.5 cm in diameter (Fig. 9B). The tunnels are filled with massive sandstones similar to the host rock (Fig. 9A). *Ophiomorpha* is a good marine environmental indicator, in loose substrates, with horizontal burrows generally corresponding to low-energy environments, whereas the vertical ones predominate in high-energy environments (Frey *et al.* 1978; Howard & Frey 1984; Pollard *et al.* 1993; Rotnicka 2005).

Palaeophycus isp. and *Planolites* isp. (Fig. 9C–E) were observed as sub-horizontal to almost vertical tubes with an elliptical cross-section of 0.5–1 cm. They differ in two main aspects (Pemberton & Frey 1982): firstly, the presence of a lining in the case of *Palaeophycus*, which is commonly darker than the structureless fill and the host rock (Fig. 9C);

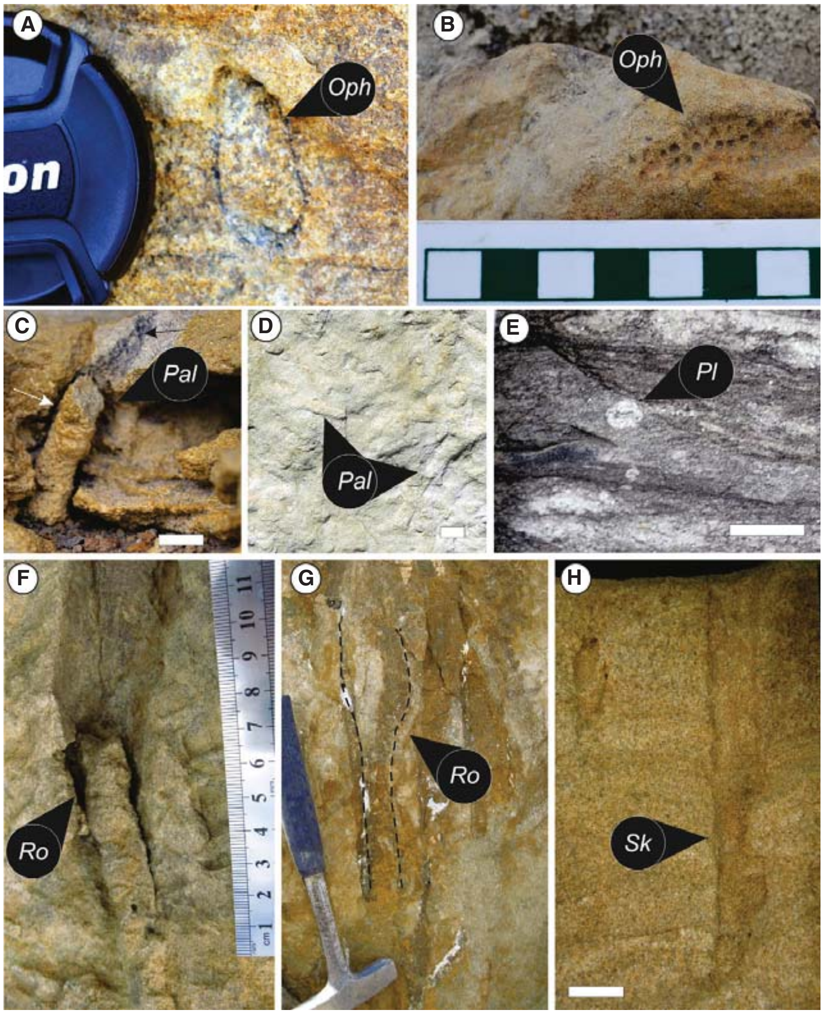

Fig. 9. Trace fossils recovered from the sandy initial transgressive deposits of Springhill Formation at Lago San Martín region. A, B, *Ophiomorpha* isp., as seen in oblique cross-section and external cast, respectively. C, D, *Palaeophycus* isp.; the lining either is removed and represented by an empty space (white arrow), or may be recognized a residual material that is commonly darker than the structureless fill and the host rock (black arrow). E, *Planolites* isp. in cross-section view. F, G, *Rosselia* isp. H, *Skolithos* isp. Scale bar: 1 cm; camera lens: 5.2 cm; hammer: 35 cm.

secondly, the filling sediment of the *Planolites* structure shows a different colour and appearance from the host rock (Fig 9E). In general, *Palaeophycus* is interpreted as the dwelling burrow of predaceous polychaetes, while *Planolites* is considered as the feeding burrow of a deposit feeder (Pemberton & Frey 1982).

Rosselia isp. (Fig. 9F, G) has been observed as vertical to sub-vertical conical structures, consisting of a small central burrow surrounded by concentric layers. The maximum diameter of the cones typically ranges from 2 to 5 cm, and their length varies between 10 and 25 cm (Fig. 9G). This ichnogenus is considered as feeding and sediment-stowage burrows (Frey & Howard 1990) of deposit-feeding worms/annelids (Vossler & Pemberton 1988; Nara 1995, 1997, 1998, 2002).

Skolithos isp. (Fig. 9H) is represented by vertical to oblique cylindrical tubes, with a circular cross-section of 0.3–1 cm in diameter and 3–8 cm length (Fig. 9H). Contrasting *Cylindrichnus*, *Skolithos* specimens have straight, uncurved margins without lining. The burrows are passively infilled by sediment similar to the surrounding matrix. Marine *Skolithos* is generally interpreted as the dwelling burrows of annelids or phoronids (Buckman 1996; Schlirf & Uchman 2005; among others). *Skolithos* tends to be more abundant in a high-energy, shallow marine depositional environment (foreshore). On the other hand, it also occurs frequently in almost all sedimentary marine/brackish environments from offshore turbidites, through upper/middle shoreface, to intertidal channels and wave or tide-dominated estuaries (Vossler & Pemberton 1988; Gingras *et al.* 1999;

MacEachern *et al.* 2005; Buatois & Mangano 2011; Desjardins *et al.* 2012; among others).

Distribution of trace fossils

The 10 ichnogenera recovered from the initial sandy transgressive deposits of the Springhill Formation (FA 9) at the Lago San Martín locality suggest a fully marine and well-oxygenated palaeoenvironment with variable energetic conditions. Two major ichnoassociations were distinguished: firstly, the traces recognized in Sedimentary Section 1 (*Arenicolites*, *Cylindrichnus*, *Ophiomorpha*, *Palaeophycus*, *Rosselia* and *Skolithos*) correspond to high energetic conditions interpreted as having developed in a foreshore environment. On the other hand, the ichnotaxa recovered from Sedimentary Sections 2, 3 and 4 (*Arenicolites, Bergaueria, Diplocraterion, Macaronichnus, Ophiomorpha, Palaeophycus, Planolites* and *Skolithos*) have been interpreted as mainly formed in less energetic conditions than the other ichnoassociation mentioned. This second ichnoassociation developed in a shoreface palaeoenvironment.

Foreshore ichnoassociation

The trace fossils developed in this palaeoenvironment are present in the Sedimentary Section 1, where six ichnogenera were identified: *Arenicolites*, *Skolithos*, *Palaeophycus*, *Ophiomorpha*, *Rosselia* and *Cylindrichnus* (Figs 3, 4). This assemblage of trace fossils is compared with the *Skolithos* ichnofacies developed in foreshore deposits. Dwelling structures of suspension feeders are frequent in high-energy environments (MacEachern *et al.* 2007b), for instance the pair *Arenicolites*–*Skolithos*. The occurrence of *Ophiomorpha* represents the dominance of soft loose substrate and high-energy conditions in foreshore and shoreface settings (Frey *et al.* 1978; Howard & Frey 1984). However, it is also known that *Ophiomorpha* has been reported from a wide range of dissimilar marine environments (*e.g.* Anderson & Droser 1998; Carmona *et al.* 2004; Uchman 2009). The *Rosselia*–*Cylindrichnus* couplet is known from foreshore to offshore deposits, from storm- and ice-influenced middle to outer shelf sediments and protected shoreface environments (Frey & Howard 1985, 1990; Vossler & Pemberton 1988; [7] Eyles *et al.* 1998; de Gibert *et al.* 2006; Sarkar *et al.* 2009). A highly bioturbated surface was recognized only in this section (Fig. 7G), disappearing over short distances, where the most common ichnotaxa in this potential key surface are *Cylindrichnus* and *Rosselia*. The high density of these ichnogenera (BI = 4) probably represents the colonization of the substrate by specialized organisms (Nara 1997, 1998, 2002; Netto *et al.* 2014). Vertical burrows are related to the life position of the immobile inhabitant, and each shaft could represent the activity of an individual organism (Thayer 1983; Pemberton & Frey 1984; Vossler & Pemberton 1988). This surface indicates a period of non-sedimentation or erosion. In this case, the transgressive scenario seems to have resulted in longer colonization windows favouring more intense bioturbation. To summarize, the ichnofossils recovered from Sedimentary Section 1 are considered as having developed in foreshore environments, which is in agreement with the low-angle cross-bedding structure identified in FA 9 in this section.

Shoreface ichnoassociation

This ichnoassociation shows the highest ichnodiversity (eight ichnogenera) and includes the trace fossils recovered from FA 9 in Sedimentary Sections 2, 3 and 4. In general, the BI of the FA 9 at these sections is between 1 and 2. This group of trace fossils represents a *Skolithos* ichnofacies.

In Sedimentary Section 2, where three ichnogenera were identified, *Macaronichnus* is the most abundant and *Planolites* and *Palaeophycus* are subordinated (Figs 3, 4). *Macaronichnus* is considered as a powerful tool indicator of nearshore palaeoenvironments and high energetic conditions (e.g. Seike 2007; Aguirre *et al.* 2010; Seike *et al.* 2011). Taking into account the size of the burrows, there are two main groups of interpretations: small burrows (3–5 mm wide = *M. segregatis*) are attributed to foreshore environments, whereas large burrows (5–15 mm wide = *Macaronichnus* isp.) are considered to have formed in a wider range of depositional environments (tidal flats and upper to lower shoreface; Seike *et al.* 2011). The size of the *Macaronichnus* burrows in the Springhill Formation is between 0.5 and 1 cm. This size of the trace fossil is related to shoreface environments, which is consistent with the sedimentological interpretation of FA 9 in this section.

In Sedimentary Section 3, *Ophiomorpha*, *Diplocraterion*, *Arenicolites* and *Skolithos* are present together with scarce *Bergaueria*, *Planolites* and *Palaeophycus* (Figs 3, 4). Sedimentary Section 4 only contains the ichnogenera *Planolites* and *Palaeophycus* (Figs 3, 4). The ichnotaxa *Ophiomorpha*, *Arenicolites* and *Skolithos* show a minor relative abundance than Sedimentary Section 1 (BI = 1–2). This expression of the *Skolithos* ichnofacies differs from the one described above and can be walked out along the outcrops studied over a distance of no more than 300 m. The occurrence of *Diplocraterion* is indicative of periods of erosion and/or changes in the sediment supply, representing a possible stress factor for the development of a more diverse benthic palaeocommunity resulting in low ichnodiversity.

From a sedimentological perspective, Section 3 is characterized by coarse-grained sandstones with trough cross-bedding stratification without participation of fine sediments. In turn, Section 4, located 200 m towards the SE (Fig. 1), is mainly composed of medium- to fine-grained sandstones interbedded with thin levels of fine sediments (mudstones and heterolithics). This general pattern represents a deepening trend of FA 9 from Section 1 to Sections 2, 3 and 4 (see below).

Relationship of the distribution of trace fossils with the wedge-shape geometry

The wedge-shape geometry, evidenced by the differences in thickness and lateral facies variation of the three FAs of the Springhill Formation deposits at Lago San Martín locality, allows to reconstruct the spatial orientation of the palaeoenvironments (Figs 4, 10). Considering that the Springhill Formation is filling grabens and half-graben of different scales in the Austral Basin (among others, Biddle *et al.* 1986; Kraemer & Riccardi 1997; Rodríguez & Miller 2005; Schwarz *et al.* 2011; Sachse *et al.* 2015), the most plausible explanation to the wedge geometry is the development of a half-graben. In this sense, the four sedimentary sections recovered from the initial transgressive deposits (FA 9) of the Springhill Formation could be located in the hanging-wall shoreline of a half-graben (Fig. 10). Different palaeoenvironmental conditions (energy, bathymetry) and grain size controlled the distribution of trace fossils in the four sections of FA 9. The foreshore ichnoassociation includes Section 1, which is placed at the margin of the hanging-wall shoreline (Figs 1C, D, 4, 10). On the other hand, the shoreface ichnoassociation is composed of Sections 2, 3 and 4, which are perpendicular to the hanging-wall shoreline, distant 200–300 m from each other in a WNW–ESE direction (Figs 1C, D, 4, 10).

From Section 1 to Section 4, the change of some sedimentary aspects perpendicular to the palaeoshoreline (WNW–ESE) was observed. The ori-

Colour online, B&W in print

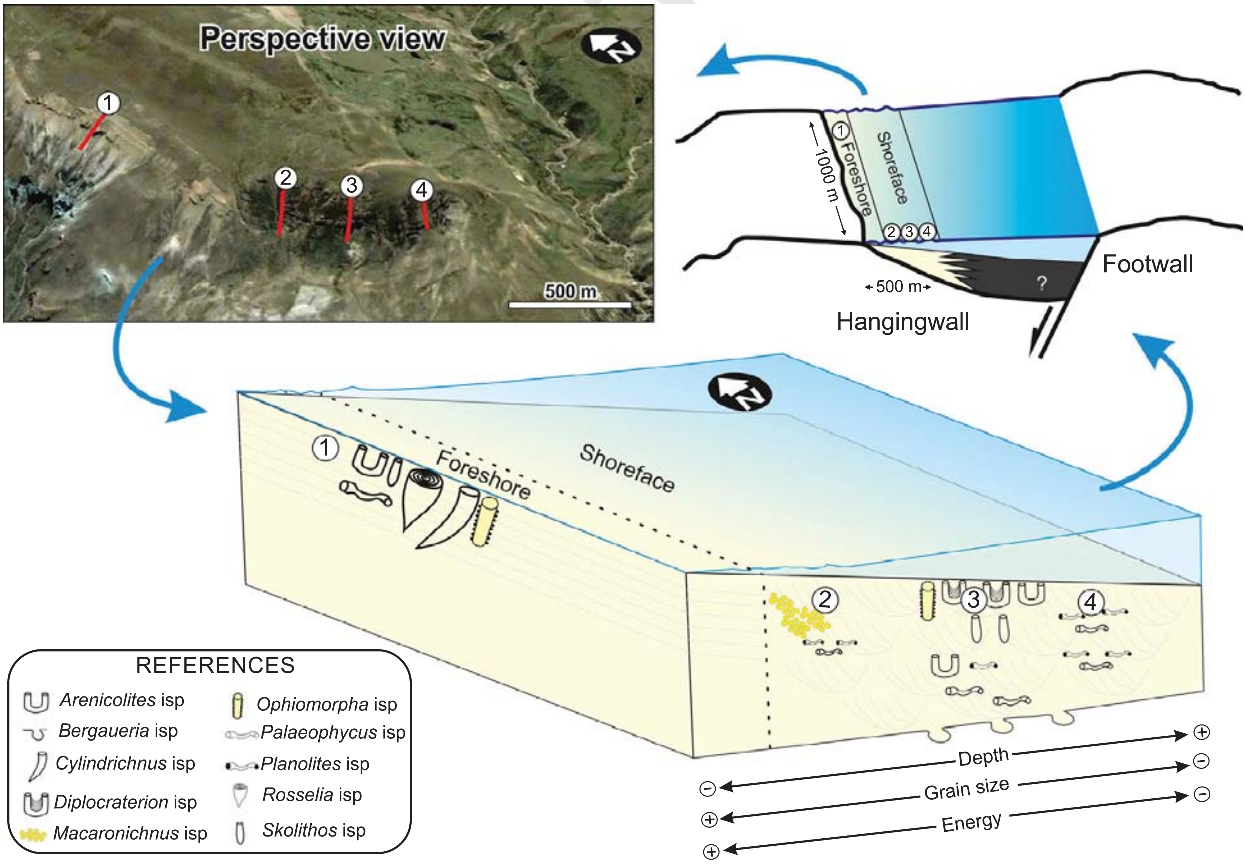

Fig. 10. Schematic block diagram showing the trace fossil distribution in the hanging-wall shoreline.

entation of *Macaronichnus* in section 2, as expected, is perpendicular to the interpreted palaeoshoreline for the inferred half-graben. In general, a decrease in the grain size of the sand, an increase in the amount of fine sediments (mudstones) and a shifting from planar to trough cross-bedding stratification were identified in this transect (Fig. 10). All of these variations were interpreted as a response to a deepening palaeoenvironment towards the ESE, that is towards the footwall (Fig. 10).

Similar studies carried out in half-graben deposits from the Suez Rift (Egypt) show the transition from upper shoreface to offshore over a distance of more than 5 km (Malpas *et al.* 2005). These authors observed lateral ichnofabric relationships deposited in a rapidly deepening shallow marine setting (Malpas *et al.* 2005). For the Springhill Formation, the foreshore to middle/lower shoreface deposits are developed in ca. 500 m perpendicular to the palaeocoastline, whereas the offshore deposits are not observed. In this sense, the transgressive shallow marine deposits of the Springhill Formation represent ichnological changes in a similar high-gradient shelf setting.

In the beginning of the modern ichnology, bathymetry was considered the principal controlling factor of trace-fossil associations in different depositional environments (e.g. Seilacher 1967; Buatois & Mangano 2011). Nevertheless, it soon became clear that ichnofacies and trace-fossil distribution reflect sets of environmental factors rather than sedimentary environments and specific bathymetric zones (Buatois & Mangano 2011). While ichnofacies remain essential to palaeoenvironmental reconstructions, palaeobathymetry constitutes only one aspect of the modern concept (Knaust & Bromley 2012). Nowadays, the heterogeneous distribution across an individual sedimentary unit is known as spatial heterogeneity (Buatois & Mangano 2011). In this sense, the ichnology of the Springhill Formation shows the transition from the dominance of dwelling structures in foreshore environments to the more diverse ethologic ichnoassemblage (dwelling, feeding and resting traces) at shoreface environments (Fig. 10). This spatial heterogeneity is the response of marine benthic community to local environmental factors.

A highly bioturbated surface was recognized only in Section 1 (Fig. 7G), where the *Cylindrichnus–Rosselia* pair represents the most frequent ichnogenera (BI = 4). This surface has a very specific location occurrence, disappearing over short distances perpendicular to the palaeoshoreline. For this reason, it has extremely important implications for the subsurface correlations and for sequence stratigraphic interpretations. In well-log studies, the correlation of this kind of surfaces has to consider the changes that occurred in ichnoassociations over short distances, which are independent of the sedimentary palaeoenvironment. In this way, two cores belonging to the shallow marine transgressive deposits of the same rift deposit could lead to mistaken interpretations. To sum up, these kinds of surfaces, which developed in rift basins due to the rapid tectonic subsidence that creates 'instantaneous' accommodation (Martins-Neto & Catuneanu 2010), are only important for local interpretation and lack basin-scale implications.

Conclusions

The trace fossils of the initial transgressive deposits of the Springhill Formation at the Lago San Martín region were grouped in foreshore and shoreface ichnoassociations. The distribution of these ichnoassociations was controlled by the inferred configuration of the hanging-wall shoreline and palaeoenvironmental conditions related to bathymetry changes (mainly energy and the associated grain-size sedimentation).

The presence of a highly bioturbated surface in only one section of the transgressive foreshore deposits constrains its usefulness as a key correlative surface based on ichnology. Moreover, the representation of this kind of surface is spatially restricted within rift basins due to the high accommodation space creation by tectonism.

This study offers very valuable information for a more precise characterization of the most important reservoir in southern Patagonia and could provide new ideas to solve problems in the well-log studies of small-scale rift depocentres. Moreover, future integrated approaches among ichnology, sedimentology and stratigraphy will help to refine the actual conceptual models for sequence stratigraphy in rift basins.

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