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## The transgressive infill of an inherited-valley system: The Springhill Formation (lower Cretaceous) in southern Austral Basin, Argentina

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## ABSTRACT

The Berriasian–Valanginian Springhill Formation of the Austral Basin of southern South America comprises fluvial to marine deposits. In order to interpret depositional systems and unravel the stratigraphic architecture of this unit in the southern region of the basin (Tierra del Fuego Province, Argentina), 500 m of cores combined with well-log data from 41 wells were studied. Facies associations corresponding to fluvial (A1–A6), estuarine (B1–B5) and open-marine (C1–C4) depositional environments were identified. These facies associations succeed each other vertically across the entire study area (6800 km<sup>2</sup>) forming a ~120-m-thick transgressive succession. This unit filled a north-south-oriented valley system, developed in the underlying Jurassic volcanic complex.

Lowstand fluvial deposits of the first stage of the valley-system fill occur in downdip segments of the system above a sequence boundary (SB). These fluvial deposits are overlain by coastal-plain and tide-dominated estuarine strata across an initial transgressive surface (ITS). In the northern sector the earliest valley infill is characterized by a transgressive fluvial succession, overlying a merged SB/ITS that is probably time-equivalent of marginal-marine deposits of the southern sector. The fluvial strata in the north are overlain by wave-dominated estuarine deposits. A drastic change to open-marine conditions is marked by a marine flooding surface, with local evidence of marine erosion (FS-RS). Open-marine strata are thin (<10 m) and dominated by lower-shoreface and offshore-transition deposits. They are capped by a younger flooding surface (FS), which represents the onset to offshore conditions across the study area due to a continuous long-term transgression that persisted until the Barremian.

Although the interpreted depositional systems and stratigraphic architecture of the Springhill Formation resemble transgressive incised-valley-fill successions, the greater thickness and larger size of the Springhill valleys suggest inherited rift topography rather than valley development during a relative sea-level fall.

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## 1. Introduction

Transgressive successions grading from fluvial to estuarine deposits in turn passing vertically into open-marine deposits commonly occur within incised-valley fills. Incised-valley systems are created by fluvial erosion during lowering of sea level and the resulting depositional space is filled during the subsequent sea-level rise (Zaitlin et al., 1994). Since the publication of SEPM Special Publication 51 (Dalrymple et al., 1994), the formation and filling of incised valleys have been the focus of extensive research and incised-valley fills have been recognized across different geological settings and ages (see recent summary in Boyd et al., 2006). One

common feature of incised-valley successions is that they are commonly thin, in the order of 10–30 m thick. Incised-valley-fill successions are also economically important for hydrocarbon exploration and production as they can contain clean sandstones encased in mudstones (Boyd et al., 2006).

The lower Cretaceous Springhill Formation represents a transgressive succession composed of fluvial, coastal-plain, estuarine and open-marine siliciclastics deposits (Kielbowicz et al., 1984; Biddle et al., 1986; Arbe and Fernández Bell Fano, 2002), commonly developed as the infill of extensive topographic depressions. The unit is up to 120 m thick and deposited at the earliest stage of the Austral Basin evolution in the southernmost tip of South America. This transgressive unit also provides the vast majority of the total proven and probable hydrocarbon reserves of the Austral Basin, both in Argentina and Chile (González et al., 1998; Peroni et al., 2002). Despite the economic significance of the Springhill Formation, a few

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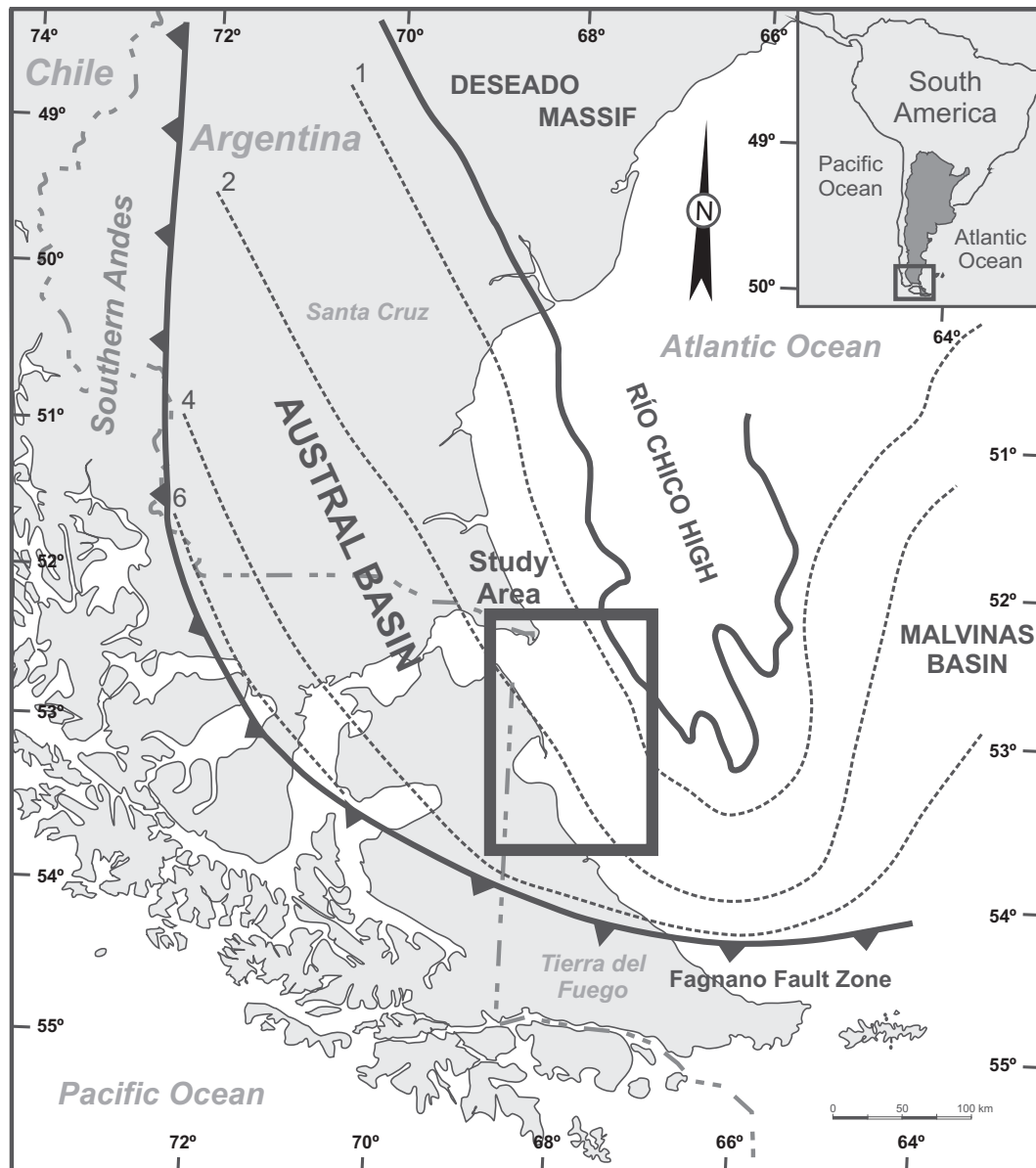


Fig. 1. Location map of the Austral Basin (after Peroni et al., 2002). Isopachs (in km) after Rossello et al. (2008).

studies have thoroughly described sedimentary facies as well as interpreted its depositional systems, and those few studies are focused at the scale of a hydrocarbon field (e.g. Limeres et al., 2000) rather than integrating information across larger areas of the basin in order to reconstruct the large-scale stratigraphic architecture of the unit.

This paper is based on an extensive subsurface database. In order to develop a coherent facies association analysis and to interpret the main depositional systems of the Springhill Formation in the southern area of the Austral Basin (Tierra del Fuego Province, Argentina, Fig. 1), 500 m of cores from 11 wells distributed across the area were analyzed and integrated with supplementary well-log data. The studied cores cover the entire stratigraphic record of the investigated unit, from the basal fluvial deposits to the open-marine strata.

The purpose of this study has been three-folded. First, we describe and interpret facies associations in order to thoroughly identify depositional systems in the Springhill Formation. Subsequently, by integrating the regional distribution and vertical evolution of the

interpreted depositional systems with key identified surfaces, we present a high-resolution sequence stratigraphic framework for the unit. The third goal is to discuss the implications of the resulting stratigraphic architecture in terms of valley-system-fill successions, because the transgressive Springhill Formation, although relatively thick (>100 m thick), might superficially resemble idealized incised-valley-fill sequences. The results of this contribution can, ultimately, provide key insights for hydrocarbon exploration and production in the Austral Basin, but also for other locations where relatively thick transgressive successions are developed.

## 2. Geological and stratigraphic context

The Austral or Magallanes Basin is located in the southernmost region of South America (Fig. 1) and is limited by the Southern Patagonian Andes to the west and by the Deseado Massif to the east (Biddle et al., 1986; Robbiano et al., 1996). The Río Chico High represents its continuation to the south, separating this basin from the Malvinas Basin (Galeazzi, 1998). The Austral basin has an “L”

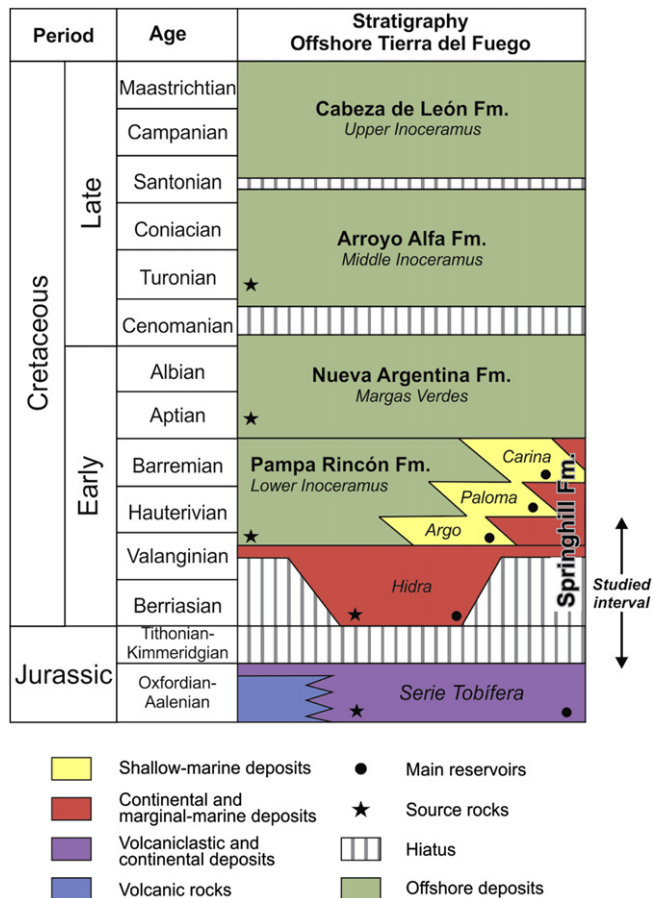


Fig. 2. Chronostratigraphy of the Austral Basin in offshore Tierra del Fuego (after Robbiano et al., 1996; Peroni et al., 2002; Arbe and Fernández Bell Fano, 2002). Informal names in italics.

shape (Fig. 1), and covers about 230,000 km<sup>2</sup>, being ~85% in Argentina territory (Peroni et al., 2002). Its sedimentary record dates from Late Jurassic to Cenozoic and comprises up to 8000 m of stratigraphy (Fig. 1).

The evolution and development of the basin can be considered in three stages (Biddle et al., 1986; Robbiano et al., 1996).

1. *Rift stage*. Middle-Late Jurassic. Marginal Basin o Rocas Verdes Basin, linked to the opening of the Wedell Sea. Extensional tectonics created asymmetric hemigrabens mostly filled with lacustrine, volcaniclastic and alluvial sediments of the “Serie Tobífera”/El Quemado Formation (Fig. 2). Oxfordian–Kimmeridgian marine deposits to the top in the western (chilenian) region on the basin. Coeval sandstone-rich facies are termed Springhill Formation (Salmon Facies) in this western sector, but according to Arbe and Fernández Bell Fano (2002) they are not genetically related with the study unit in the Tierra del Fuego area.

2. *Sag phase*. Lower Cretaceous (?Tithonian, Berriasian–Barremian). The basin lies inboard of a magmatic arc with active subduction and represents a back-arc setting under relatively constant subsidence. The Springhill Formation (Fig. 2) deposited during this sag phase and represents a long-term (>25 m.y.) transgressive cycle likely controlled by low-frequency sea-level fluctuations (Robbiano et al., 1996).

3. *Foreland Phase*. Lower Cretaceous (Aptian) to Cenozoic. Several pulses of deformation. Deformation and depocentre migration to south and east with time. Several transgressive-regressive megasequences during the Cretaceous (Fig. 2) controlled mainly by regional tectonics and/or global eustasy (Arbe and

Fernández Bell Fano, 2002). The Tierra de Fuego region remained an offshore setting for the most part of the Cretaceous (Fig. 2).

The Springhill Formation is the oldest sedimentary fill of the Austral basin, deposited mostly during Berriasian–Barremian times (Fig. 2). The Springhill strata, up to 120 m thick, are composed of fluvial, marginal-marine, coastal and shallow-marine siliciclastics deposits with a general retrogradational stacking pattern (Kielbowicz et al., 1984; Biddle et al., 1986; Arbe and Fernández Bell Fano, 2002).

The fluvial and marginal-marine deposits of the Springhill Formation lie unconformably above the “Serie Tobífera” (Fig. 2). These deposits are informally known as the Hidra member (Robbiano et al., 1996; Pittion and Arbe, 1999; Rodríguez and Miller, 2005). It has been suggested that these oldest Springhill strata mostly filled the remaining accommodation space of Jurassic-created depocentres, once mechanical subsidence and volcanism ceased or was significantly reduced (Robbiano et al., 1996). However, more recently Arbe and Fernández Bell Fano (2002) argued that in fact a regional tectonic uplift and truncation of previous strata occurred prior to Springhill deposition. This tectonic event (dated as Berriasian) was followed by an extensional phase, locally accompanied by reactivation of Jurassic faults, which modeled the depocentres where the Hidra fluvial and estuarine sediments were accumulated (Arbe and Fernández Bell Fano, 2002). In any case, it is clear that these oldest strata were strongly controlled by local irregularities in the basement (“Serie Tobífera”). Its thickness is reduced and almost disappears in areas of local basement highs (Biddle et al., 1986; Rossello et al., 2008, their Fig. 11).

The younger marine strata of the Springhill Formation (Valanginian–Barremian) are more regionally extensive, but clearly diachronic toward the margins of the basin (Fig. 2). In Tierra del Fuego, these deposits are referred to as Argo, Paloma and Carina “members” (Robbiano et al., 1996; Pittion and Arbe, 1999; Rodríguez and Miller, 2005). These sandstone-rich units have an *onlap* relationship over the Dungeness Dorsal or Río Chico high, toward the east–northeast (Fig. 1). Towards the opposite side (south and southwest) these shallow-marine strata of the Springhill Formation are gradually replaced by *offshore* fine-grained deposits (Fig. 2), known as “Favrella Bearing Beds”, “Lower Inoceramus” and the Pampa Rincón Formation strata (Biddle et al., 1986; Robbiano et al., 1996; Rodríguez and Miller, 2005).

From the hydrocarbon perspective, the “Lower Inoceramus”/Springhill is the most important petroleum system and the one that provided almost the total proven and probable reserves of the Austral Basin, both in Argentina and Chile (González et al., 1998; Peroni et al., 2002). Both continental shales of the Springhill Formation (Hidra member) and marine shales of the “Lower Inoceramus” are good source rocks (Pittion and Arbe, 1999). Fluvial and marine reservoirs with up to 15 m of net sandstone, up to 100% of net-to-gross ratio, and good to excellent petrophysical properties (up to 24% of porosity) occur within the Springhill Formation (Arbe and Fernández Bell Fano, 2002).

### 3. Study area and dataset

The study area is located in the southern sector of the Austral Basin, both in continental territory and offshore Tierra del Fuego Province, Argentina (Figs. 1 and 3). This area is 170 km long (from the Magellan Strait to the latitude of Río Grande city) and about 40 km wide (from the Argentina–Chile border in the west to the Argentine continental platform to the east). The total surface adds up to 6800 square kilometers.

In this region several hydrocarbon fields are presently in production. Exploration and discoveries started during the 60s and 70s in the onshore region of Tierra del Fuego (e.g. San Sebastián, Río

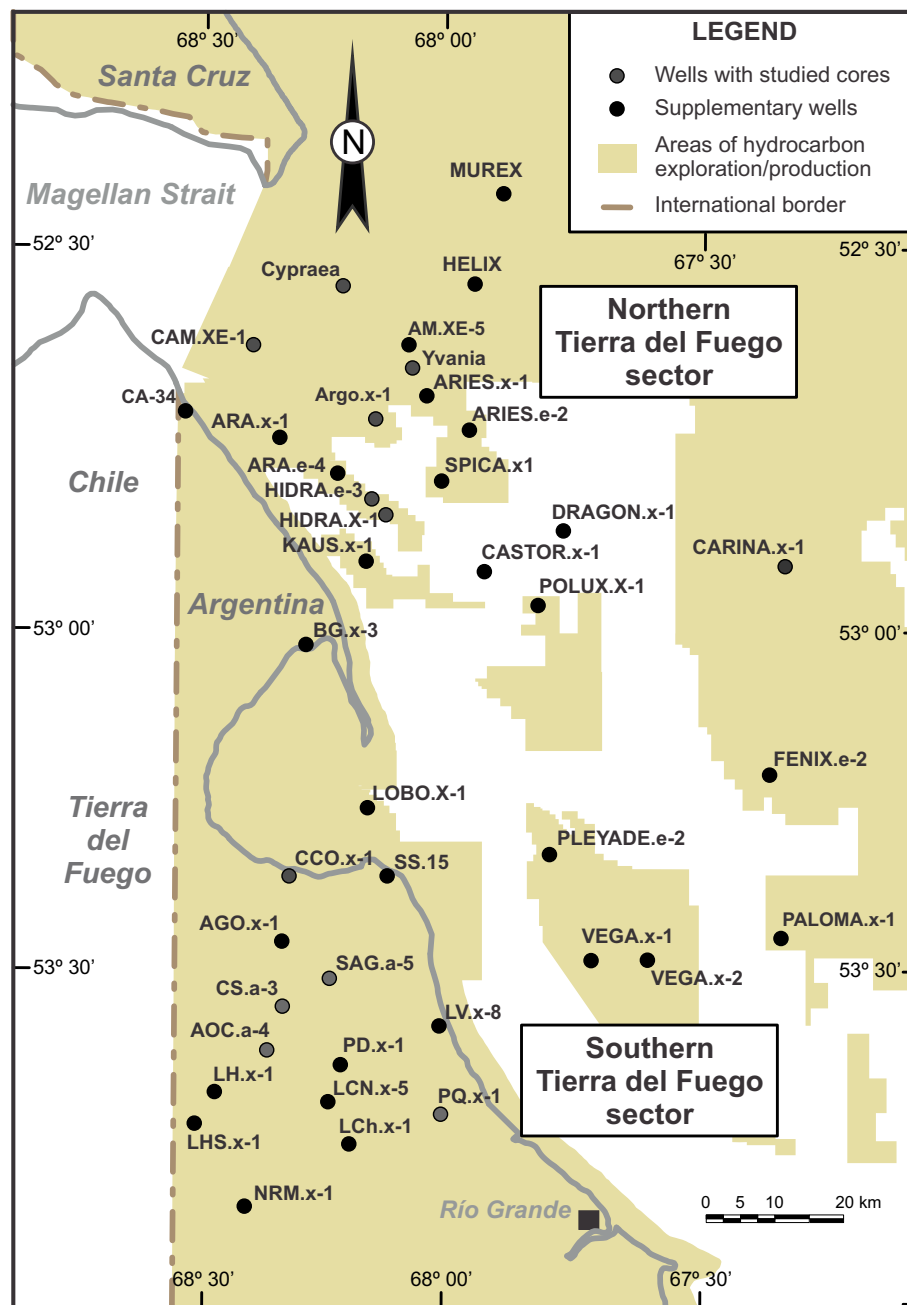


Fig. 3. Study area and distribution of wells included in the present contribution. Areas of hydrocarbon exploration/production located in the Argentinean territory are also shown.

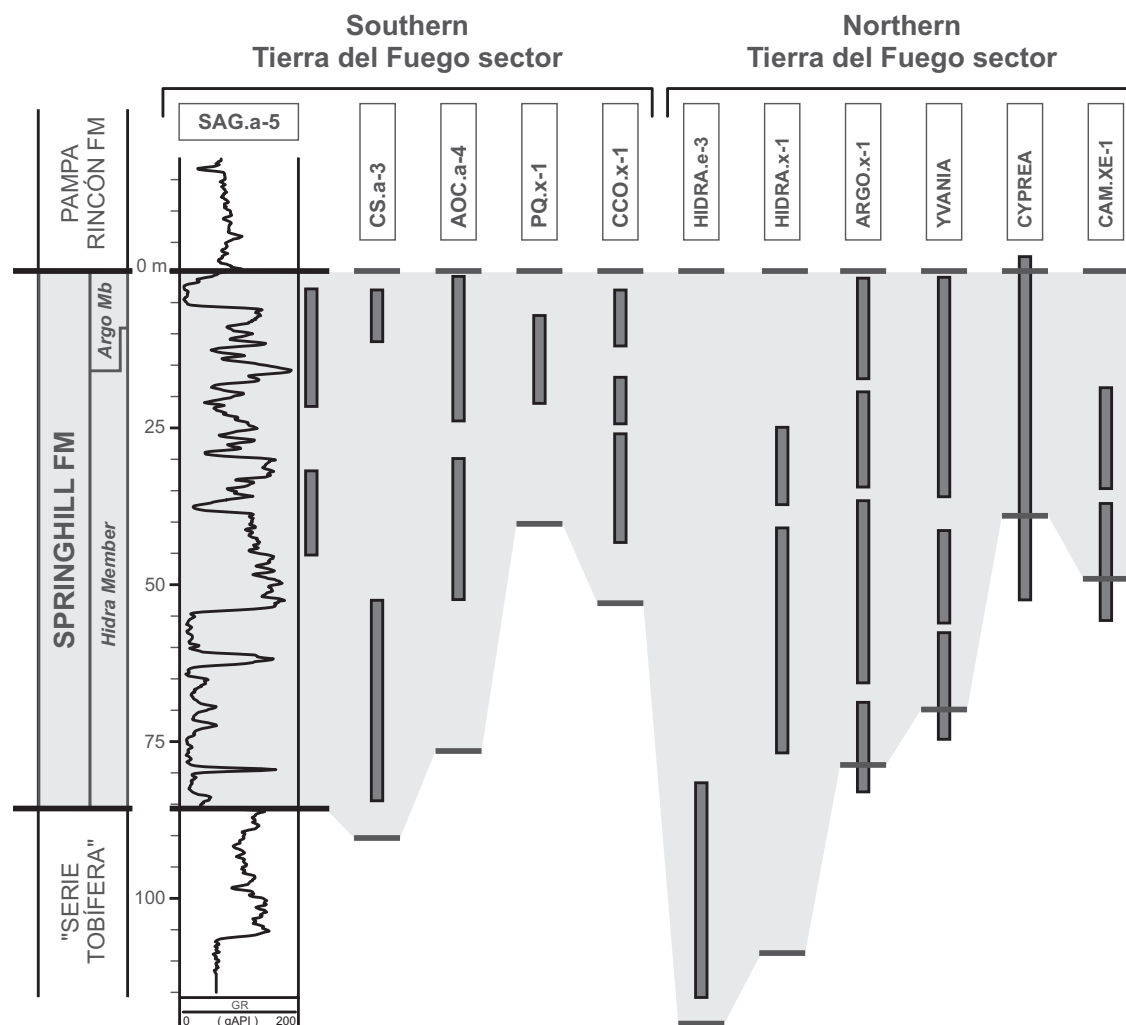
Cullen, Cañadón Alfa fields), but later on the exploration efforts moved into the offshore sector, where significant discoveries were achieved during the early 80s (e.g. Hidra, Argo, and Carina fields, Fig. 3). By 2008, more than 1030 wells had been drilled solely in the onshore territory, and only about 250 were in production (Rossello et al., 2008).

In the study area the Springhill Formation is up to 120 m thick (Fig. 4) and is represented by the Hidra and Argo members (Fig. 2). The unit has been extensively cored during the exploration and production history of the hydrocarbon basin. This study uses 500 m of cored intervals that were provided by formerly Repsol-YPF S.A. (now YPF S.A.). The study cores belong to 11 wells that are distributed across the entire study area. For the purpose of this contribution cored wells have been regrouped in two main areas (Figs. 3 and 4), so-called Northern Tierra del Fuego (mostly offshore) and Southern Tierra del

Fuego (mostly onshore) sectors. In the northern sector, 325 m of the Springhill Formation were described, with almost continuous cored intervals ranging from 30 to 77 m. In the southern sector, total cores were 175 m but maximum continuous thickness was 30 m (Fig. 4). Cored intervals from the Springhill Formation, as well as selected cores from the underlying "Serie Tobífera" and the overlying Pampa Rincón Formation have been studied (Fig. 4).

#### 4. Methodology

Studied cores were logged in detail. Physical sedimentological (texture, composition, mechanical structures, contacts, etc.) and ichnological attributes, as well as vertical trends and stacking patterns, were all integrated to define and interpret facies and facies associations. This information provided a basis for the



**Fig. 4.** Selected gamma-ray log of the studied interval showing the stratigraphic units and the dataset used in this investigation. The Springhill Formation, the studied unit, is very well represented by 325 m of cored intervals in the Northern Tierra del Fuego Sector (6 wells) and satisfactorily documented by 175 m of cores in the Southern Sector (5 wells).

interpretation of sedimentary processes (facies) and depositional systems (facies associations).

Facies associations' main characteristics were compared with geophysical well-log responses of 41 wells (namely Gamma-ray and Spontaneous potential well-log suites). Core and log data were integrated in the construction of several stratigraphic and facies associations cross sections. Where possible, uncored intervals were populated with facies association interpretation derived from this comparison. The datum used as the basis for correlations was a key surface of regional extension present in all the studied wells, which represents the first marine flooding surface in nearly all of the studied area. Additionally, biostratigraphic information from ten wells was used for better constraining marine chronostratigraphic intervals.

## 5. Facies and facies associations analysis

Facies associations of the Springhill Formation were established on the basis of spatial relationships between physically and genetically related deposits, including cyclicity and elemental sequence development (fining-upward and coarsening-upward trends). Fourteen facies associations were identified encompassing three main depositional systems: fluvial to coastal-plain systems (A1–A6), estuarine systems (B1–B5) and open-marine systems (C1–C4). Fluvial facies associations were defined based on unit

dimensions and internal facies trends following the criteria established by Bridge (2003). Estuarine associations were identified and interpreted following conceptual models proposed by Boyd et al. (1992), Dalrymple et al. (1992), Allen and Posamentier (1994), and Dalrymple and Choi (2007). Finally, open-marine associations were mainly defined on the basis of texture, bioturbation and macrofauna content, because mechanical structures are uncommon. Interpretation of marine subenvironments followed general models proposed by Walker and Plint (1992), Reading and Collinson (1996), combined with an ichnological approach (e.g. MacEachern et al., 2007a,b,c).

### 5.1. Fluvial to coastal-plain facies associations (A1–A6)

#### 5.1.1. Large-scale fluvial channels (A1)

**5.1.1.1. Description.** This facies association is mostly composed of granule conglomerates to coarse-grained sandstones, with subordinated pebble conglomerates and medium-grained sandstones. Planar and trough cross-stratification, as well as horizontal to low-angle cross-stratification are frequent sedimentary structures (Fig. 5a,b). Massive beds and soft-sediment deformation structures occur in rare cases. Individual beds are 0.4–0.8 m thick and normally amalgamated in packages 2–4 m thick with a blocky or a fining-upward trend marked at top by finer-grained sandstones



with ripple cross-lamination (Fig. 5a,c). Mudstone rip-up clasts occur both at the base of individual beds and fining-upward packages. This is the more common and widespread sandstone-dominated fluvial association.

**5.1.1.2. Interpretation.** This association represents the accumulation of bedload related to unidirectional currents, probably as composite bars with rapid deposition (Haszeldine, 1983; Røe, 1987; Miall, 1996) that filled relatively large fluvial channels. The proportion of bedload deposits may be related to high supply of coarse-grained sediments and a steep gradient of the fluvial system.

#### 5.1.2. Intermediate-scale fluvial channels (A2)

**5.1.2.1. Description.** This association comprises 1–2-m thick fining-upward units, bounded at their base by intraformational conglomerates. Internally they are mostly composed of coarse- to fine-grained sandstones with trough cross-stratification and ripple cross-lamination (Fig. 5d,e). Planar and low-angle cross-stratification as well as convolute lamination are less frequent structures. Occasionally, large-scale cross-stratification involving the entire unit is observed. This fairly uncommon facies association typically overlies FA A1 and is capped by mudstone facies of FA A5.

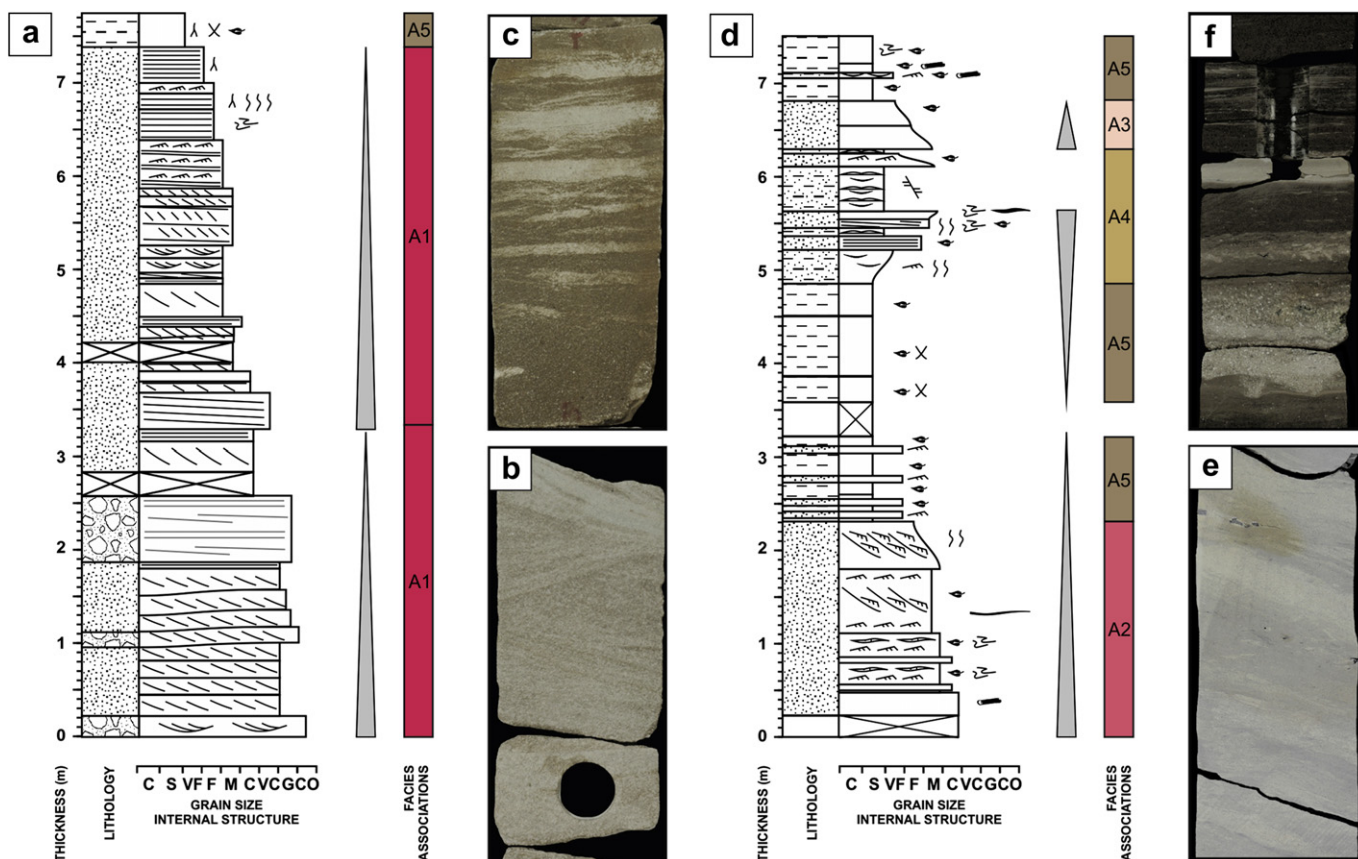
**5.1.2.2. Interpretation.** This facies association is interpreted as an infill of fluvial channels that were smaller than those of association A1. These channels could have been filled with small point bars or diagonal bars, given the marked fining-upward facies trend and the

apparent large-scale low-angle cross-stratification observed in these deposits (Allen, 1964, 1970; Miall, 1985; Galloway and Hobday, 1996). These intermediate-scale channels might be attributed to a mixed-load system, more likely developed as a consequence of a lower gradient relatively to A1 deposits.

#### 5.1.3. Small-scale fluvial channels (A3)

**5.1.3.1. Description.** This association comprises fining-upward packages less than 1.5 m thick, which commonly have an erosional base draped by mudstone or tuff rip-up clasts. Packages consist of 1–4 beds, and individual beds fine rapidly from granule conglomerates at the base to crudely cross-stratified or massive, medium- or fine-grained sandstones to the top (Fig. 7a, b). Carbonised wood fragments and plant detritus are frequent in these sediments, while soft-sediment deformation occurs locally. This association is typically sandwiched between floodplain deposits (facies association A5, Fig. 7a). Although not a common fluvial facies association, is locally abundant in some wells (e.g. Hidra.x-3).

**5.1.3.2. Interpretation.** This association is interpreted as the infill of relatively small-scale fluvial channels dominated by deposition of bedload, but in conditions of less kinetic energy as opposed to facies associations A1/A2. These fining-upward sequences encased in mudstones may be the product of filling of crevasse channels originated in the floodplain as the result of levee breaching or overbanking of main fluvial channels during flood events (cf. Plint and Browne, 1994; Miall, 1996; Spalletti and Barrio, 1998; Bridge, 2003).



**Fig. 5.** Main characteristics of fluvial facies associations. (a) Selected log (Cypraea) showing large-scale fining-upward units that characterize FA A1. (b) Trough cross-bedded very coarse-grained sandstones. (c) Fine-grained sandstone with current ripple lamination. (d) Selected log (Yvania) showing intermediate-scale fining-upward units of FA A2, interbedded with massive mudstones (FA A5) and coarsening-upwards heterolithic sequences (FA A4). (e) Close-up of cross-bedded fine-grained sandstone with superimposed ripples. (f) Intercalation of massive mudstones and thin normally graded sandy layers of FA A4. Cores are 9.5 cm wide in all cases. For log references see Figure 6.

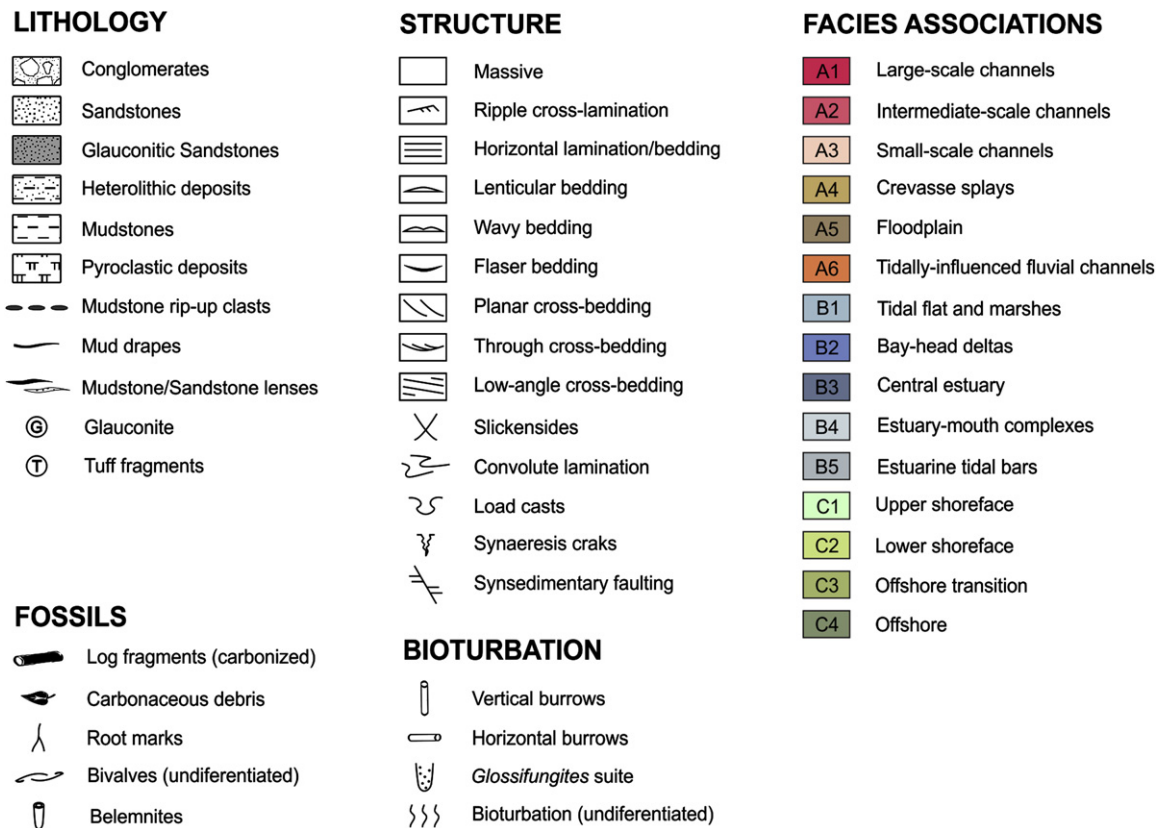


Fig. 6. Legend for Figures 5,7–9.

#### 5.1.4. Crevasse splays (A4)

**5.1.4.1. Description.** This association is characterized by 0.5–1.5-m thick, sandier-upward units composed of heterolithics at the base, coarsening upward to fine-, medium- and eventually coarse-grained sandstone beds (Fig. 5d). Heterolithics are dominated by sandstone layers with or without cross-lamination (Fig. 5f). In turn, thicker sandstone beds (<0.4 m thick) at the top of packages can be normal graded and commonly have horizontal and/or ripple cross-lamination. Alternatively sandstone beds can be massive and with soft-sediment deformation features. This facies association invariably grades vertically from mudstones of association A5.

**5.1.4.2. Interpretation.** Both heterolithics and individual sandstone beds were deposited by unidirectional currents and collectively are considered to reflect overbank accumulation during flood events. Due to their close relationship with fine-grained facies, the coarsening-upward units are attributed to represent the local progradation of lobes (crevasse splays) in a fluvial floodplain (Smith et al., 1989; Bridge, 2003).

#### 5.1.5. Floodplains (A5)

**5.1.5.1. Description.** This association is mostly composed of massive mudstones, with a small proportion of very fine-grained tuffs and thin heterolithic and sandstone intercalations (Figs. 5d and 7a). Carbonaceous material is abundant and, in some cases, layers of coal may be present. Rootlets and slickensides are also abundant (Fig. 7c). This association is 1–9.5 m thick and commonly vertically interbedded with channel-fill facies associations (A1–A3). A vertical transition to tidal-flat deposits (B1) has been recorded in some cores (e.g. Hidra.x-1 and Cypraea wells).

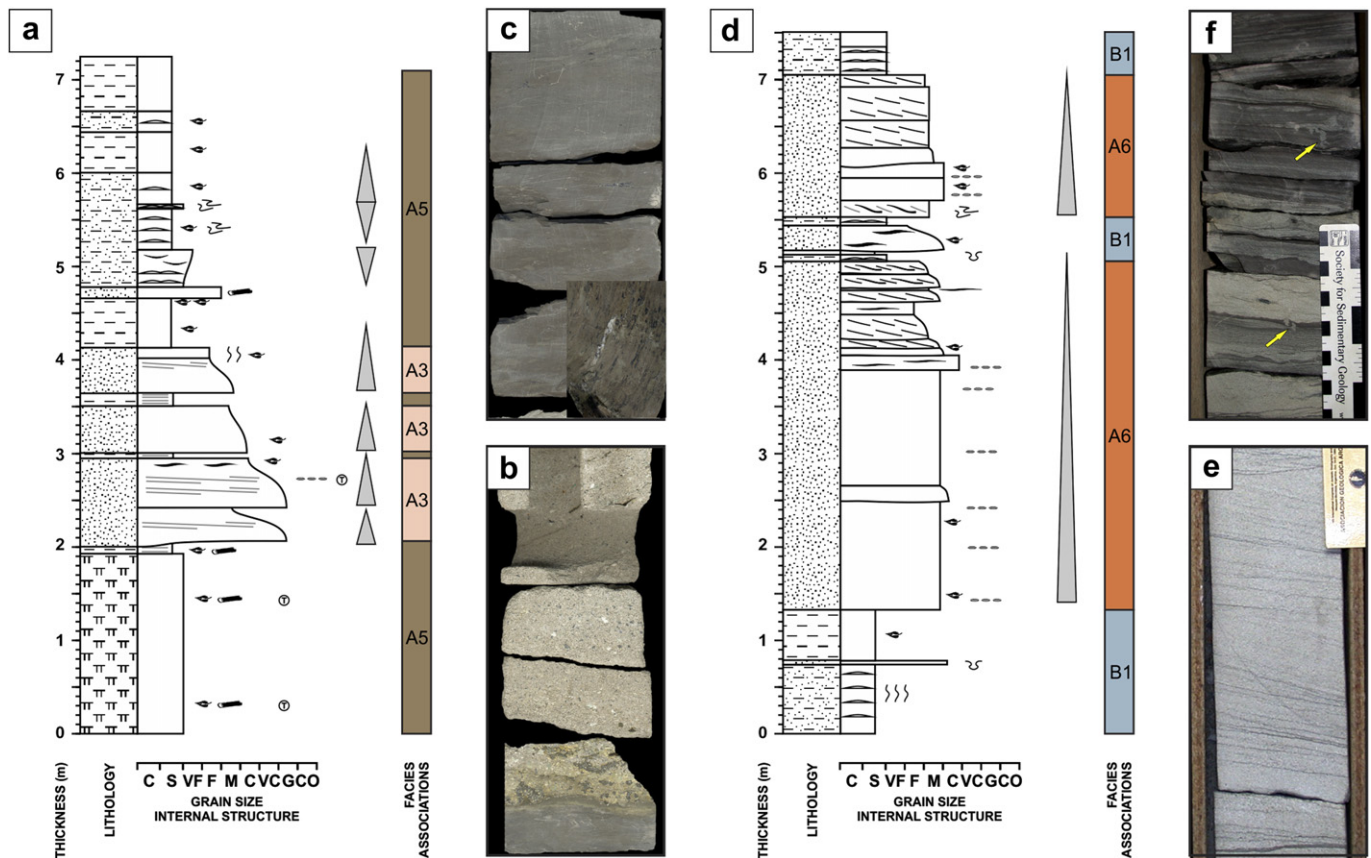
**5.1.5.2. Interpretation.** This association is thought to be the product of settling from suspension in a floodplain environment (Plint and

Browne, 1994). Rootlets and slickensides suggest frequent subaerial exposure and incipient soil development (Dasog et al., 1987), while tuff layers are associated with ash falls related to a relatively distal source. Given the vertical connection of this association with fluvial channels but also with tidal-flat sediments, these mudstone-dominated deposits may represent overbank accumulation in relatively proximal fluvial regions (fully continental) as well as in downdip regions, where tidal activity would start influencing adjacent in-channel sedimentation (coastal-plain setting).

#### 5.1.6. Tidally-influenced fluvial channels (A6)

**5.1.6.1. Description.** This facies association is composed of coarse- to fine-grained sandstones with high- to medium-angle cross strata (Fig. 7d). Significantly, mm-thick layers composed of muddy material or, more frequently, carbonaceous debris are draping the inclined foresets (Fig. 7e). Mudstone rip-up clasts mark the base of cross sets in places, whereas at their tops heterolithic intervals with ripple cross-lamination may occur. Remains of carbonised wood have been observed and, more rarely, soft-sediment deformation due to fluid escape. Bioturbation is null to very rare and represented by sporadic vertical burrows. This association has invariably sharp bases and gradual or sharp tops. Individual sedimentary units range from 3 to 6 m and can have either no vertical trend or they can fine weakly upward (Fig. 7d). These units are capped by massive mudstones of fluvial floodplains (A5), but also by mudstone-dominated heterolithics of facies association B1 (marginal estuarine setting).

**5.1.6.2. Interpretation.** Coarse-grained sediments, cross-stratified layers with carbonaceous and mudstone drapes are attributed to bedforms that developed mainly due to unidirectional currents but with recurring energy variations that allow suspension settling of fine-grained material (Shanley et al., 1992; Spalletti, 1996). These



**Fig. 7.** Main characteristics of fluvial and coastal-plain facies associations. (a) Selected log (Hidra.x-3) showing small-scale fining-upward units of FA A3, interbedded with massive mudstones of FA A5. (b) Close-up of massive to crudely stratified sandstone with abundant carbonised material. (c) Massive mudstone with abundant carbonaceous debris and slickensides (inset). (d) Selected log (CSa.a-3) showing tidally-influenced fluvial channel deposits (FA A6) interbedded with heterolithic deposits of tidal flats and marshes (FA B1). (e) Close-up view of cross-stratified medium-grained sandstone with carbonaceous drapes. (f) Unburrowed sand-dominated and mudstone-dominated heterolithic deposits commonly showing synaeresis cracks (arrows), which are interpreted to represent tidal-flat deposits (FA B1). Cores are 9.5 cm wide in all cases.

attributes are related to tidal impact on fluvial discharge (Allen and Posamentier, 1994), and therefore facies association A6 is considered as the filling of tidally-influenced fluvial channels seaward of the limit of tidal action (Dalrymple et al., 1992; Ichaso and Dalrymple, 2006).

## 5.2. Estuarine facies associations (B1–B5)

### 5.2.1. Tidal flats and marshes (B1)

**5.2.1.1. Description.** This association mostly comprises heterolithic successions with lenticular, wavy and flaser structures (Fig. 7d). Sandstone beds, typically <5 cm thick, are composed of very fine- and fine-grained sandstones with current ripple cross-lamination, associated with common synaeresis cracks and soft-sediment deformation structures due to loading (Fig. 7f). Mudstones are massive or finely laminated, ranging in thickness from several centimetres to a few millimeters. Plant remains are common in places. The intensity of bioturbation in these heterolithic packages varies from very low to moderate, and the diversity by layer is low to moderate. The burrows are mainly horizontal (*Planolites*, *Palaeophycus* and *Teichichnus*). Occasionally, sandstone beds (<0.5 m thick) with planar lamination or cross-stratification intercalate within the heterolithics. Facies association B1 ranges from 0.5 to 9.5 m thick and shows no vertical trends in bed thickness or in grain size. This association is more abundant in the southern sector of the study area, where it commonly alternates with channel-fill deposits

of tidally-influenced channels (association A6). However, B1 can also vertically grade into associations A5 or B2.

**5.2.1.2. Interpretation.** Facies association B1 is interpreted to reflect alternate processes of traction and fall-out in a low-energy environment (Visser and Howard, 1974). The low ichnofacies diversity is interpreted to represent an impoverished *Cruziana* ichnofacies (MacEachern et al., 2007c), probably developed in brackish waters. In this sense, changes in the salinity conditions may also be responsible for the development of synaeresis cracks. This association is interpreted as the product of deposition in tidal flats and marshes located in marginal zones of estuarine environments (cf. Shanmugam et al., 2000). Relatively thicker sandstone beds may represent higher-energy conditions in the transition from tidal flats to inner parts of the estuary (e.g. upper-flow regime sand flats of Dalrymple et al., 1992).

### 5.2.2. Bay-head deltas (B2)

**5.2.2.1. Description.** This association is characterized by coarsening-upward successions (0.70–3.2 m thick), which commonly start with wavy and/or flaser heterolithic intervals that grade upwards into fine- to coarse-grained sandstones (Fig. 8a). Heterolithics are composed of massive to ripple cross-laminated sandstones interbedded with laminated or massive mudstones (Fig. 8b). Bioturbation diversity in the heterolithics varies from very low (an ichnogenere per level, e.g. *Planolites*) to moderate (3–4 ichnogenere per level). Bioturbation intensity is low to very low but can be



locally higher at the top of the coarsening-upward packages. Synaeresis cracks and plant remains can be common in mudstone layers. Sandstone beds typically form more than one half of coarsening-upward packages and individual beds range between 0.30 and 1.0 m thick. Cross-lamination and trough or planar cross-stratification are dominant structures, but horizontal or crude stratification are also frequent. Both normal and inverse grading can be recorded in individual sandstone beds and bioturbation is typically low. Facies association B2 is closely related to mudstone-dominated deposits of facies association B3 (Fig. 8a). Less frequently, B2 association overlies tidal-flat deposits of B1 association, and it can also be sharply overlain by other estuarine facies associations representing more marine-influenced settings (outer-estuary facies associations).

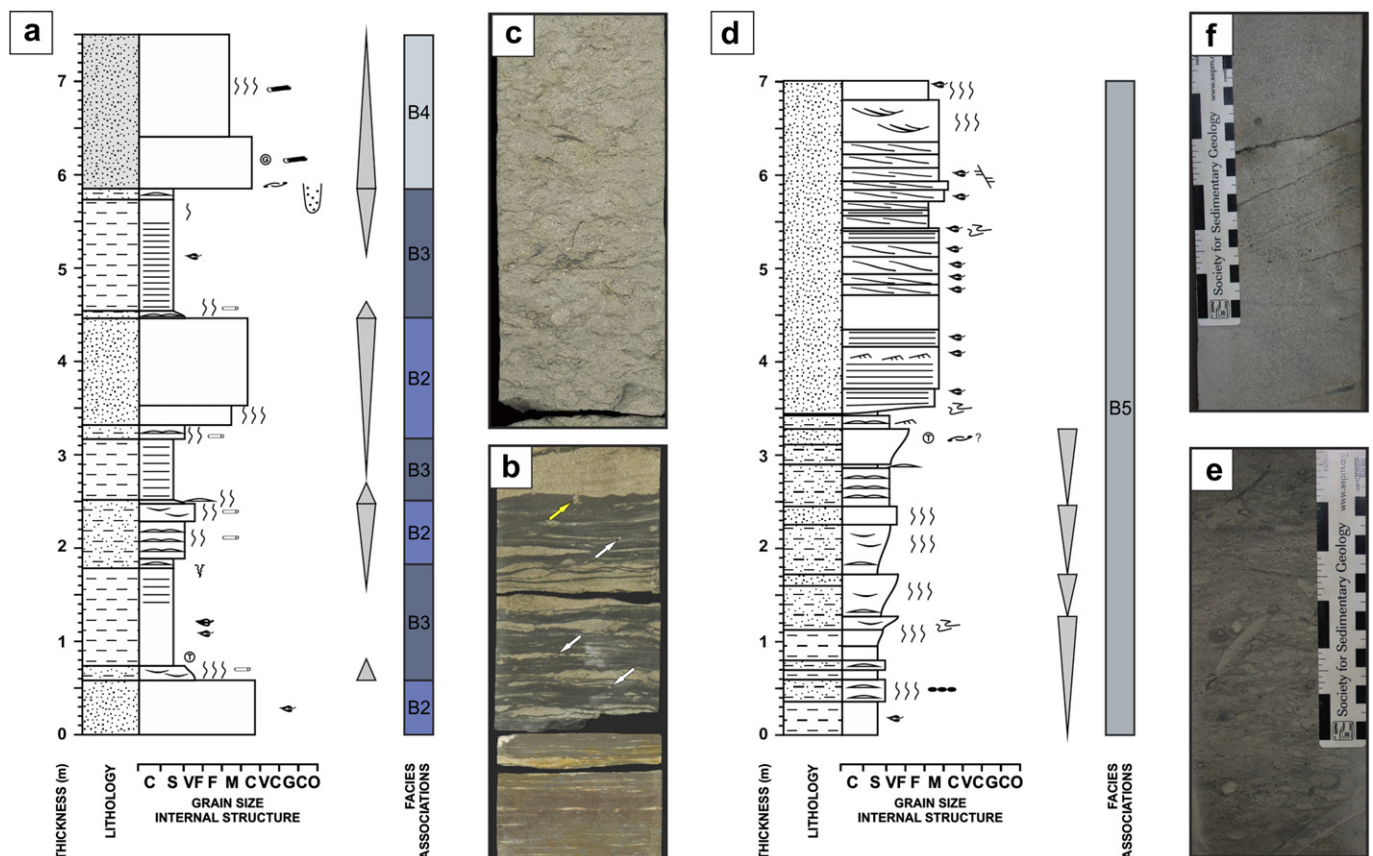
**5.2.2.2. Interpretation.** This facies association represents the progradation and/or aggradation of sand lobes within a restricted, marginal-marine environment. These bars evolve from subtidal conditions of moderate energy and recurrent traction-suspension processes (heterolithics), to areas with greater kinetic energy and migration of bi and tridimensional sandwaves with low preservation of fine-grained material (Dalrymple and Rhodes, 1995; Fenies and Tastet, 1998; Pontén and Plink-Björklund, 2009). These sand bars, with well-preserved primary structures, abundant plant remains and low bioturbation might have been developed at the

mouth of fluvial channels (bay-head bars, [Fenies and Tastet, 1998](#)), more likely in the inner regions of estuaries (e.g. [Dalrymple et al., 1992](#); [Anthony et al., 2002](#)).

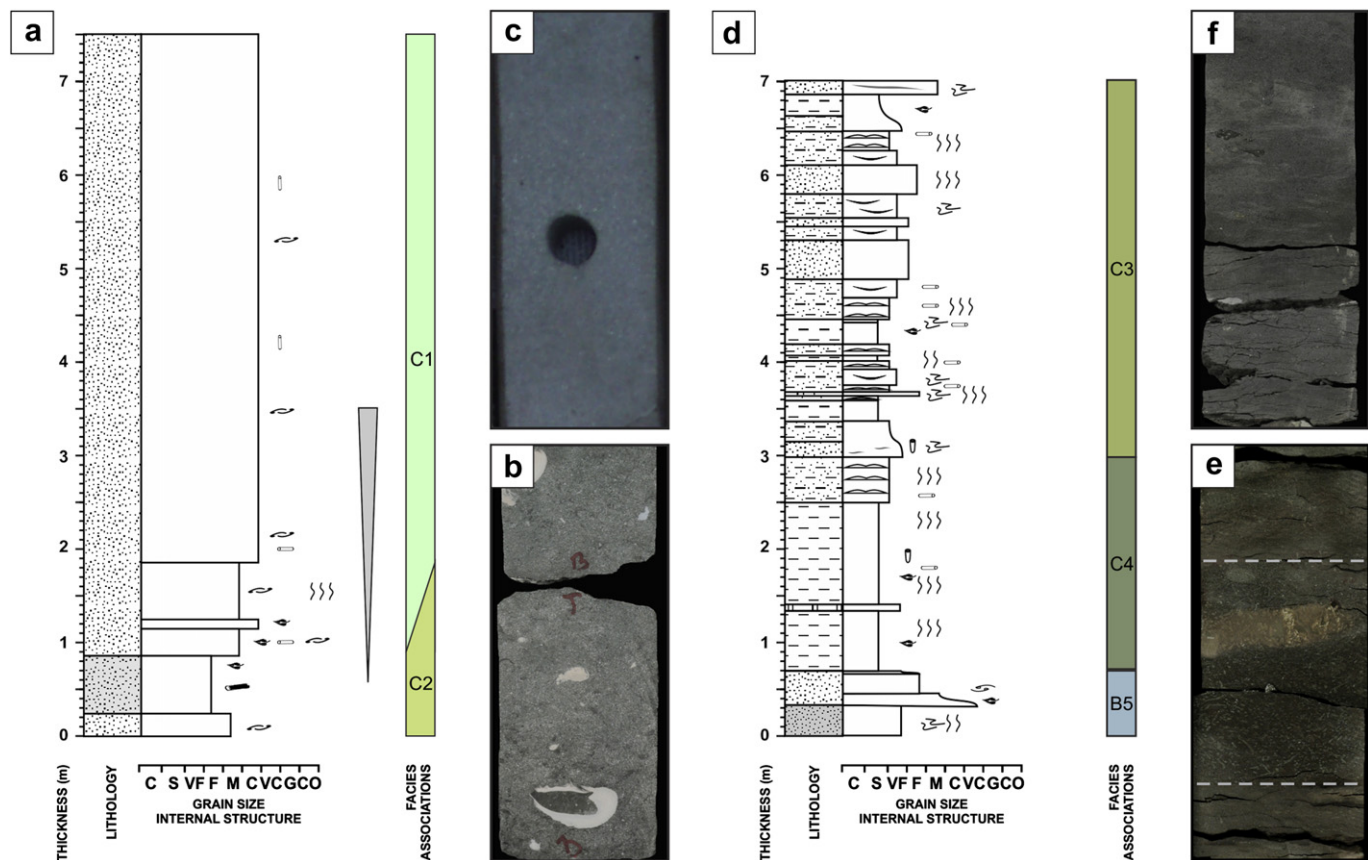
### 5.2.3. Central estuary (B3)

5.2.3.1. *Description.* This association is composed of fine-grained deposits, mainly mudstones and subordinate mixed sand and mud lenticular beds (Reineck and Singh, 1980) (Fig. 8a). Mudstones are finely laminated, and sometimes include scattered coarser-grained pyroclastic material. In mixed lenticular intervals, very fine-grained sandstone layers are less than 1 cm thick (Fig. 8b). Bioturbation is absent or very low and is mainly composed of *Planolites* and *Teichichnus* burrows. Carbonaceous remains are uncommon, although their abundance increases locally, and in those cases well-preserved plant remains are recorded. Association B3 varies from 0.30 to 2.5 m thick and is more common in the northern studied region, where it typically grades to coarser-grained sediments of association B2 (Fig. 8a). Combined, these two associations form coarsening- and thickening- upward sequences up to 6 m thick. B3 deposits can be also erosionaly overlain by facies association B4.

**5.2.3.2. Interpretation.** Facies association B3 represents low-energy conditions with only occasional incursions of low-regime tractional currents. The low bioturbation degree, attributable to an impoverished *Cruziana* ichnofacies, suggests extreme stress conditions in



**Fig. 8.** Main characteristics of estuarine facies associations. (a) Selected log (CAM.XE-1) showing the intercalation of central-estuary (FA B3) and bay-head delta deposits (FA B2). Note the development of coarsening-upward sequences. The log also shows sharply-based muddy sandstones reflecting an outer-estuary setting (FA B4) developed on top of a surface with a *Glossifungites* suite. (b) Detail of the vertical transition from mudstone-dominated deposits of FA B3, to sandstone-dominated heterolithic deposits of lower FA B2. White arrows point to minute *Planolites*; yellow arrow show synaeresis cracks. (c) Massive, glauconitic, coarse-grained muddy sandstones showing intense bioturbation typical of barriers FA B4. (d) Selected log (AOC.a-4) showing heavily bioturbated sandy mudstones and muddy sandstones at the base, passing upward into cross-stratified sandstones having sporadic mud drapes and abundant plant debris (association B5). This succession is interpreted to represent distal and proximal tidal estuarine bars. (e) Close-up of intensely bioturbated muddy sandstone (f) Medium-grained sandstone with mud drapes. Cores are 9.5 cm thick in all cases. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).



**Fig. 9.** Main characteristics of open-marine facies associations. (a) Selected log (Argo.x-1) showing glauconitic fine-grained sandstones and muddy sandstones of FA C2 grading upward into coarser sandstones with diffuse bedding planes (FA C1). (b) Close-up view of glauconitic, bioturbated sandstone with abundant skeletal fragments (oyster and other undifferentiated bivalves) typical of lower shoreface. (c) Detail of medium- and coarse-grained sandstone interpreted to represent upper-shoreface conditions. (d) Selected log (CCo.x-1) showing massive mudstones grading into thinly bedded mudstones and sandstones, representing offshore (FA C4) and offshore-transition (FA C3) settings. (e) Offshore mudstones showing a thin layer with abundant *Chondrites*. (f) Close-up view of sandy mudstone that likely resulted from bioturbation of thinly bedded heterolithic deposits in the offshore-transition environment.

low-energy environments, with periodic and/or significant salinity fluctuations (Savrdá and Nanson, 2003; Mángano and Buatois, 2004). These features point to an estuarine central basin environment, in the distal end of bay-head deltas (cf. Mack et al., 2003).

#### 5.2.4. Estuary-mouth complexes (B4)

**5.2.4.1. Description.** This association principally consists of amalgamated sandstone beds with abundant gravel-size skeletal fragments (Fig. 8a). Beds mostly comprise medium- and coarse-grained glauconitic sandstones, with less common muddy sandstones and granule conglomerates. Most sandstone beds are massive with diffuse vertical and horizontal burrows (?*Diplocraterion*, ?*Palaeophycus*). The skeletal remains, derived mainly from bivalves, either concentrate at the base of beds or occur throughout of them. Units of association B4 have sharp, sometimes erosive bases and tops, they vary from 1.5 to 5 m in thickness, and they coarse slightly upwards of have no vertical trends. The lower boundary of this facies association is usually demarcated by *Thalassinoides* burrows, which are penetrating the fine-grained underlying (host) sediments and are filled with coarse sand and skeletal fragments. These passively-filled burrows, typically presented as subspherical sections of horizontal and inclined tubes, are attributed to a *Glossifungites* ichnofacies (Gingras et al., 2000). This facies association is solely present in the northern region where it lies above central-estuary deposits (association B3) and it is invariably overlain by open-marine deposits (facies associations C2 and C3).

**5.2.4.2. Interpretation.** The relatively thick sandstone-dominated packages of facies association B4 were deposited in moderate- to high-energy conditions. Additionally, the internal facies trend, glauconite participation and fossil content suggest environments related to a shallow open-marine setting (Pattison, 1995). These deposits are thus interpreted as sandy barrier beaches, flood-tidal deltas and tidal inlets, developed in the outer, marine-dominated segments of estuarine systems (Zaitlin et al., 1994; Buynevich and FitzGerald, 2005). These outer-estuary complexes could have partially enclosed the estuary mouth, favouring the development of low-energy conditions in the central portion of some estuarine systems (facies association B3). The lower boundary of these deposits, commonly demarcated by a *Glossifungites* ichnofacies in several wells across the study area, suggests the development of a regional erosional event (Gingras et al., 2000).

#### 5.2.5. Estuarine tidal bars (B5)

**5.2.5.1. Description.** This facies association mainly comprises thick successions (4–15 m) of heterolithics to medium-grained sandstones and occurs only in the Tierra del Fuego southern sector. The association includes sandstone-dominated packages without a vertical trend and finer-grained, coarsening-upward succession (Fig. 8d). Sandstone packages (2–4 m thick) are typically composed of medium-grained, cross-stratified sandstones with subordinated thin ripple cross-laminated beds (Fig. 8f). Mudstone drapes are locally present. Plant remains are common and bioturbation is very

rare (scarce horizontal burrows). Finer-grained successions (<3 m thick) start with mudstone-dominated heterolithics and become sandier upwards, eventually ending in muddy sandstones and fine-grained massive sandstones (Fig. 8d). Sandstone-rich heterolithics and sandstone beds may, in some cases, be glauconitic, and show a mottled structure. Bioturbation degree is variable ranging from low to high (Fig. 8e) and the ichnofauna is composed of *Diplocraterion*, *Ophiomorpha*, *Planolites*, *Palaeophycus*, *Teichichnus* and *Thalassinoides*. This association is interpreted to represent an impoverished *Cruziana* ichnofacies (MacEachern et al., 2007c). Association B5 is vertically related to tidal-flat and marsh deposits (association B1) and is sharply overlain by open-marine deposits (associations C2–C4).

**5.2.5.2. Interpretation.** The sedimentary structures and low bioturbation of sandstone packages suggests cyclic energy fluctuations from dune to ripple migration in a stressed subaqueous setting. Less frequent mudstone drapes suggest that slack-water periods were not very significant. These deposits are thus interpreted to represent tidal sand bars within an estuarine environment (Dalrymple et al., 1992; Allen and Posamentier, 1994). Relatively finer-grained successions also show regular alternation of suspension fall-out and traction processes, but texture, increasing bioturbation and abundant glauconite suggest that these deposits may have been deposited in the most external part of tidally-dominated estuaries in the transition to the open-marine environment, where sedimentation is equally influenced by wave and tidal processes (Plink-Björklund and Steel, 2006; Dalrymple and Choi, 2007; Such et al., 2007).

### 5.3. Open marine facies associations (C1–C4)

#### 5.3.1. Upper shoreface (C1)

**5.3.1.1. Description.** This association comprises sandstone bodies up to 14 m thick, which are composed of medium- to coarse-grained bioclastic sandstones that coarsen slightly upward or have no well-defined vertical trends (Fig. 9a). Gravel-size skeletal remains (derived mainly from bivalves) are abundant, randomly distributed or concentrated in patches. Large *Ophiomorpha* (up to 2 cm wide) burrows are also common and plant remains are rare. Individual beds have diffuse boundaries and are mostly massive, but some beds also fine weakly upward. The base of these units is transitional from facies association C2 in the study area (Fig. 9a). The upper boundary of this association has not been cored in any of the studied wells but, according to well-log responses, it is likely to be sharp and overlain by fine-grained offshore deposits (C4).

**5.3.1.2. Interpretation.** The mixed nature of these deposits (intra and extrabasinal components present), the relatively coarse grain size and the presence of *Ophiomorpha* related to the *Skolithos* ichnofacies suggest an open marine upper-shoreface depositional environment (cf. Pattison, 1995; Hamberg and Nielsen, 2000; Such et al., 2007), well above fair-weather wave base. The size and lining in the *Ophiomorpha* (pellets) also point to unstable, high-energy conditions, common in shallow coastal environment (Woods and Hansen, 1985; Daly, 1997).

#### 5.3.2. Lower shoreface (C2)

**5.3.2.1. Description.** This association is composed of muddy sandstones and fine- to medium-grained, predominantly massive, glauconitic sandstones (Fig. 9a, b), typically comprising small-scale coarsening-upward successions (0.30–1.80 m thick). Gravel- and sand-size skeletal remains of bivalves, belemnites, foraminiferous and gastropods are frequent (Fig. 9b). Bioturbation in each bed varies from high to low, and the ichnofauna includes vertical and horizontal burrows of a mixed of *Skolithos* and *Cruziana* ichnofacies.

This facies association is 1.5–4.5 m thick, and either grades vertically from finer-grained deposits of facies association C3 or rests abruptly on top of the estuarine deposits. Coarser or finer open-marine deposits (C1, C3 or C4) always overly association C2.

**5.3.2.2. Interpretation.** The relatively finer grain size, ichnological content (*Skolithos* and *Cruziana* ichnofacies) and open-marine invertebrate fauna suggests that this association was deposited in a lower-shoreface environment (cf. MacEachern et al., 2007a), near and slightly above fair-weather wave base (cf. Walker and Plint, 1992).

#### 5.3.3. Offshore transition (C3)

**5.3.3.1. Description.** This association is dominated by thinly bedded mudstones and sandstones, with subordinated dark mudstones and sandy mudstones (Fig. 9d). Mudstones are mostly massive, showing variable degree of bioturbation dominated by *Chondrites* burrows (up to 2 mm wide). Well-preserved belemnite and ammonite remains are also common. Diffuse cross-lamination occurs in thinly bedded sandstone layers (<3 cm thick). Thicker sandstones typically show very intense bioturbation (mottled structure) dominated by horizontal burrows such as *Teichichnus*, *Planolites* and *Palaeophycus* (*Cruziana* ichnofacies), and plant remains can be common locally. Cored intervals of association C3 may show no clear vertical trends but, more commonly, coarsening-upward successions (0.40–3 m thick) from dark mudstones to heterolithics or from heterolithics to muddy sandstones occur (Fig. 9d). This facies association (2–10 m thick) overlies both open-marine and estuarine deposits but it is always capped by marine deposits.

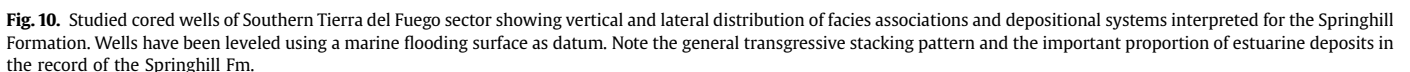
**5.3.3.2. Interpretation.** Thinly bedded mudstones and sandstones are thought to reflect alternating fall-out and traction (ripple migration) processes in an open-marine environment. Significant preservation of mud within the sediments and trace fossils (*Cruziana* ichnofacies) suggest that this association likely deposited in areas below fair-weather wave base, in the transition between the shoreface and offshore environments (Reading and Collinson, 1996; Evoy, 1997; Doyle et al., 2005). Sandy mudstones common in some intervals are likely the product of intense bioturbation of thinly bedded heterolithics by deposit-feeder organisms.

#### 5.3.4. Offshore (C4)

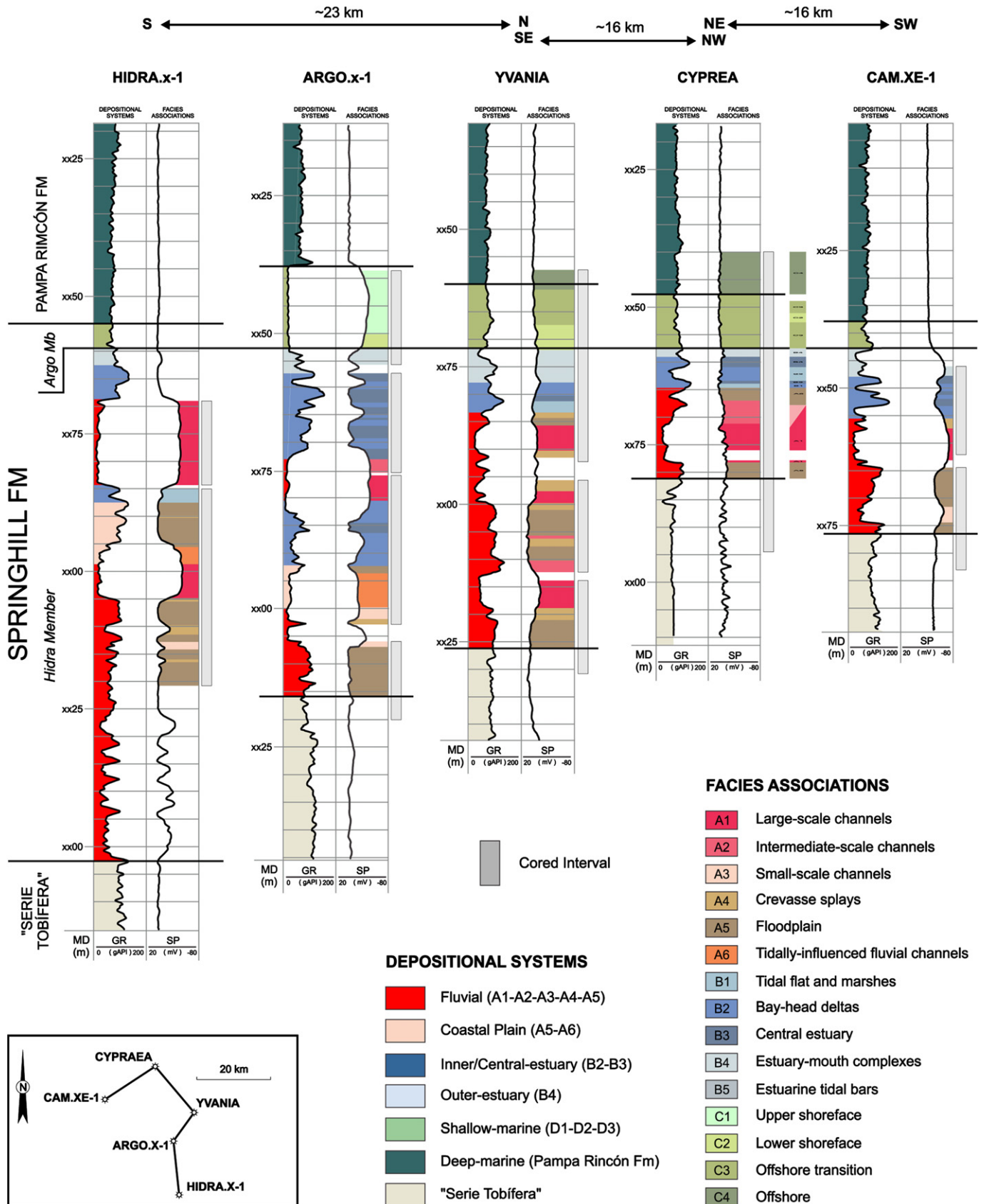
**5.3.4.1. Description.** This association consists of dark grey mudstones and minor siltstones (Fig. 9d), with sporadic fine-grained pyroclastic layers. Mudstones are typically massive, with mottled structure evidencing intense bioturbation (Fig. 9d), but there are also mudstones with well-developed horizontal lamination (black shales). Thin beds (<0.3 m thick) with high abundance of *Chondrites* are common within the laminated intervals (Fig. 9e). This facies association occurs near the top of the Springhill Formation in the southern studied sector, where it sharply overlies estuarine deposits (Fig. 9d). On the contrary, the C4 deposits at the top of northern cored wells are already the basal section of the overlying Pampa Rincón Formation (Cypraea and Yvania wells in Fig. 4).

**5.3.4.2. Interpretation.** This association accumulated from suspension below storm wave base (Reading and Collinson, 1996), in marine substrates with fluctuating conditions in terms of oxygen levels. Dark laminated mudstones suggest periods when anoxic conditions predominated in the substrate. This oxygen-deficient substrate was sporadically colonized by *Chondrites*, probably indicating short periods of increasing oxygen concentration (Bromley and Ekdale, 1984; Savrda and Bottjer, 1986; Ekdale and Mason, 1988). On the other hand, mudstone intervals with high bioturbation likely reflect long-term periods with higher oxygenation and water circulation in the bottom (Doyle et al., 2005).

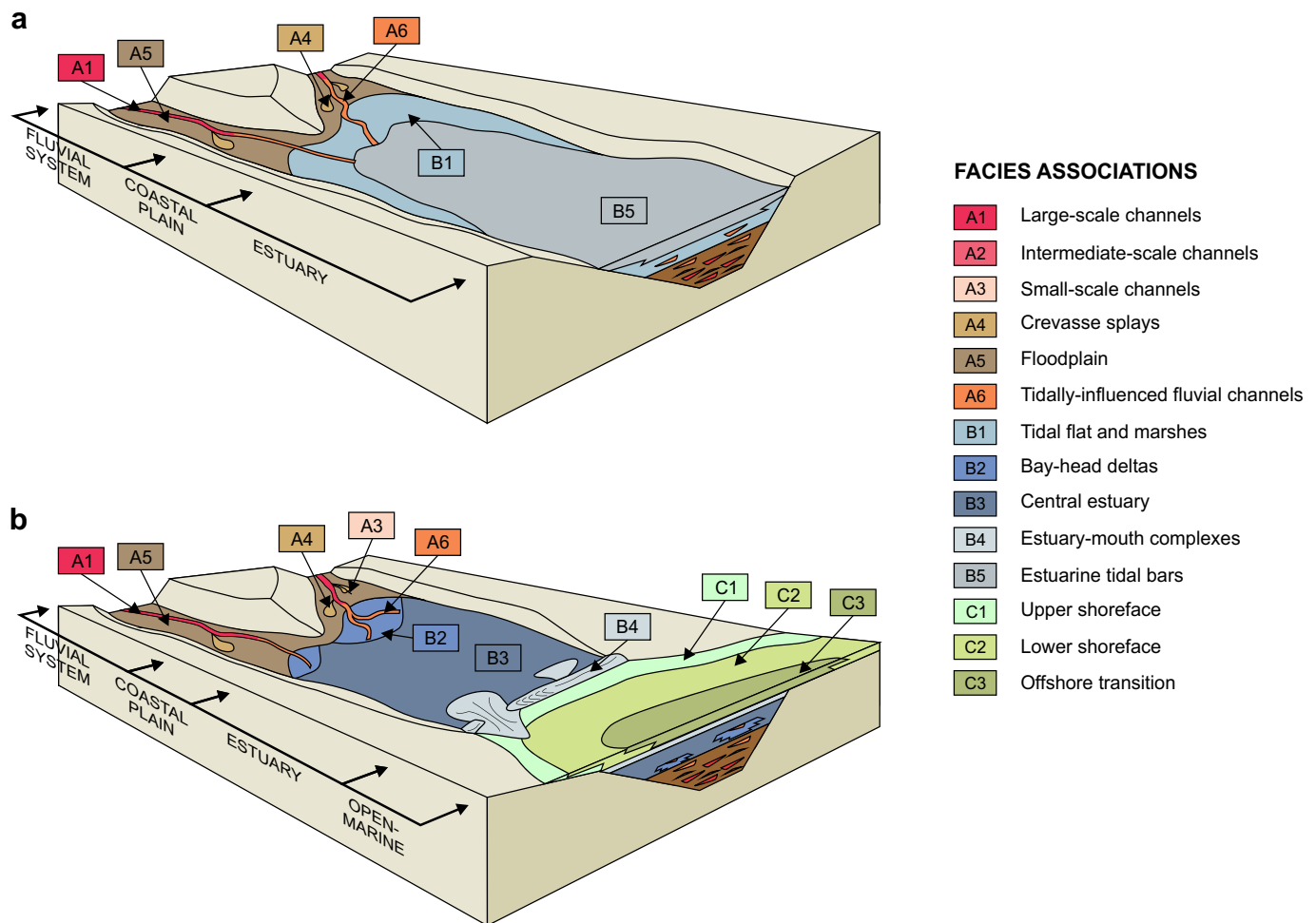








**Fig. 11.** Studied cored wells of Northern Tierra del Fuego sector showing vertical and lateral distribution of facies associations and depositional systems interpreted for the Springhill Formation. Wells have been leveled using a marine flooding surface as datum. As in the Southern Sector, a general transgressive stacking pattern is recorded. However, in this area the unit is mostly composed of fluvial deposits (with high proportion fine-grained floodplain facies), and estuarine deposits are thinner (<15 m).



**Fig. 12.** Conceptual representation of depositional systems recognized in the Springhill Formation based on facies association analysis. (a) Fluvial to tide-dominated estuarine systems inferred for the Southern Tierra del Fuego sector. (b) Fluvial, wave-dominated estuary and open-marine systems inferred for Northern Tierra del Fuego sector.

## 6. Depositional systems: vertical and regional distribution

The studied succession of the Springhill Formation records non marine to open-marine depositional systems which replaced each other vertically (Figs. 10 and 11). Firstly, a well-developed fluvial system is established, interacting downward and vertically with a coastal-plain system. Subsequently, the unit records the instauration of an estuarine system that grades into an open-marine depositional system (Figs. 10 and 11). This broad vertical trend is recorded both in the Northern and Southern Tierra del Fuego sectors, across at least an area of 6,800 square kilometers (Fig. 3). Therefore it is reasonable to assume that this regionally homogeneous vertical evolution responds to large-scale basinal factors rather than to local controls.

### 6.1. The fluvial system

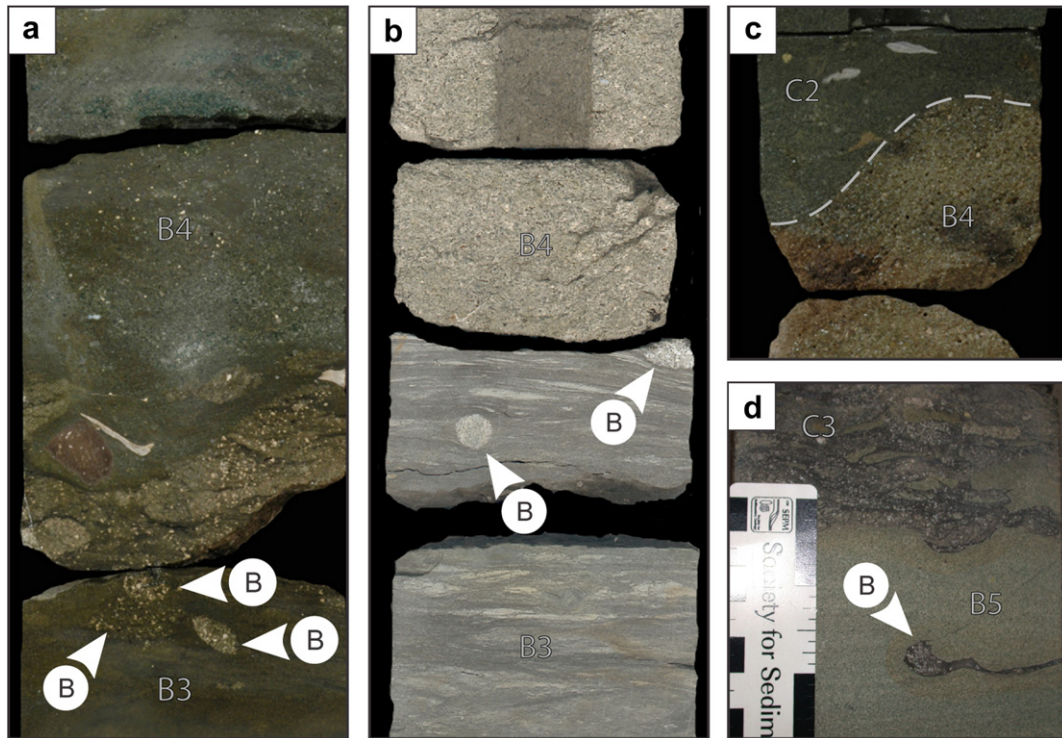
Facies Associations A1–A5 are different elements of a fluvial environment. A1 channel-fills, dominated by coarse sediments (conglomerates and coarse-grained sandstones) and thick fining-upward successions, are the main channels and channel belts within the fluvial system. These channels were probably filled with composite bar deposits in areas with relatively high gradients. Channel-fills of A2 are finer and smaller and their attributes suggest that they could have been filled with small point bar or diagonal bar deposits. Mixed-load systems like A2 occur on gentler gradients

and could have been common in downdip areas. In the cored wells, however, A2 typically overlies A1, and thus suggests that main channels within a single channel belt could have evolved to relatively more sinuous and less energetic channels during pre-avulsion conditions, just prior to final abandonment (cf. Bristow, 1999).

Fluvial floodplains are widely represented within the lower section of the Springhill Formation and are characterized by massive, greyish mudstones with incipient pedogenetic features, abundant plant remains, and rare thin layers of coal (association A5). This suggests that the unit most likely developed in humid climate conditions. Flooding events were common on the fluvial plains leading to the formation of crevasse splays (A4) and small-scale channels (A3) (Fig. 12).

Channel-fill and floodplain facies associations are rather similar both in the Southern and Northern Tierra del Fuego sectors, thus, indicating comparable fluvial systems. However, contrasting patterns of alluvial plain aggradation and resulting preservation of fine-grained deposits are observed. In the southern sector there is a very low proportion of fine-grained deposits and channel-fill facies are highly amalgamated (Fig. 10), whereas in the northern sector floodplain deposits are equal or exceed channel-fill facies in any single well (Fig. 11). This difference is interpreted to be a result of a marked change in the relationship between accommodation creation and sediment supply.

Floodplain deposits of associations A5 are also vertically associated with sandstone-rich, channel-fill deposits which record



**Fig. 13.** (a) and (b) Attributes of the erosional surface recognized in the northern sector at the base of outer-estuary deposits. The surface is demarcated by horizontal burrows (*Thalassinoides*?) entering a few centimetres below the stratigraphic contact, which are passively filled with coarse-grained sand and skeletal fragments not present in underlying central-estuary mudstones. These burrows are interpreted to represent a substrate-controlled *Glossifungites* trace fossil suite. (c) and (d) Attributes of the contact between open-marine deposits and underlying outer-estuary deposits showing (c) truncation and (d) a *Glossifungites* trace fossil suite. Cores are 9.5 cm wide and scale in (d) is in cm and inches.

evidence of tidal action, such as recurring energy variations and draping of avalanche surfaces with carbonaceous material (association A6). These tidally-influenced channel-fills can be capped by A5, but also they can grade to mudstone-dominated heterolithics representing tidal flats and marshes (Association B1). These stratigraphic successions mostly composed of associations A5 and A6, with subordinated B1 deposits are interpreted to represent tidally-influenced channels and low-energy plains in a coastal-plain environment. The upper part of these plains was still fully fluvial, whereas in the downdip direction they were influenced by tidal action and gradually passed into an estuarine setting (Fig. 12a).

## 6.2. The estuarine systems

Facies associations B1–B5 represent deposits developed in coastal systems, namely estuarine settings. Facies associations indicative of this system are well developed all across the study area (Figs. 10 and 11). However, the vertical relationships of individual facies associations in the southern and northern sectors allows for the identification of two markedly different estuarine systems.

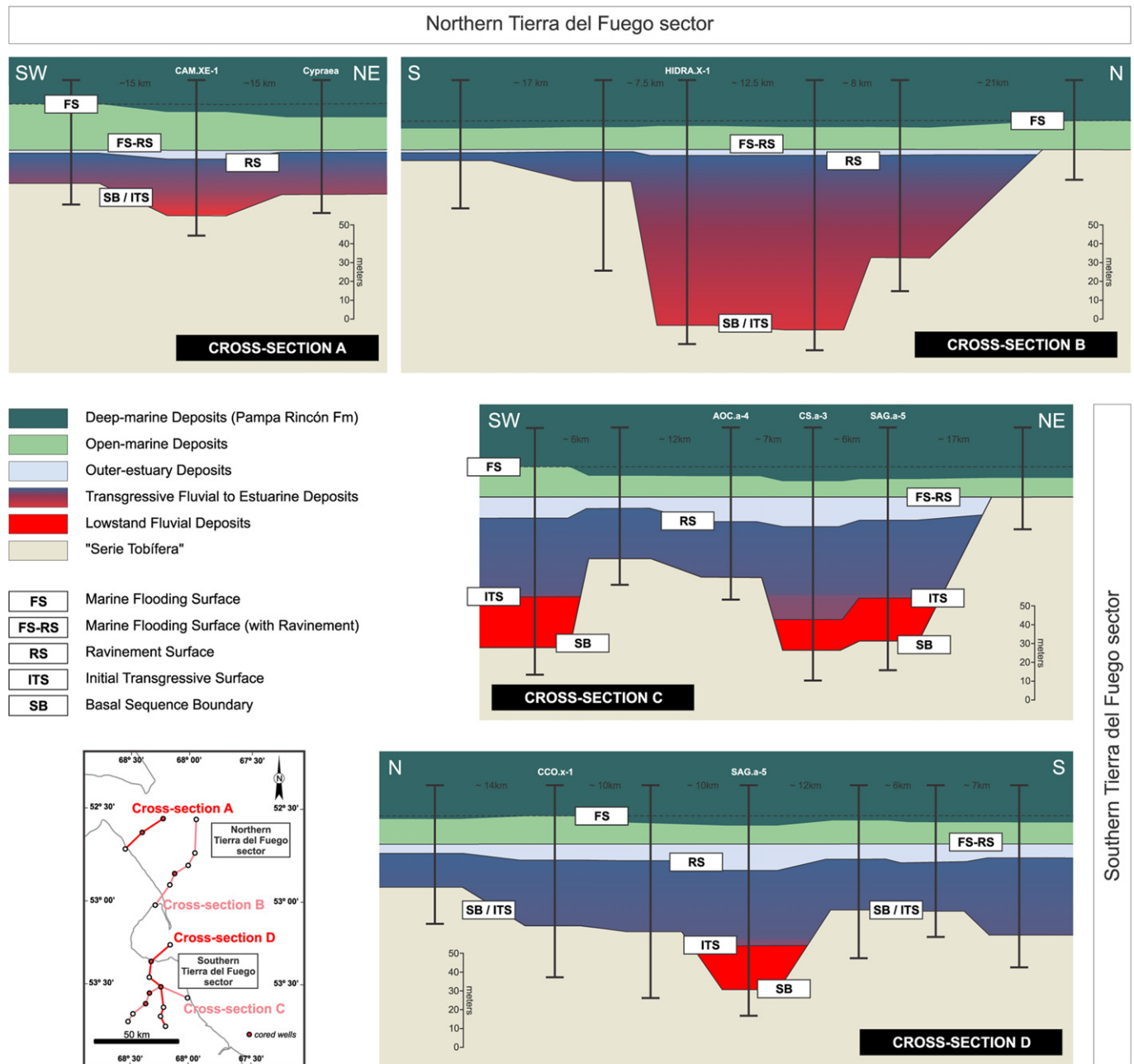
In the southern sector, facies associations B1 and B5 are dominant, with a few intercalations of A6 deposits (Fig. 10). Widespread (and thick) distribution of B1 heterolithic deposits is interpreted to represent well-developed and likely extensive marginal estuarine conditions, from marshes to sand flats. These deposits are occasionally cut by small-scale fining-upward successions of association A6, interpreted to reflect the distal portions of tidally-influenced fluvial channels reaching the estuarine systems. Relatively thick successions of fine-grained sandstones with mud drapes, muddy sandstones and heterolithics (collectively grouped in facies association B5), are interpreted to represent estuarine tidal bars within the central or middle part of the estuarine system. Finer-grained,

more bioturbated and glauconitic deposits included in association B5 are likely reflecting more distal or outer settings. In this context, and although intense bioturbation in these deposits precludes for further interpretation, wave process could have been influencing these distal outer-estuarine sediments as much as tidal action, as seen in other tide-dominated estuarine systems (Plink-Björklund and Steel, 2006; Dalrymple and Choi, 2007).

Stratigraphic successions with vertical superposition of B1 and B5 (less common A6) are considered to represent tide-influenced to tide-dominated estuarine systems (see Dalrymple et al., 1992), developed solely in the southern sector (Fig. 12a). These estuarine systems were gradually being transgressed and they were ultimately replaced by fully-marine systems (Fig. 10). However, local coarsening-upward patterns (e.g. Carmen Silva well in Fig. 10) suggest that significant *in situ* infill of the estuarine system might have occurred (Dalrymple et al., 1992; Plink-Björklund and Steel, 2006).

In the Northern Tierra del Fuego sector, the stratigraphic succession comprising estuarine deposits is much thinner than in the southern sector (<15 m), and is dominated by associations B2, B3 and B4, with subordinated B1 deposits (Fig. 11). Collectively, these associations are interpreted to represent wave-dominated estuarine systems (Fig. 12b, Boyd et al., 1992; Dalrymple et al., 1992; Anthony et al., 2002). Low proportion of lenticular to flaser deposits of association B1 suggests limited extension and development of marginal, tidally-influenced flats associated with these estuarine systems. On the contrary, inner segments of the estuary are well represented and were characterized by unburrowed and relatively coarse sediments (up to coarse-grained sandstones) interpreted as bay-head deltas heavily affected by fluvial discharge (Fig. 12b). Central portions of the estuarine systems were characterized by mud accumulation showing a minimum level of energy (association B3). The vertical stacking of meter-scale cycles with





**Fig. 14.** Selected cross-sections across Southern and Northern Tierra del Fuego sectors showing sequence stratigraphic architecture of the Springhill Formation that resulted from integration of vertical and lateral distribution of main depositional systems combined with identification and correlation of key stratigraphic surfaces.

central-estuary mudstones at the base grading into bay-head sand bars that characterized several estuarine successions in this region (Fig. 8a) possibly reflect avulsion due to aggradation of feeding channels up to the water level.

Sandstone bodies of association B4, composed of amalgamated skeletal sandstones with impoverished *Skolithos* ichnofacies, are thought to reflect high-energy conditions and influence of marine processes (tides and waves) at the mouth of northern estuarine systems. Although geometry and orientation of these bodies was not observed, the presence of well-developed, mud-dominated basal settings (association B3) suggests that at least some sandstone bodies were likely parallel to the shore (e.g. barrier complexes/spits) and produced partial closing of the estuary mouth (Fig. 12b). Sandstone packages of B4 sharply overlie B1–B3 successions in all

studied cored wells (Fig. 11) and the basal bounding surfaces are marked by a *Glossifungites* ichnofacies (Fig. 13a, b). Although *Glossifungites*-demarcated discontinuities could be the product of autocyclic process (e.g. at the base of tidal creeks, Gingras et al., 2000), the regional distribution of the surface and its stratigraphic position suggest that erosion in this case was associated with tidal and wave activity during the transgression of the estuarine system (MacEachern et al., 2007b).

### 6.3. The open-marine system

Open, fully-marine conditions are represented by facies associations C1 to C4. Medium- to coarse-grained bioclastic sandstones (C1) are interpreted to represent shallowest conditions in



upper-shoreface settings, whereas heavily bioturbated fine-grained sandstone and muddy sandstones having a mixed of *Skolithos* and *Cruziana* ichnofacies (C2) likely represent lower-shoreface conditions (MacEachern et al., 2007a). Thinly bedded mudstones and sandstones dominated by a *Cruziana* ichnofacies (C3) and well-preserved nektonic macrofauna (belemnites and ammonites) are considered the transition from lower shoreface to offshore. Finally dark, massive and laminated mudstones (C4) were deposited in offshore settings, where sea bottom likely fluctuated from oxygen-depleted to oxygen-normal conditions.

These open-marine strata invariably overlie estuarine deposits across the study area (Figs. 10 and 11). Southern tide-dominated estuarine systems were abruptly covered by relatively distal marine settings (offshore and transition associations), whereas northern wave-dominated systems were subjected to relatively shallower conditions immediately after the onset to marine accumulation. The sharp contact between marine deposits and the underlying estuarine strata in both sectors locally shows evidence of erosion (Fig. 13c, d). Subsequently, offshore conditions were established all across the Tierra del Fuego studied area (beginning of Pampa Rincón deposition).

## 7. Sequence stratigraphic architecture

The stratigraphic succession (up to 120 m thick) of the Springhill Formation in the Tierra del Fuego studied area has a general retrogradational stacking pattern from fluvial deposits at the base to open-marine deposits at the top. According to previous studies (Robbiano et al., 1996; Arbe and Fernández Bell Fano, 2002) this general transgressive trend started in the Berriasian, and by late Valanginian (i.e. after ~10 m.y.) the entire studied area was undergoing offshore fine-grained sedimentation (Pampa Rincón Formation). Nonetheless, the backstepping continued through the Hauterivian and Barremian, with progressive onlapping of siliciclastic marine deposits onto the Río Chico or Dungeness High (Fig. 2; Biddle et al., 1986; Robbiano et al., 1996; Galeazzi, 1998).

The high-resolution sequence stratigraphic architecture reconstructed for the Springhill Formation was elaborated taking into account the vertical relationships between major groups of facies associations (representing main depositional systems), and the identification of key surfaces across large regions. Cross-sections integrating cored wells (11) plus well-log data from 30 additional boreholes allowed extrapolating (and testing) key surfaces across the study area. In this way, four major regionally extensive surfaces with stratigraphic significance have been recognized within the Springhill Formation in the Tierra del Fuego area (Fig. 14). A basal sequence boundary (SB) separates the Springhill Formation from the underlying “Serie Tobífera”. The transition from fluvial to coastal-plain deposits allowed the definition of an initial transgressive surface (ITS). A ravinement surface (RS) and a marine flooding surface with minor local erosion (FS/RS), are defined respectively at the base and top of outer-estuarine deposits (Fig. 14). The top of the Springhill Formation represents a second regional marine flooding surface (FS) which represents the transition from shallow- to deep-marine systems all across the studied area (Pampa Rincón Formation).

### 7.1. Basal sequence boundary and lowstand fluvial deposits

The Berriasian fluvial deposits of the Springhill Formation lie unconformably above the volcanics and volcanoclastics of the “Serie Tobífera”. This sharp contact represents a mayor discontinuity within the evolution of the basin and is considered a sequence boundary (Fig. 14). The temporal hiatus involved in this discontinuity depends on the age attributed to the youngest rocks of the

Tobífera, which varies from Callovian (Biddle et al., 1986; Galeazzi, 1998; Peroni et al., 2002) to Tithonian (Robbiano et al., 1996).

Immediately above the basal sequence boundary, highly-amalgamated coarse-grained channel-fill deposits with low proportion of floodplain deposits occurred in several wells of the southern sector (e.g. Sur Arroyo Gamma and Carmen Silva, Fig. 10). These up to 25-m thick channel-fill strata are interpreted to reflect low-accommodation conditions (Shanley and McCabe, 1994; Aitken and Flint, 1995; Catuneanu, 2006; Veiga et al., 2007), likely developed as a result of a general low base level. In turn, these amalgamated fluvial strata are sharply overlain by coastal-plain deposits, with high proportion of fine-grained sediments (Fig. 10). This vertical change indicates an increase in accommodation space associated with a retrogradation of the fluvial systems (Shanley and McCabe, 1994; Olsen et al., 1995). Therefore this surface represents a transgressive surface (cf. Allen and Posamentier, 1994; Plink-Björklund and Steel, 2006), and the underlying fluvial strata are considered lowstand deposits (Fig. 14).

Interestingly, the lowstand strata occurred solely in wells of the southern sector where the Springhill Formation succession reaches the maximum thickness (Fig. 14), suggesting a preferential location in the axis of the depressions developed on the “Serie Tobífera” volcanics. Therefore the geometry of the basal sequence boundary clearly indicates the development of a significant topography (up to 100 m high) prior to the deposition of the lowstand fluvial deposits (Fig. 14).

### 7.2. Transgressive fluvial to estuarine deposits

In the Southern Tierra del Fuego sector, the initial transgressive surface (ITS) marks the onset of marine influence in the stratigraphic record. Coastal-plain deposits characterized by tidally-influenced channel-fill facies surrounded by fine-grained deposits having low or null tidal influence dominate at the base, but they are gradually replaced vertically by facies associations representing marginal to inner-estuary conditions with strong evidence of tidal action (Fig. 12a). This stratigraphic succession is up to 35 m thick and the maximum thickness correlates well with the location of previously described lowstand deposits (Fig. 14).

In the northern sector, the basal succession of the Springhill Formation is dominated by fluvial deposits, reaching up to 50 m in thickness in some wells (Fig. 11). Those fluvial strata are characterized by a high proportion of floodplain deposits, interbedded with up to 10-m-thick channel-fill facies. This fluvial succession, evidencing low amalgamation, is interpreted to represent high-accommodation conditions (Aitken and Flint, 1995; Veiga et al., 2007) and therefore is not correlated with lowstand deposits in the southern sector. In any case, the basal contact of the Springhill Formation in the northern sector is considered a complex surface representing both the sequence boundary and the initial transgressive surface (SB/ITS, Fig. 14).

In the long-term evolution, fully fluvial deposits of the northern sector grade upward to coastal-plain and wave-dominated estuarine deposits (Figs. 12b and 14), suggesting a continuous backstepping of the fluvial systems and a general transgressive trend since the initial transgressive surface (ITS). Additionally, these marginal-marine deposits are more common in the southern wells of the northern sector, likely suggesting relatively distal conditions toward the south (Fig. 11).

Despite the general transgressive trend, some fluvial channel-fill facies (less than 15 m thick) occur interbedded with coastal and estuarine deposits in cored wells Hidra.x-1 and Argo.x-1 (Fig. 11). Although these fluvial strata were interpreted as lowstand deposits (Arbe and Fernández Bell Fano, 2002), the fact that they are not recorded in all the northern sector wells suggests that this fluvial

package could be considered the result of a local rather than basinwide regression, superimposed over the long-term transgression. This regression could have been the result of a local increase in the contribution of coarse-grained sediment to the estuarine system.

### 7.3. Ravinement surfaces and outer-estuary deposits

All across the studied region inner- and mid-estuary deposits are overlain by facies associations representing outer segments of estuarine systems (Fig. 14). In the southern sector, that vertical relationship is only recorded in two cored wells (CCo.x-1 and AOc.a-4, Fig. 10). There, heterolithics and thin-bedded sandstones of marginal to inner estuarine segments are abruptly passing into highly bioturbated, muddy sandstones, interpreted to represent outer-estuarine distal bars, deposited in the transition to open-marine conditions. As sandier sediments reflecting more proximal sectors of the outer-estuary are missing between the two previous packages, the sharp contact is interpreted to be a transgressive surface of ravinement (Fig. 14), resulted mainly from landward migration of the estuary-mouth during transgression (Zaitlin et al., 1994).

In the northern sector, glauconitic skeletal sandstones, probably representing barrier complexes and spits in outer segments of wave-dominated estuarine systems, sharply overlie inner- and mid-estuary facies. Invariably, these outer-estuarine packages (up to 8 m thick) lie on an erosional surface, typically demarcated by a *Glossifungites* suite (Fig. 13a, b). This surface is considered a regionally extensive ravinement surface cut by wave (and tidal?) action during transgression. Ravinement surfaces as the one described here have been reported in many Quaternary and ancient examples (e.g. Allen and Posamentier, 1994; MacEachern et al., 2007b), and have been also documented for the Springhill Formation in other areas of the Austral Basin (e.g. Limeres et al., 2000).

### 7.4. Marine flooding surfaces and open-marine deposits

The contact between the outer-estuary deposits and the overlying open-marine strata is well documented in nine of the eleven cored wells (Figs. 10 and 11). In the southern sector, the open-marine deposits (up to 15 m thick) consist of heavily bioturbated mudstones, heterolithics and sandy mudstones interpreted to represent offshore and offshore-transition marine settings (Figs. 9d and 10) overlying sand-rich tidal estuarine deposits. This boundary represents an abrupt deepening of depositional systems from marginal-marine to offshore conditions (Fig. 14). Therefore, this surface is interpreted to represent a marine flooding surface (cf. Cattaneo and Steel, 2003). However, local truncation of underlying deposits has been recorded by an erosional surface and/or a trace fossil suite attributed to a *Glossifungites* ichnofacies (AOC.a-4 and SAG.a-5 wells, Fig. 13d). Thus, the discontinuity can be considered locally as a ravinement surface (FS-RS in Fig. 14), likely produced by wave action above fair-weather wave base during shoreface retreat (Allen and Posamentier, 1994; Cattaneo and Steel, 2003).

In the northern sector, open-marine deposits at the top of the Springhill Formation have a similar thickness (<15 m) and a similar abrupt, erosional vertical relationship with the underlying estuarine succession (Fig. 13c). Therefore, in this region a marine flooding-ravinement surface is also placed at the base of the open-marine strata (FS-RS, Fig. 14).

Open-marine strata both in the southern and northern sectors are eventually capped by a thick succession (>100 m) of greyish mudstones rich in ammonites and belemnites. This upper boundary, representing a second significant increase in water depth and the onset to continuous offshore sedimentation in the study area (Pampa

Rincón Formation) is interpreted as a younger marine flooding surface (FS, Fig. 14). In this case, however, the vertical relationships between facies associations and the lack of direct evidence of erosion suggest that this contact does not involve erosion and can be regarded as a purely non-depositional discontinuity.

Internally, the marine strata sandwiched between the two flooding surfaces (FS/RS and FS) are characterized by undefined vertical trends both in the southern and northern cored wells (Figs. 10 and 11), with the only exception of two cases where a slight progradational pattern from offshore to offshore-transition settings is recorded. This open-marine, dominantly aggradational succession probably indicates that low-frequency transgression was punctuated by short-term periods when accommodation space roughly equalled sediment supply. Aggradational stacking patterns in this general transgressive context could have been reached due to a temporary decrease in the rate of sea-level rise, an increase of sediment supply, or, alternatively, controlled by underlying topography (e.g. less net transgression when drowning high-gradient topography, Cattaneo and Steel, 2003).

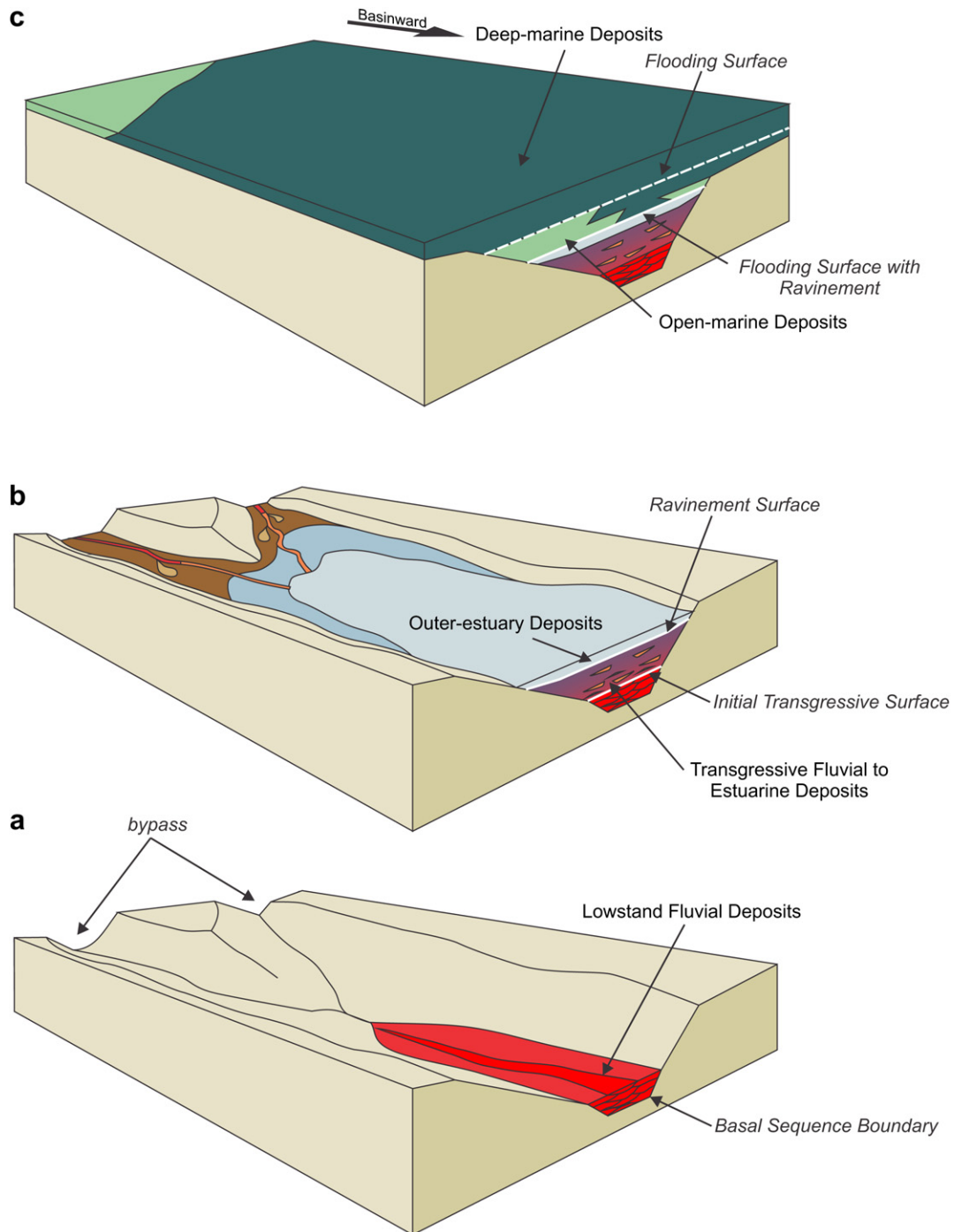
## 8. Discussion

### 8.1. The Springhill Formation: infill of an inherited-valley system

The results presented in this contribution and previous studies (Arbe and Fernández Bell Fano, 2002; Cordo et al., 2002) show that fluvial and estuarine strata of the Springhill Formation in Tierra del Fuego region filled significant topography because they have rapid lateral thinning and pinch-outs against the basement or “Serie Tobífera” (Fig. 14). Pre-Springhill relief was mainly inherited from structural valleys, likely developed during a previous extensional event (cf. Arbe and Fernández Bell Fano, 2002). Although the “rift geometry” of these inherited valleys controlled the distribution of the Springhill Formation, syn-depositional tectonics (or mechanical subsidence) has not been observed in the area, and neither can be inferred from the well-sorted and relatively fine-grained deposits of this unit (mainly sandstones). Additionally, the lowstand fluvial strata are mostly composed of mature sediments (quartz arenites), suggesting that they were supplied from relatively stable areas (Deseado Massif, Fig. 1) rather than from a local volcanic source. Thus, fluvial incision seems to have been a minor contributor in carving the pre-Springhill relief. Based on this evidence and the temporal hiatus represented by the sequence boundary we postulate that the stratigraphic organization of the Springhill Formation in the Tierra del Fuego area is thought to represent the infill of a large (~100 km long), inherited system of valleys under relatively low subsidence conditions.

Facies associations and stratigraphic architecture suggest that valley-fill evolution reconstructed in the southern sector is the downdip expression of this inherited-valley system in relation to the infill of the northern sector. Additionally, the cross-sections elaborated for the study area (Fig. 14) show that axial sectors of the valley system – mainly oriented northwest–southeast – occurred around Hidra.x-1 and SAG.a-5 wells. Despite the fact that physical connection between the valley fills of the two studied areas has not been proved by other means (e.g. seismically), the following discussion assumed a strong link in the evolution of both areas (separated 60 km apart).

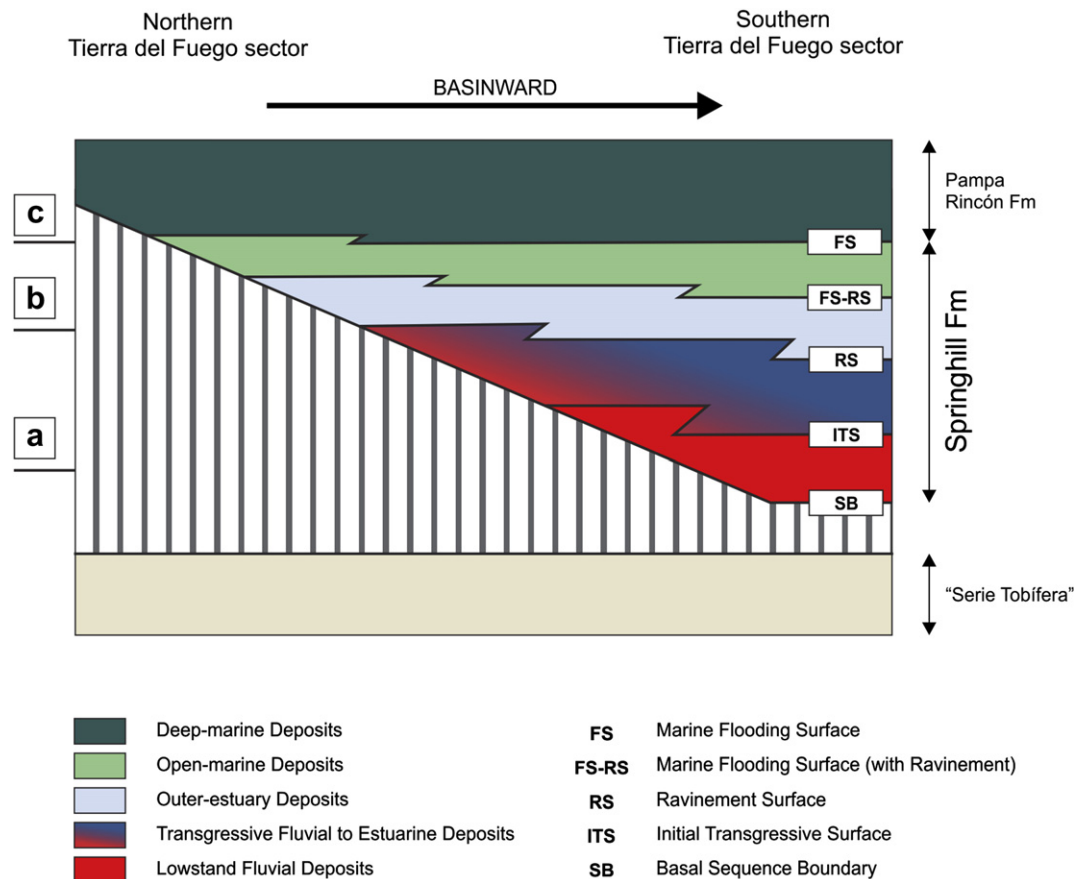
Amalgamated fluvial deposits representing lowstand conditions are present at the base of the succession in the distal segments of the valley system (south), whereas bypass predominates in the updip (northern) regions (Fig. 15a). After the initial transgression, the southern segments became marine influenced and fluvial channels suffered the impact of tidal action. At this stage, a low-energy coastal-plain system was established. As the updip (northern)



**Fig. 15.** Schematic representation of the evolution of the Springhill Formation, interpreted to represent the infill an inherited large system of valleys during continuous transgression. (a) Lowstand fluvial deposits on top of sequence boundary (SB) separating from the "Serie Tobifera" (basement). While low-accommodation fluvial strata deposited in the downdip (southern) sector, bypass predominated in updip areas. (b) After the initial transgression (ITS), southern segments became marine influenced and a low-energy coastal-plain system, grading distally into a tidally-influenced estuary, was established. In the northern sector, coeval fluvial systems developed under high-accommodation conditions. (c) Continuous transgression and the filling of most of inherited topography caused the development of open-marine conditions for most of the studied area. In a last stage (not shown) offshore conditions developed in the entire area.

sectors of the valleys start to undergo the effect of the initial transgression, a drastic change from bypass to accumulation occurred in this area. Due to net transgressive conditions, the proximal segments of the valleys were occupied (and filled) mostly by fluvial systems with high preservation of floodplain deposits in a high-accommodation setting (Fig. 15b).

The ongoing transgressive conditions recorded in the Springhill Formation allowed estuarine systems to replace older fluvial systems (Fig. 15b). However, southern and northern Springhill estuaries markedly differ in their dominant process (tides and waves, respectively) and their relationship with inherited topography. Southern (downdip), tidally-influenced estuarine deposits



**Fig. 16.** Schematic chronostratigraphic evolution of the Springhill valley-fill successions along the depositional profile. Note the diachronism of key stratigraphic surfaces that might be less pronounced during latest stages of the valley fill as the topography is progressively flooded. No scale intended. (a), (b) and (c) indicate the approximate time-slices depicted in Figure 15.

are up to 50 m thick and fully confined within valleys (Fig. 14). On the contrary, northern wave-dominated estuarine deposits are much thinner (<15 m) and they could have overlapped, but locally exceeded, the original valley morphology (Fig. 14). Therefore we speculate that tidal action was enhanced in downdip early estuaries due to significant confinement and funnel shape morphology (Dalrymple et al., 1992; Nordfjord et al., 2006). Tidal prism could have been large enough to generate tidal currents which largely overcame wave-generated currents. Conversely, wave-dominated estuaries could have been more common in updip sectors of the valley system once most of the antecedent topography had been eliminated and shoreline became more rectilinear (Fig. 12b). At this stage, the effect of wave energy and tidal currents on sedimentation would have been relatively higher and lower, respectively. Additionally, at a certain point in the evolution of updip wave-dominated estuaries, the progressive deepening could have established open-marine conditions in the distal (southern) sector of the valley system (Fig. 15c).

The above presented evolution implies that the ravinement surface (RS) and the marine flooding surfaces (FS/RS and FS) identified in both sectors could be diachronous (Fig. 16). This situation is common in transgressive surfaces across vast regions (cf. Cattaneo and Steel, 2003). In any case, marine deposits above the first flooding surface are relatively sandier, and thus shallower, in the northern sector suggesting that the marine system was deeper to the south. Eventually, as transgression persisted in the entire study area, offshore marine conditions rapidly expanded (Fig. 16) and shallow-marine environments migrated far to the east and north of the

Austral Basin. Offshore conditions continued in the area at least until the end of the Cretaceous (Fig. 2).

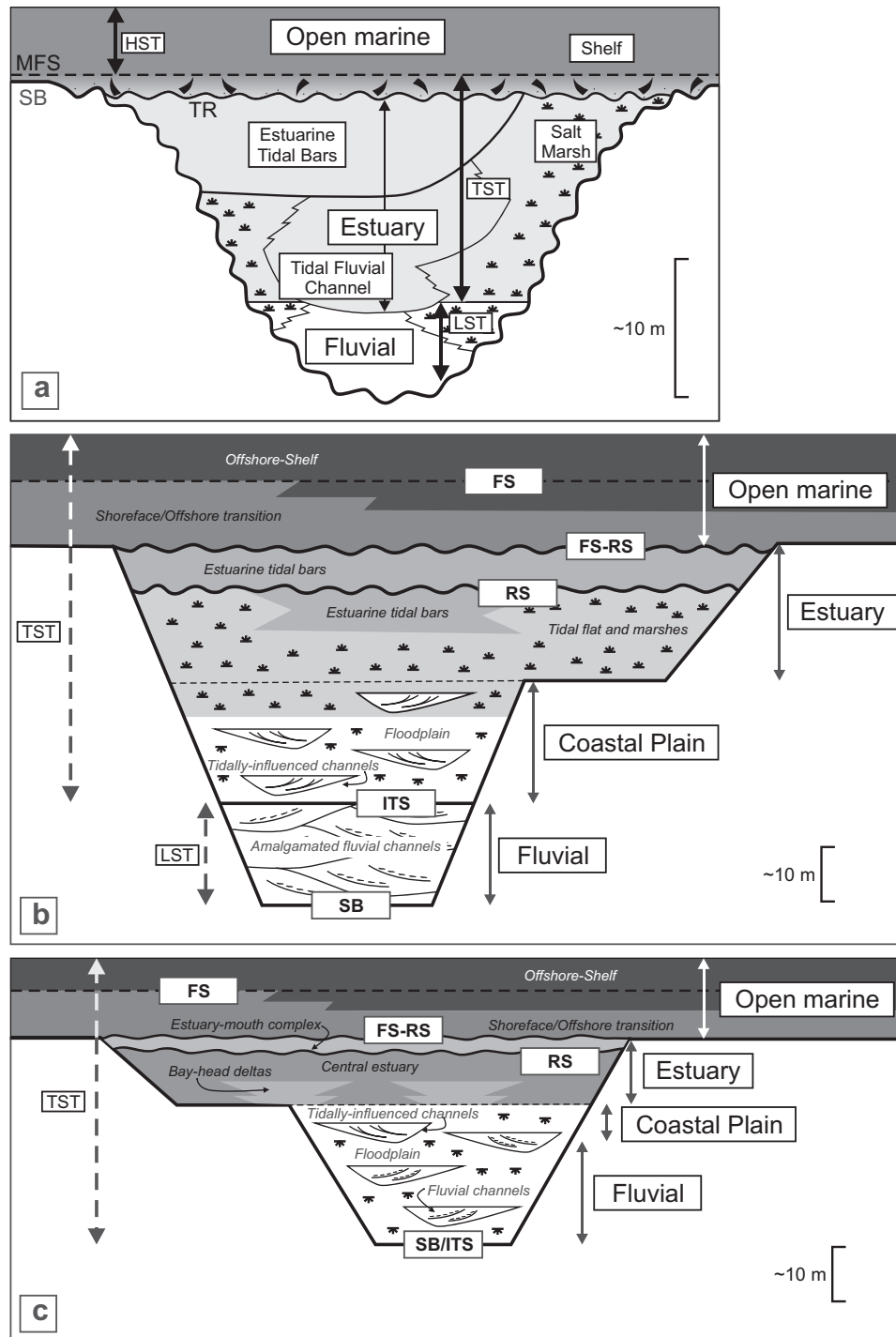
Each deepening event and the resulting transgressive surface within the Springhill stratigraphic organization (Fig. 16) could be the result of an acceleration of relative sea-level rise (assuming a relatively constant sediment supply). Alternatively, these deepening pulses could be related to the gradual flooding of the antecedent relief. Thus, the inundation of high and low-relief areas (see Fig. 14) could have triggered a rapid increase in accommodation creation, even without changes in the absolute rate of transgression. Similar responses have been reported to occur during the flooding of Quaternary incised valleys, when sea-level reaches low-gradient fluvial terraces (Rodríguez et al., 2005). At that moment, a back-stepping of the system is recorded, even when the rate of sea-level rise is decreasing (Rodríguez et al., 2005).

In the same way, as the rate of transgression increases when a low-relief surface is being drowned (Cattaneo and Steel, 2003; Dalrymple, 2006), it is also possible to assume that the youngest surfaces (FS-RS and FS) flooding across gentle slopes might be less diachronous in comparison with those developed during the early stages of inherited-valley-system fill (ITS and RS, Fig. 16).

## 8.2. Comparison with incised-valley systems

Despite that the lower Cretaceous Springhill succession filled an inherited topography rather than a fluvial valley cut during a sea-level fall, the sequence stratigraphic architecture reported here (Figs. 14–16), closely resembles the proposed general models for





**Fig. 17.** (a) Idealized cross-section of an incised-valley-fill succession (after Dalrymple and Choi, 2007). (b) Schematic cross-section of the inherited-valley-fill succession of the Springhill Formation in the downdip, tide-dominated, Southern Tierra del Fuego sector. Note the similar stratigraphic organization with (a), but the different vertical scale. No horizontal scale. (c) Schematic cross-section of the inherited-valley-fill succession of the Springhill Formation in the updip, wave-dominated, Northern Tierra del Fuego sector. Note the reduced vertical development and the lack of lowstand deposits. No horizontal scale.

incised-valley fills (Dalrymple et al., 1992; Allen and Posamentier, 1994; Zaitlin et al., 1994). Incised-valley systems are created by fluvial erosion during a sea-level fall and are filled during the subsequent rise (Zaitlin et al., 1994). An idealized incised-valley-fill succession (Fig. 17a) includes amalgamated fluvial deposits at the base, followed by inner- to outer-estuary strata on top, representing lowstand to early-transgressive deposition, respectively (Dalrymple, 1992; Zaitlin et al., 1994; Cattaneo and Steel, 2003). The

estuarine deposits can grade either into progradational successions assigned to highstand conditions, or can be sharply overlain by open-marine deposits which represent a late-transgressive deposit (Fig. 17a, Dalrymple, 1992; Cattaneo and Steel, 2003). The resulting incised-valley-fill architecture (including the proportion of lowstand vs. transgressive deposits) is controlled by several factors, such as the location of the study area relative to the lowstand shoreline, the relationship between accommodation and sediment

supply, and the rate of transgression, highly influenced in turn by the gradient of the surface being transgressed (Dalrymple, 2006).

Vertical stratigraphic stacking of lowstand and early-transgressive strata within the Springhill Formation (Fig. 17b, c) is remarkably similar to equivalent successions defined for “simple” incised-valley fills (see Dalrymple, 1992; Allen and Posamentier, 1994; Zaitlin et al., 1994). Also the absence of lowstand fluvial deposits in updip segments of the valley and the overall low proportion of lowstand vs. transgressive deposits filling the valley system conforms to the idealized sequences (Fig. 17b, c). Additionally, open-marine deposits at the top of the Springhill Formation are bounded by a flooding surface with ravinement (FS-RS) which is also predicted for incised-valley fill evolution (wave ravinement surface of Dalrymple, 1992; Allen and Posamentier, 1994; Zaitlin et al., 1994). It has been postulated that late-transgressive, open-marine deposits capping valley-system successions can be expected when the incised valley is located near or at the lowstand shoreline (Nordfjord et al., 2006; Plink-Björklund and Steel, 2006). In the case of the Springhill Formation, the long-term transgression (that continued for several million years once the valleys were filled), was the likely driving mechanism behind the resulting stratigraphic organization. Thus, the surface capping the open-marine deposits does not represent the maximum flooding surface but just a younger flooding surface (Fig. 17b, c).

On the contrary, the temporal switch from tide-dominated to wave-dominated Springhill estuaries as the transgression progressed from downdip to updip segments of the valley system (see Fig. 17b, c), has not been widely reported for incised-valley-fill successions. Although a change from tide- to wave-dominated estuarine strata within a single incised-valley fill has been observed (Nordfjord et al., 2006), the transformation documented for the Springhill example seems to be related to a drastic change in the physiography of the shoreline as transgression progressed and the complex antecedent topography was eliminated. Thus, this situation could be a distinctive feature in the evolution of transgressed structural valleys as the one represented by the Springhill Formation.

## 9. Conclusions

- 1) Five hundred meters of studied cores combined with well-log data from supplementary 41 wells allowed for a detailed facies association analysis and a high-resolution sequence stratigraphic architecture of the Berriasian–Valanginian Springhill Formation (<120 m thick) in the southern Austral Basin (Tierra del Fuego, Argentina).
- 2) Fifteen facies associations were identified in the Springhill Formation, representing three main depositional systems: fluvial, estuarine and open-marine environments, which replaced each other vertically. This vertical transgressive stacking pattern is recorded both in the northern and southern defined studied sectors (a total area of ~6800 km<sup>2</sup>), and was controlled by a long-term transgressive cycle which ended in the Barremian.
- 3) The Springhill Formation infills deep valleys (up to 100 m deep) within a valley system inherited from a preceding extensional event. Downdip segments of the valley system were located toward the south of the studied area.
- 4) Lowstand fluvial deposits (above an SB and below an initial TS) represent the first stage of the valley-system fill, but they are solely present in the axial areas of downdip segments of the valley system (southern sector).
- 5) Transgressive fluvial deposits are more common in the northern sector (overlying an SB/ITS) and they are interpreted to be the time-equivalent of transgressive coastal-plain and tide-dominated estuarine deposits of the southern sector

(overlying the ITS). Collectively these transgressive deposits represent the main infill of the valley systems (up to 80 m thick) and tidal action was probably enhanced by the funnel shape of inherited topography. In turn, wave-dominated estuarine deposits overlying fluvial strata in the northern sector likely developed once the antecedent relief had been eliminated and shoreline physiography was less complex.

- 6) Ravinement surfaces (RS) generated during continuous transgression of estuarine systems are recognized across the study area. The ravinement surface in the distal segment of the valley system (southern sector) was probably the youngest and generated by tide-generated currents, whereas wave and tidal erosion associated with estuary-mouth retreat occurred in the proximal region (northern sector) as the valley system was gradually flooded.
- 7) A drastic change in sedimentation from marginal-marine (estuarine) to open-marine conditions is marked by a marine flooding surface in the northern and southern sectors (FS/RS), although this surface is likely diachronous across the valley system. Open-marine strata are thin (typically < 10 m thick) and dominated by lower-shoreface and offshore-transition deposits. They are capped by a flooding surface (FS), which represents the drowning of the low-relief study area due to continuous long-term transgression.
- 8) The evolution and architecture of the Springhill Formation can be compared to incised-valley fills for the most part, despite the fact that the valley system filled by the unit was an inherited geography rather than the incision created during a sea-level fall.
- 9) Distribution and stacking of lowstand and early-transgressive, fluvial to estuarine deposits of the Springhill Formation are markedly similar to incised-valley fills. Also late-transgressive marine deposits, as the one capping the Springhill Formation, are commonly observed in Quaternary incised valleys located near or at the lowstand shoreline. On the contrary, the postulated transformation from tide- to wave-dominated estuarine systems as the transgression progressed within the valley system (~100 km long) could be distinctive of inherited-valley-system successions as the one represented by the Springhill Formation.

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