Journal Pre-proof

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PII: S0895-9811(20)30031-6

DOI: https://doi.org/10.1016/j.jsames.2020.102519

Reference: SAMES 102519

To appear in: *Journal of South American Earth Sciences*

Received Date: 15 January 2020

Accepted Date: 22 January 2020

Please cite this article as: Raigemborn, M.S., Beilinson, E., Stratigraphic architecture and paleosols as basin correlation tools of the early Paleogene infill in central–south Patagonia, Golfo San Jorge Basin, Argentinean Patagonia, *Journal of South American Earth Sciences*, https://doi.org/10.1016/j.jsames.2020.102519.

Stratigraphic architecture and paleosols as basin correlation tools of the early Paleogene infill in central–south Patagonia, Golfo San Jorge Basin, Argentinean Patagonia

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Abstract

The Paleogene infill of the eastern Golfo San Jorge Basin, Patagonia, Argentina, is composed of marine and terrestrial deposits. The latter are fluvial, pedogenically modified successions interlayered with eolian volcaniclastic deposits during the Eocene. Several authors have highlighted the stratigraphic significance and usefulness of strongly developed paleosols in the definition of sequence stratigraphic studies. Even though the area hosts abundant geological and paleopedological data, no large-scale (i.e., basin-scale) stratigraphic architectural correlation including paleosols and relationships within the sequence stratigraphic context had hitherto been carried out. By integrating previously published and unpublished data sets, this paper proposes a sequence stratigraphic framework for the middle Danian–middle Eocene successions of the eastern Golfo San Jorge Basin. Here, spatio-temporal changes in fluvial/alluvial architecture of the Paleogene infill allow us to define four depositional sequences (S), limited by sequence boundaries (SB) that internally presents a low-accommodation system tract (LAST), and a high-accommodation system tract (HAST). Part of these sequences occur as fining-upwards fluvial successions that are pedogenically modified on top by strongly developed paleosols, or are erosively overlain by the coarse-grained base of the following sequence without the development of well-developed paleosols. The sedimentological and paleopedological analysis of the four sequences identified for the early Paleogene infill of the basin indicates that the interplay between subsidence, base level, and climate have controlled both fluvial style and landscape evolution, as well as soil development. Volcaniclastic supply also played a significant role, especially during the Eocene.

Keywords: Río Chico Group; Non-marine Sequence Stratigraphy; System Tracts; Ultisol-like paleosols; Allogenic Controls

1. Introduction

The development of an integrated model that includes paleosols, fluvial facies, and the associated bounding surfaces is crucial to the prediction of non-marine stratigraphic architecture (e.g., Wright and Marriott, 1993; Kraus, 1999; Varela et al., 2012; Ashley et al., 2013; Beilinson et al., 2013; McCarthy and Plint, 2013; Amorosi et al., 2014; 2017, among others). Fluvial-alluvial systems may respond to a variety of allogenic controls such as eustasy, climate, tectonics, and basin subsidence, and the relative impact of these in the resulting architecture can be identified (e.g., Wright and Marriott, 1993; Shanley and McCabe, 1994). Particularly, paleosols represent a powerful tool for stratigraphic correlation in alluvial deposits (Bown and Kraus, 1987; Wright and Marriott, 1993; Kraus, 1999, among others) because they can be used as regional stratigraphic markers to trace genetic packages across sequence-bounding unconformities at different scales (e.g., Demko et al., 2004; Amorosi et al., 2014). Another notable application of the paleosols is that their temporal evolution, recorded by the change in the dominant pedofeatures, attests for base-level changes (e.g., Kraus et al., 1999; Catuneanu, 2006). Theoretically, paleosol types change with a fluctuating base level, allowing them to assess their relative importance/significance from a sequence stratigraphic viewpoint (Wright and Marriott, 1993; Catuneanu, 2006). From this perspective, paleosols provide key evidence for the reconstruction of syndepositional conditions during the accumulation of system tracts, or the temporal significance of stratigraphic hiatuses related to sequence-boundary unconformities. Thus, more developed or mature paleosols form either during stages of non-deposition or erosion and in association with sequence boundaries; on the contrary, less developed or immature paleosols and generally aggrading ones (i.e., compound, composite, cumulative following Kraus, 1999) take place during stages of sediment accumulation associated with the deposition of sequences (e.g., Catuneanu, 2006).

Outcrop exposures of the early Paleogene succession of the Golfo San Jorge Basin (GSJB) located in central Argentinean Patagonia, represent an excellent opportunity to verify the benefits of the paleosols in stratigraphy as well as to examine the distribution of depositional systems and the stacking patterns of marine and terrestrial sequences. The eastern area of the GSJB (North Flank, Center of the Basin, and South Flank; Fig. 1A) has a conspicuous background of stratigraphic information of the early Danian marine–estuarine Salamanca Formation and the overlying middle Danian–middle Eocene fluvial–alluvial and eolian deposits, in part bearing paleosols, of the Río Chico Group (Fig. 2). The area hosts abundant sedimentological and paleopedological data (Feruglio, 1949; Andreis et al., 1975; Legarreta et al., 1990; Martínez, 1992; Legarreta and Uliana, 1994; Matheos et al., 2001; Iglesias, 2007; Raigemborn, 2008; Raigemborn et al., 2009a, b, 2010, 2014, 2018a, b; Krause et al., 2010a, b, 2017; Krause and Piña, 2012; Foix et al., 2013, 2015; Clyde et al., 2014; Woodburne et al., 2014; Comer et al., 2015; Ruiz et al., 2017, 2020; Lizzoli et al., 2018; Zucol et al., 2018), at which recently was added a temporal resolution (Clyde et al., 2014; Krause et al., 2017). The Salamanca Formation and the lowermost Río Chico Group have been recently correlated with globally recognized sea-level events, highlighting the role of fluctuating sea level as a primary control (e.g., Clyde et al., 2014; Comer et al., 2015). On the other side, outcrops and subsurface data of the Salamanca Formation and the Río Chico Group at the North Flank of the basin have been related to changes in accommodation space and to differential subsidence across the basin (Foix et al., 2013, 2015). However, up to date, no large-scale (i.e., basin-scale) stratigraphic architectural correlation, including paleosols and relationships within the sequence stratigraphic context of both the Salamanca Formation and the Río Chico Group, have hitherto been carried out. Consequently, the aims of this research are 1) to analyze spatio-temporal changes in depositional environments, paleosol types, and total thickness of the Río Chico Group, making correlations throughout the eastern part of the GSJB (see Fig. 1A and B), and 2) to construct a sequence stratigraphic scheme for the middle Danian–middle Eocene successions of this part of the basin.

2. Geological context

The GSJB is an extensional intracontinental basin located in southern Argentina that developed on Paleozoic continental crust linked to the Gondwana break-up (e.g., Fitzgerald et al., 1990). It suffered different phases of extensional reactivation during the Cretaceous, followed by the process of positive inversion tectonics along the San Bernardo Fold Belt (Fig. 1A), which rose mainly during the Neogene (Homovc et al., 1995; Paredes et al., 2018). Figari et al. (1999) internally divided this basin according to its structural style into five zones: North Flank, Center of the Basin, South Flank, San Bernardo Fold Belt, and Western Sector (Fig. 1A). Using the Figari´s scheme, which was defined to the Castillo Formation, our research is mainly placed in the Eastern Sector of the basin (i.e., North Flank, Center of the Basin, and South Flank) (Fig. 1A and B), where an extensional style prevails (Figari et al., 1999;

Giampaoli, 2015). However, the locality of Cerro Abigarrado (Fig. 1A and B) is located on the less deformed eastern margin of the San Bernardo Fold Belt, where Gianni et al. (2017) indicated that a contractional tectonic regime took place during the Eocene. Paleogeographic reconstructions consider the Eastern Sector of the GSJB as a large engulfment with W-E orientation open to the Atlantic Ocean (e.g., Malumián et al., 1999; Malumián and Nañez, 2011; Gomez Peral et al., 2019).

The earliest Cenozoic infill of the GSJB is characterized by a near-horizontal succession of marine and continental sedimentary rocks deposited in a passive margin setting in an extensional context (e.g., Figari et al., 1999; Foix et al., 2008, 2012), exceeding the Cretaceous boundaries of the Chubut Group basin (Foix et al., 2015). This infill starts with the marine–estuarine deposits of the Salamanca Formation, which correspond to an Atlantic transgression that flooded the Eastern Sector of the basin during the Danian (Fig. 2). The Salamanca Formation is stratigraphically composed of five sections known as Lignitífero, Glauconítico, Fragmentosa, Banco Verde, and Banco Negro Inferior (in stratigraphic order, according to Feruglio, 1949). In the westernmost North Flank and the surroundings of the San Bernardo Fold Belt, the Salamanca Formation was deposited during the early Danian; instead, farther east, it has been assigned to be middle-late Danian (Clyde et al., 2014). The Salamanca Formation was covered during the middle Danian by the continental deposits of the Río Chico Group, that persisted active up to the middle Eocene (following Clyde et al., 2014; Krause et al., 2017; Raigemborn et al., 2018a) (Fig. 2). Internally, the Río Chico Group is composed of four units that, from the oldest to the youngest, are Las Violetas, Peñas Coloradas, Las Flores, and Koluel-Kaike formations (Raigemborn et al., 2010). Deposition of the Río Chico Group took place in the Eastern Sector of the basin and in the vicinity of the San Bernardo Fold Belt and the Deseado Massif to the south (Fig. 1). The tectonic setting of the Río Chico deposits is still debated, while field information in the eastern of the basin attest to deposition during extension (Foix et al., 2013), outcrop data point out to syntectonic deposition of the Koluel-Kaike Formation to the west and south of the San Bernardo Fold Belt, suggesting a contractional regime (Gianni et al., 2017). The Río Chico Group is overlain by marine and continental units that represent the middle-late Cenozoic infill of the basin (Fig. 2).

The localities selected for this paper, based on the presence of early Cenozoic outcrops, along the Eastern Sector of the GSJB and the eastern margin of the San Bernardo Fold Belt (Patagonia, Argentina; Fig. 1A and B) are: Estancia Las Violetas, Punta Peligro–Estancia La Rosa (Rocas Coloradas area), Cañadón Hondo area, Estancia La Campanita–Gran Barranca (Las Flores area), Cerro Blanco, Bosque Ormaechea (Cerro Abigarrado area), Cañadón Lobo, Río Deseado area, and Laguna Manantiales (from north to south; see Fig. 1B). An integrated stratigraphic chart is provided in Figure 2 to correlate studied lithostratigraphic units throughout the different localities of the basin.

In the northeastern area of the North Flank (Estancia Las Violetas–Rocas Coloradas; see Fig. 1B), the Salamanca Formation outcrops start with the Glauconítico and Fragmentosa deposits, which are followed by the estuarine deposits of the Banco Verde and the pedogenized swamp deposits of the Banco Negro Inferior (BNI) (Feruglio, 1949; Andreis et al., 1975; Legarreta et al., 1990; Legarreta and Uliana, 1994; Raigemborn, 2008; Raigemborn et al., 2010, 2014; Foix et al., 2015; Ruiz et al., 2017, this volume). The Río Chico Group in this area comprises the low-sinuosity fluvial systems of the Las Violetas Formation, the moderate- to high-sinuosity fluvial systems of the Peñas Coloradas Formation, and the moderate- to high-sinuosity fluvial systems of the Las Flores Formation (Feruglio, 1949; Andreis et al., 1975; Legarreta et al., 1990; Legarreta and Uliana, 1994; Raigemborn, 2008; Krause, 2009; Raigemborn et al., 2010, 2014; Krause and Piña, 2012; Foix et al., 2013, 2015). Foix et al. (2013, 2015) related the first of these fluvial architectures to a high aggradation rate, and to a low aggradation rate to the latter, and attributed both styles to variations in subsidence rates and sedimentary supply, assuming a constant climate across the Golfo San Jorge Basin. The Las Violetas and Peñas Coloradas formations show a lateral stratigraphic relationship (Raigemborn et al., 2010; Krause et al., 2017). However, a significant erosional unconformity separates the Las Flores Formation from the underlying Peñas Coloradas (e.g., Legarreta and Uliana, 1994; Krause et al., 2017). Both the age and the regional extent of the basal unconformity over which the Las Flores Formation lies suggest that this surface could have been caused by an erosive event related to a fall in base level. One possible origin of this unconformity could be the effects of global eustatic sea-level fall near the Paleocene–Eocene boundary (ca. 56 Ma) (Krause et al., 2017).

In the southwestern part of the North Flank and the eastern margin of the San Bernardo Fold Belt (Las Flores and Cerro Abigarrado areas, respectively; see Fig. 1B), the Salamanca Formation is represented by the marine–estuarine and coastal swamps deposits of the Glauconítico–Banco Negro Inferior (Feruglio, 1949; Legarreta et al., 1990; Martínez, 1992; Legarreta and Uliana, 1994; Matheos et al., 2001; Iglesias, 2007; Raigemborn, 2008; Raigemborn et al., 2010, 2014; Clyde et al., 2014; Comer et al., 2015). The Río Chico Group is represented by the fluvial deposits of the Peñas Coloradas, Las Flores, and the pedogenically modified fluvial Koluel-Kaike Formation (Raigemborn, 2008; Krause et al., 2010, 2017; Raigemborn et al., 2010, 2014; Clyde et al., 2014; Woodburne et al., 2014; Comer et al., 2015). Taking these into consideration, Clyde et al. (2014) and Comer et al. (2015) proposed a general sequence stratigraphic framework for the Salamanca Formation and the lower Río Chico Group (i.e., Peñas Coloradas Formation) deposits of the area. These authors recognized an erosional surface between the Banco Negro Inferior and the Peñas Coloradas Formation and sedimentary systems tracts, and combined them with chronologic data and the global eustatic sea-level curve. In this context, the Banco Negro Inferior is interpreted as a highstand system tract that overlays the late transgressive one of the upper Banco Verde. A eustatic sea-level fall gave place to a sequence boundary that separates the Banco Negro Inferior from the Peñas Coloradas Formation, which also represents the end of the early Paleogene marine sedimentation in the basin.

Although in the Center of the Basin and most of the South Flank (see Fig. 1B) the Salamanca Formation and the Río Chico Group occur at subsurface (e.g., Fitzgerald et al., 1992; Figari et al., 1999; Hechem and Strelkov, 2002; Paredes et al., 2015), towards the south of the South Flank (Río Deseado area and Laguna Manantiales; see Fig. 1B) both units are outcropping. The outcrops of the Salamanca Formation are restricted to the Banco Verde–Banco Negro Inferior (Raigemborn et al., 2018b); meanwhile, the Río Chico Group comprises the outcrops of the fluvial Las Flores Formation and the distal eolian-dominated fluvial Koluel-Kaike Formation, both of them pedogenically modified (Lizzoli et al., 2018; Raigemborn et al., 2018a, b).

3. Methodology

Although a significant part of the early Cenozoic deposits is in the subsurface of the South Flank and the Center of the Basin, in this study, we carry on a revision of the latest works dealing with the Paleogene sedimentology based on outcrop data of the Eastern Sector of the GSJB. Here we include our own and bibliographic information (see previously), covering the east of the GSJB (i.e., the North Flank and the South Flank) (Fig. 1B).

We consider spatio-temporal changes in facies, facies associations, fluvial styles, the geometry of fluvial-alluvial bodies, preservation of floodplain deposits, paleosols, and thickness of the units throughout the study area to define the early Cenozoic stratigraphic architecture of the GSJB.

Facies were described following Miall's (1996) and Bridge's (2003) schemes but adapted to volcaniclastic successions (Table 1). The terms tuffaceous sandstones, siltstones, and mudstones were respectively used for reworked sand-, silt-, and mud-sized pyroclastic sediments with sporadic reworked epiclastic grains. Facies associations were described following Miall's (1996) scheme (Table 1).

Paleosols were identified in outcrop based on macroscopic pedofeatures, such as structure, mottles, nodules, color, slickensides, burrows, and rhizoliths (e.g., Retallack, 2001). Colors were described according to the Munsell notation (Munsell Soil Color Book, 2013). In paleosol horizons, thickness, contact types, mineral composition, mean grain size, ped structure, type of nodules, and evidence of bioturbation were described (e.g., Soil Survey Staff 1999; Retallack, 2001). Classification of the paleosols was made following the criteria of USDA, Soil Taxonomy (1975, 1998), and the modifications for paleosols by Retallack (1994). Some of these items are summarizing in Tables 1 and 2.The description of pedofeatures at macroscale together with the differentiation of the soil horizons, the interpretation of main soil-forming processes, and the paleosols classification served as the basis for the definition of very weakly, weakly, strongly, and very strongly developed paleosols (see Table 2). The well-exposed and the great lateral continuity of the paleosols-bearing outcrops of the Río Chico Group in the study area allowed an analysis of the laterally continuous paleosols within the unit. Thus, using a combination of macroscopic properties of the different types of paleosols identified and their stratigraphic position throughout the Río Chico Group, a large-scale correlation can be established, and for this reason, they represent powerful stratigraphic markers within the study unit. In this sense, we give special consideration to the identification and lateral tracing of strongly- and very strongly-developed paleosols as key surfaces on a regional scale. Very weakly and weakly-developed paleosols (i.e., Entisol-, Andisol-, and Inceptisol-like paleosols; Table 2) within the Río Chico Group were observed as laterally discontinuous, and given a different hierarchical value than the more mature ones (i.e., paleosols with strong–very strong degree of development), and consequently, we do not consider them as key surfaces. Unlike, intensely modified beds that are laterally continuous represent key markers for our high-resolution stratigraphic analysis of the GSJB. Strongly- and very strongly-developed paleosols (i.e., Alfisol-, Ultisol- and Ultisol-like paleosols with plinthitic horizon and equivalent paleosols, and Aridisol-like paleosols with calcic horizon; Table 2) suggest temporal persistence of broadly similar soil-forming conditions as the entire soil sequence developed. On the contrary, very weakly-developed paleosols reflect cessation of sedimentation for only a very short–short period of time (e.g., Retallack, 2001). In the study area, regionally extensive paleosols are the dominant stratigraphic markers at the westernmost North Flank and the South Flank (basin margin), while channel/floodplain cycles are the main key markers in the eastern North Flank.

In order to simplify previous sedimentological and paleopedological results, we selected the most complete succession of the Río Chico Group for each studied area of the GSJB. Although data from these sections are original, some sedimentological details were taken from the literature to complement our observations. Thus, the profile of the Estancia Las Violetas locality is the representative for the eastern North Flank (Figs. 1B and 3); the composite section of the Punta Peligro–Estancia La Rosa (Rocas Coloradas area) represents the coastal area of the North Flank (Figs. 1B and 3); the composite section of the Estancia La Campanita–Barranca Colhué Huapi (Las Flores area) characterizes the western North Flank (Figs. 1B and 3), and the profiles of the Río Deseado area and Laguna Manantiales are the characteristics of the southern and southernmost South Flank (Figs. 1B and 3). Other localities mentioned in the text are shown in Fig. 1B.

The chronostratigraphic framework used in this paper was following Clyde et al. (2014) and Krause et al. (2017) for the Salamanca Formation and the Río Chico Group, and following Ré et al. (2010) and Dunn et al. (2013) for the lower Sarmiento Formation (see Fig. 2).

4. Results: Sequence stratigraphy

After the marine withdrawal at the end of Salamanca Formation (Banco Negro Inferior), continental conditions developed during the accumulation of the Río Chico Group deposits. In this context, the absence of marine or contemporary coastline deposits makes it difficult to use classical sequence stratigraphical terminology. In order to solve this, we will use Dahle et al. (1997) sequence stratigraphic approach, and introduce the high- and low accommodation system tracts, which are defined mainly based on facies associations present in the succession, also taking into account the relative proportion of channel deposits and floodplain deposits. Each of these systems tracts refers to periods in which there was an increase or decrease in the rate of generation of accommodation (Dahle et al., 1997; Catuneanu, 2006). They refer to tendencies in accommodation and sedimentation with no implications for relative sea level.

For the early Paleogene deposits of the eastern GSJB, the correlation of the facies association between the studied outcrops revealed the stratigraphic architecture (Fig. 3). Independently of the lithostratigraphic data (i.e., without taking in consideration the limits previously assigned to the stratigraphic units), we divided the Río Chico Group into four intervals: lower, middle, upper, and uppermost, all of them separated by erosive surfaces (Figs. 4–6). Thus, each of these intervals defines a sequence (S1, S2, S3, S4), limited by sequence boundaries (SB1, SB2, SB3, SB4, SB5), that internally presents a low-accommodation system tract (LAST1, LAST2, LAST3, LAST4), and a high-accommodation system tract (HAST1, HAST2, HAST3, HAST4) (Figs. 4–6).

4.1. Sequence 1 (S1)

Sequence 1 corresponds to the lower part of the Río Chico Group, including Las Violetas and Peñas Coloradas formations (Fig. 4). These are continental deposits that overlay the swamp deposits of the Banco Negro Inferior (Salamanca Formation) and were interpreted by Clyde et al. (2014) and Comer et al. (2015) as lowstand systems tract deposits following late transgressive/highstand system tract deposits.

The basal boundary of the S1 (sequence boundary 1; SB1) is represented by an irregular or plane and erosional surface marked by the basal surface of the channels belonging to either the Las Violetas (Estancia Las Violetas and Cañadón Hondo; Fig. 1B) or the Peñas Coloradas Formation (Rocas Coloradas area, Las Flores area, Cerro Abigarrado; Figs. 1B), depending on the area (Figs. 3, 4 and 5A, B). Usually, this surface incises the upper part of the Salamanca Formation, but at the western North Flank (Las Flores area) (Fig. 1B), the SB1 erodes down to the Banco Verde of the Salamanca Formation (Iglesias, 2007).

After the development of the SB1, the LAST1 deposits were accumulated (Figs. 4 and 5A, B). These are represented by 16 to 30 m of very coarse- and coarse-grained fining-upward successions ranging from greenish-gray epiclastic and tuffaceous conglomerates to coarse- and medium-grained sandstones (facies Gm, Gt, Gp, St, Sp, Sm, Se, Sl of the FA1 and FA2; see explanation of these codes in Table 1). Such deposits were interpreted by Foix et al. (2013, 2015) as braided channels and as a low- and moderate- to high-sinuosity fluvial system with mixed load (sandy-gravelly), where the channels would be multiple and mobile by Raigemborn et al. (2010; 2014). Fine-grained (sandy-muddy) tabular beds of St, Sr, Sm, Sl, Fm, and Fl facies (FA4 and FA5; see an explanation of these codes in Table 1) with sporadic paleosols with a very weak degree of development are interbedded into this coarser facies (Fig. 3; Table 2).

The LAST1 is followed by the HAST1 (Figs. 3, 4 and 5A, B, E), which is characterized by 12 to 50 m of stacking tabular bodies composed of gray to orange-reddish tuffaceous sandy-siltstones (St, Sm, Sr, Sl, Fm, Fl, TSm, TMb and TMm of the FA3, FA4 and FA5; see explanation of these codes in Table 1) interpreted as sheet-flood deposits, distal floodplain deposits, and in less proportion as proximal floodplain deposits, respectively (Raigemborn et al., 2009, 2014). Paleosols with very weak- to strong-degree of development (Entisols, Inceptisols, and Alfisols; see Table 2) developed over such deposits (Krause et al., 2010b; Raigemborn et al., 2009b) (Figs. 3, 4, 5A, and 6A, B). Channel-fill deposits are absent in the HAST1.

At the South Flank of the basin, there are no outcrops assigned to deposits of the Las Violetas and/or Peñas Coloradas formations (see below) (Fig. 4).

4.2. Sequence 2

The contact between S1 and S2 is characterized by an erosive and irregular surface (SB2) (Figs. 4 and 5C–E). Lithostratigraphically, this surface corresponds to the contact between the Salamanca Formation or Las Violetas/Peñas Coloradas formations and the Las Flores Formation, and it can be followed through the outcrops of the northern and southern part of the study area (e.g., Raigemborn et al., 2010, 2018b; Krause et al., 2017) and in the subsurface in the Center of the basin (Legarreta and Uliana, 1994). Thus, this surface is regionally extended throughout the study area. Notably, in the southernmost of the GSJB, the SB2 is an erosional and discordant surface developed between the deposits of the Banco Verde–Banco Negro Inferior (Salamanca Formation) and the Las Flores Formation (Figs. 3 and 5C).

The LAST2 comprises 25 to 30 m of pinky to grayish or orangey and whitish coarse-grained facies (Gm, Gt, St, Sp, Se facies; see an explanation of these codes in Table 1) interpreted as sandy-gravelly low- and moderate- to high- sinuosity fluvial channels (FA1 and FA2; Table 1) (Raigemborn et al., 2010, 2014; Foix et al., 2013, 2015), interbedded with thin packages of fine-grained bodies corresponding to distal floodplain deposits (Foix et al., 2013, 2015). These last beds are mainly epiclastic and in less proportion volcaniclastic in composition (Fm, and TMm facies; see an explanation of these codes in Table 1), and are interpreted mainly as distal floodplain deposits (Raigemborn et al., 2018b) (FA5; Table 1). At the Rocas Coloradas area, the LAST2 is cover concordantly by pedogenically modified white tuffaceous deposits assigned to the Gran Barranca Member of the Sarmiento Formation (Krause and Piña, 2012).

In the north North Flank (Estancia Las Violetas; Fig. 1B), the HAST2 is characterized by c.10 m of reddish–brownish tabular muddy bodies (Fm facies; see an explanation of this code in Table 1) interpreted as distal fluvial floodplain areas (FA5, Table 1) which are eroded by the shallow marine deposits of the Miocene Chenque Formation (Figs., 3, 4 and 5A). Towards the west (Las Flores area), the HAST 2 is represented by 30 to 44 m of grayish–greenish homogeneous muddy deposits, epiclastic and volcaniclastic in composition (Fm, Fl, TSm, TMb, and TMm facies; see an explanation of these codes in Table 1), interpreted as sheet-flood deposits (FA3, Table 1) and distal fluvial floodplain settings (FA5, Table 1) (Fig. 5F) (Raigemborn et al., 2009a and b, 2010, 2014; Woodburne et al., 2014; Krause et al., 2017). Paleosols with very weak- to weak-degree of development are recorded (see Table 2 and Fig. 6C). However, in the middle-upper part of the Las Flores Formation at Las Flores area, Krause et al. (2017) described a condensed section with the occurrence of orange and red beds, interpreted as paleosols that could imply duration of c. 2 m.y. (Fig. 6D). These are strong–very strong developed paleosols, and we interpret them as the next sequence boundary (SB3; see below and Fig. 4). In the southernmost South Flank (Laguna Manantiales; Fig. 1B), the HAST2 deposits are practically absent, and instead strongly and very strongly developed Ultisol- and Oxisol- like paleosols (Lizzoli et al., 2018; Raigemborn et al., 2018b) (Table 2) developed (Figs. 3, 4, 5C and 6E).

4.3. Sequence 3

S3 corresponds to the upper part of the Las Flores Formation and the lower Koluel-Kaike Formation (following Krause et al., 2017) (Figs. 3, 4, 5F, and 6D). The contact (SB3) between S2 and S3 is only recorded in the western North Flank (Las Flores area and Cerro Blanco; Figs. 1B, 5F and 6D) and the south of the South Flank of the basin (Laguna Manantiales; Figs. 1B and 5C), where is defined by the occurrence of very strongly developed Ultisol-like paleosol with a plinthitic horizon (Raigemborn et al., 2018) or equivalents (Table 2 and Figs. 3, 4, 5C, 6D, F).

Overlying this paleosol surface, the LAST3 is represented by c. 5 to 30 m of mainly volcaniclastic fine-grained deposits (TMb, TSm, and TSt facies; see an explanation of these codes in Table 1) corresponding to unconfined (i.e., sheet-flood, FA3, Table 1) and confined (i.e., low hierarchy fluvial channels, FA6, Table 1). Such levels transition to the HAST3 deposits, represented by tephric loessites (TMm facies, FA7; see an explanation of these codes in Table 1), and shallow ponded areas (TMl facies, FA8; see an explanation of these codes in Table 1) (Krause et al., 2010, 2017; Raigemborn et al., 2018 a, b) (Figs. 3, 4 and 5C). LAST3 and HAST3 deposits show pedogenic modification (Fig. 5C), which at western North Flank (Las Flores area–Cerro Blanco) and South Flank (Río Deseado area–Cañadón Lobo) presents a vertical trend from very weakly developed paleosols to very strongly developed ones, and that upwards the trend is reversed (Table 2; see a discussion about this trend in Krause et al., 2010 and Raigemborn et al., 2018a).

4.4. Sequence 4

Similarly to the Sequence 3, the contact between S3 and S4 is only evident towards the west of the North Flank (Las Flores area and Cerro Blanco; Fig. 1B) and the south of the South Flank (Río Deseado area and Cañadón Lobo; Fig. 1B). SB4 (Figs. 4 and 6D) is characterized as a non-erosive discontinuity related to long-time pedogenesis, and it is defined by the presence of very strongly developed paleosols (Ultisol-like paleosols with plinthitic horizon and equivalents; Table 2) weathered on top of fine-grained volcaniclastic beds (TMm facies; see an explanation of this code in Table 1) of tephric loessites of the HAST3 (FA7; Table 1) (Fig. 4).

Overlying this surface, the LAST4 (Fig. 4) is represented by a succession of c. 5 to 30 m of fine-grained volcaniclastic beds (TMm, TSm, and TMl facies; see an explanation of these codes in Table 1) that correspond to sheet-flood deposits, tephric loessites, and shallow ponded areas (FA3, FA6, and FA7, respectively; see Table 1) (Krause et al., 2010, 2017; Raigemborn et al., 2018 a, b). Frequently, these levels are modified by pedogenesis into weakly developed paleosols (Table 2).

The HAST4 (Fig. 4) is represented by c. 60 m of pedogenically modified whitish tuffaceous deposits of the Gran Barranca Member (Lower Sarmiento Formation), which cover in gradational contact to the underlying Koluel-Kaike Formation (Bellosi, 2010a, b; Krause et al., 2010, 2017; Raigemborn et al., 2010) (Fig. 6F). These deposits correspond to tephric loessites and ephemeral ponded areas over which very weakly to weakly developed paleosols were formed (Bellosi, 2010a, b; Bellosi and González, 2010; see Fig. 20.3 in Bellosi and González, 2010). These deposits are overlaid by the strongly developed Aridisol-like paleosol with calcic horizon (Table 2) of the Rosado Member. The top of this paleosol was assigned to a high hierarchy by Bellosi (2010b), representing a sequence boundary (SB5; Fig. 4) that involved prolonged subaerial exposure and pedogenesis.

5. Discussion

Fluvial systems respond to allogenic controls such as base level, climate, tectonics, basin subsidence, and volcanic supply modifying the basin-fill architecture (e.g., Wright and Marriott, 1993; Shanley and McCabe, 1994 Paredes et al., 2007; Amorosi et al., 2017, among others) at low frequencies (10^4–10^6 yr) (e.g., Miall, 1996). Changes in the fluvial architecture of the Río Chico Group in the northeast of the GSJB, based on outcrops and subsurface data, have been associated with variations in aggradation, accommodation, and subsidence rates. Although Foix et al. (2013, 2015) have highlighted the role of tectonics as a primary control on sedimentation, Raigemborn et al. (2014, 2018a) have also pointed out the role of climate and volcanic input as controlling factors.

Spatio-temporal changes in the fluvial architecture of the Río Chico Group in the eastern realm of the GSJB are here recognized (see Fig. 3). In this paper, the early Paleocene–middle Eocene deposits were grouped in four depositional sequences (S1–S4). Part of these sequences occur as fining-upwards fluvial successions that are pedogenically modified on top by strongly-developed paleosols (e.g., Alfisol-like paleosols at the top of the Las Violetas Formation at Estancia Las Violetas), or they are erosively overlain by the coarse-grained base of the following sequence without the development of well-developed paleosols (e.g., lower Las Flores Formation at Las Flores area).

Non-marine sequence bounding unconformities record null to negative accommodation/sediment supply rate (A/S ratio), and are defined as regional surfaces of non-deposition and associated subaerial erosion, marking an abrupt change in channel/floodplain ratio or recorded as strongly-developed or mature paleosols that can be traced laterally on a broad scale (e.g., Wright and Marriott, 1993). Sequence boundaries (SB) can be placed at the top of these paleosols because they represent a hiatus in sedimentation and the pedogenic modification of the depositional surface (e.g., Di Celma et al., 2015). Within the analyzed units, five sequence boundaries (SB1–SB5) were recognized (see Fig. 4), two of them related to fluvial incision (SB1 and SB2) and the remaining three related to mature paleosols (SB3, SB4, and SB5), and can be described as follows. On a regional scale, the SB1 is an erosional surface that separates the coastal swamp deposits of the Banco Negro Inferior (upper Salamanca Formation) from the fluvial ones of the lower Río Chico Group (Las Violetas/Peñas Coloradas formations) (see Fig. 4). This unconformity records a landward shift in depositional environments and, following Clyde et al. (2014), a gap of c. 1 my in the stratigraphic record. Clyde et al. (2014) and Comer et al. (2015) correlated this erosional surface with a eustatic sea-level fall. This unconformity has a variable erosional relief on underlying strata that at Rocas Coloradas area reaches its maximum of 8 m. However, there is no evidence of the development of incised valleys. In the here analyzed area, the SB2 is a regionally extended erosional surface that has a lower relief of 2–3 m. It occurs between the upper deposits of the Salamanca Formation (Banco Verde–Banco

Negro Inferior) or the lower ones of the Río Chico Group (Las Violetas or Peñas Coloradas formations) and the fluvial beds of the Las Flores Formation (see Fig. 4). Krause et al. (2017) point out that this surface could have been caused by an erosive event related to a global eustatic fall near the Paleocene-Eocene boundary. On the other side, SB3, SB4, and SB5 are related to very strongly-developed paleosols, which features suggest long geomorphological stability, subaerial exposure and pedogenesis under warm and seasonal humid climatic conditions for SB3 and SB4 (Krause et al., 2010, 2017; Raigemborn et al., 2018a, b), and semi-arid to arid and temperate climatic conditions for the SB5 (Bellosi and González, 2010). The Río Chico Group was deposited in coincidence with the Early Paleogene Greenhouse World (e.g., Raigemborn et al., 2009, 2014, 2018a), during which two hyperthermal events and several thermal events took place (Zachos et al., 2001, 2008). The change from Ultisol-like paleosols with plinthitic horizon and equivalents paleosols (SB3 and SB4) to Aridisol-like paleosols with calcic horizon (SB5) could reflect the transition from greenhouse to icehouse world, which establishes at the Eocene-Oligocene boundary. Stratigraphic correlation of the very strongly developed paleosols of the middle part of the Las Flores Formation over distances of hundreds of kilometers (see Las Flores area and Laguna Manantiales in Fig. 1B) and across different fluvial/alluvial domains suggests an external forcing on paleosols development. Climate and a low base level were probably the main allogenic controlling factors. Krause et al. (2017) and Raigemborn et al. (2018b) suggested a link between these mature paleosols with the early Eocene Climate Optimum (51–53 Ma; Zachos et al., 2008). Similarly, stratigraphic correlation of strongly and very-strongly developed paleosols of the Koluel-Kaike Formation over hundreds of kilometers (see Las Flores area, Río Deseado area, Cañadón Lobo, and Laguna Manantiales in Fig. 1B), point in the same direction. Thus, the lateral persistence of these paleosols types (Ultisol- and Ultisol-like paleosols with plinthitic horizon) suggests similar spatial climate conditions.

Changes in sediment supply to the fluvial/alluvial systems can be controlled by both river dynamics and by climate conditions that influence the vegetation cover on the slopes and their erosion (e.g., Di Celma et al., 2015; Opluštil et al., 2015). Colder and drier conditions could led to the formation of low-accommodation system tracts when rates of sediment supply are high and accommodation space is low; whereas warmer and wetter conditions allow the development of high-accommodation system tracts, when rates of generation of accommodation space are higher than sediment supply rates. Within the studied HAST´s, several paleosols with very weak to weak degree of development or immature paleosols were developed, representing short intervals of landscape stability ($<10^2$–10^3 yr; Raigemborn et al., 2018a). These paleosols types might represent the effect of climatic variations, with successive short-time spans of soil development alternating with periods of geomorphological instability, aggradation phases with continuous and rapid deposition (e.g., Marriott and Wright, 1993; Amorosi et al., 2017; Raigemborn et al., 2018a).

At a sequence scale, fluvial/alluvial architecture reflects changes in accommodation space. Sequences are represented at their base by braided or laterally amalgamated fluvial channels with null o very low preservation of fine-grained floodplain deposits (LAST´s), which become ribbon-like channel beds encased in fine-grained floodplain deposits and finally only floodplain deposits, with no channel development (HAST´s). The contact between the LAST and the HAST represents a surface in which a change in fluvial style takes place. This surface (or zone) of change could represent the expansion surface of Martinsen et al. (1999) that can be correlated with the maximum regression surface. This stratigraphic pattern reflects increasing accommodation space, with pedogenesis mainly occurring during high-accommodation system tracts. At a basinal scale, the vertical changes in the degree of development or maturity of the paleosols observed within the early Cenozoic deposits of the eastern GSJB (see Fig. 4) are consistent with the regional accommodation trends.

In the northern area of the GSJB, particularly in the Las Violetas Formation, a strong volcaniclastic component is recorded; meanwhile, its lateral equivalent, the Peñas Coloradas Formation, is predominately epiclastic in composition (Raigemborn, 2006; 2008). The architectural features indicate relatively low aggradation rate conditions and a relatively high volume of sediment supply (low A/S ratio), which in the case of the Las Violetas Formation, was mainly volcaniclastic (Raigemborn, 2008). This high sediment supply of volcaniclastic material for the Las Violetas Formation was probably provided by the erosion of the lower Paleocene basalts that crop out near to the Estancia Las Violetas section, and which could act as a local source area, as was mentioned by Foix et al. (2013). Volcaniclastic supply also increased during the Río Chico Group–lower Sarmiento Formation deposition, accompanied by a compositional change in the volcaniclastics, from basic to acid (Raigemborn, 2008; Raigemborn et al., 2018a). Raigemborn et al. (2018a and cited herein) point out that volcaniclastic material of the Koluel-Kaike Formation generated at the Pilcaniyeu Volcanic Belt and caldera field of this belt, 300–400 km to the northwest of the analyzed sections.

Facies distribution and fluvial architecture of the Río Chico Group also reflect spatial accommodation variability in the basin. Thick, amalgamated coarse-grained intervals formed during low-accommodation conditions in the basin margins (e.g., Estancia Las Violetas); meanwhile, more isolated, ribbon-shaped sandy bodies are defined as lateral equivalents towards the west and south of the basin. Foix et al. (2013, 2015) indicated that Puerto Visser locality, a site between Estancia Las Violetas and Rocas Coloradas area (Fig. 1B), would represent a break-point in the stratigraphic architecture of the unit at the northeastern North Flank of the GSJB, separating two settings of variable accommodation rates. Northwards Puerto Visser, the width/thick ratio of sandy bodies and the channel/floodplain ratio increases; meanwhile, towards the south, an increase in total thickness of the Río Chico Group and accommodation is demonstrated by Foix et al. (2013, 2015). These authors assumed that climate conditions were stable during times of the Río Chico Group, and consequently, they discarded climate and sea-level changes as controls over the fluvial architecture. Therefore, they infer that significant spatial variations are due to the differential subsidence of the basin. At the same time, Gianni et al. (2017) identified evidence of syntectonic deposition in the middle/upper part of the Koluel-Kaike Formation (~ 44 Ma) in the eastern of the San Bernardo Fold Belt, which is indicative of the occurrence of Eocene intraplate tectonics in this area of the GSJB. However, we interpreted that the overall horizontal disposition of the strata of the Río Chico Group, and the lack of degradational features (i.e., incised valleys and terraces) in the study area, indicate the occurrence of flat land surfaces and negligible tectonic activity during the deposition of the unit, and that the system was mainly aggradational.

6. Final remarks and conclusions

Because changes in the relative proportion of channel and floodplain deposits respond to changes in accommodation/sediment supply rate (A/S) (e.g., Catuneanu, 2006; Beilinson et al., 2013; Foix et al., 2013, 2015; Di Celma et al., 2015, among others), we were able to internally divide sequences into low- and high-accommodation systems tract (i.e., LAST and HAST, respectively) (Fig. 4). The LASTs defined in the Río Chico Group are typically channel-dominated and formed on top of subaerial unconformities, suggesting periods of low A/S ratio. The behavior of fluvial channels under these conditions generated regional unconformities (sequence boundaries). Although some fine-grained deposits of the floodplain can be developed during this stage, they have a low probability of preservation, and consequently, only paleosols with a very strong/strong degree of development can be formed.

The temporal resolution of the Río Chico Group at the west of the eastern GSJB and the eastern of the San Bernardo Fold Belt (Clyde et al., 2014; Krause et al., 2017) in combination with this stratigraphic sequential analysis implies that at least one of the here identified stratigraphic unconformities (SB3) might have formed during the optimum climatic of the early Eocene (EECO, c. 53 to 51 Ma; Zachos et al., 2008), and that other two might have formed during the greenhouse to icehouse transition (SB4 and

SB5). These three sequence boundaries span hundreds of thousands to millions of years (10^5–10^6 yr; Bellosi, 2010b; Raigemborn et al., 2018a).

The integration of sedimentological and paleopedological analyses of the four identified sequences into the Río Chico Group–lower Sarmiento Formation in the eastern areas of the Golfo San Jorge Basin indicate that the interplay between subsidence, base level, and climate-controlled fluvial/alluvial style and landscape evolution of the units, as well as soil development. Volcaniclastic supply also played a significant role, especially during the Eocene.

Acknowledgments

Financial and logistical support for these studies was provided by the projects PIP 100523 of the CONICET and the PI+D N890 of the UNLP (to MSR). The authors would like to thank L. Gómez Peral, L. Perez, S. Lizzoli, and E. Melendi (CONICET-UNLP, Argentina) for their assistance during field trips to the South Flank. The suggestions made by the reviewers, Dr G. Basilici and one anonymous reviewer, and by the Editor Dr J.M. Paredes, greatly improved the quality of this manuscript.

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TABLES AND FIGURES

Table 1. Summary chart of the facies associations (FA) identified in the Río Chico Group.

Table 2. Summary of the most distinctive pedogenic features within the paleosols of the Río Chico Group and lower Sarmiento Formation.

Figure 1. Map showing position, boundaries, and internal division of the Golfo San Jorge Basin (A), and location of the localities included in this paper (B). The dotted line in 1B marks the boundary between the Eastern Sector of the basin and the San Bernardo Fold Belt.

Figure 2. Stratigraphic chart of the study area (eastern of the Golfo San Jorge Basin). It extends through continental (white) and marine (gray and black) successions from the early Paleocene to the late Eocene. The vertical shading indicates a hiatus. Ages for the Salamanca Formation come from Clyde et al. (2014), ages for the Río Chico Group are based on Krause et al. (2017), and ages for the lower Sarmiento Formation are following Ré et al. (2010) and Dunn et al. (2013).

Figure 3. Representative simplified measured sedimentary sections including facies associations (FA), paleosol types, fluvial styles, and lithostratigraphic units of the Eastern Golfo San Jorge Basin (modified from Raigemborn et al., 2010, 2014, 2018a and b). Facies association color bar refer to the predominantly facies association in such part of the profiles. Abbreviations: SF: Salamanca Formation, BV: Banco Verde, BNI: Banco Negro Inferior, LVF: Las Violetas Formation, PCF: Peñas Coloradas Formation, LFF: Las Flores Formation, KKF: Koluel-Kaike Formation, SMF: Sarmiento Formation, CHF:

Chenque Formation, HF: Huemul Formation, DFD: Distal floodplain-dominated, DEDFS: Distal eolian-dominated fluvial system.

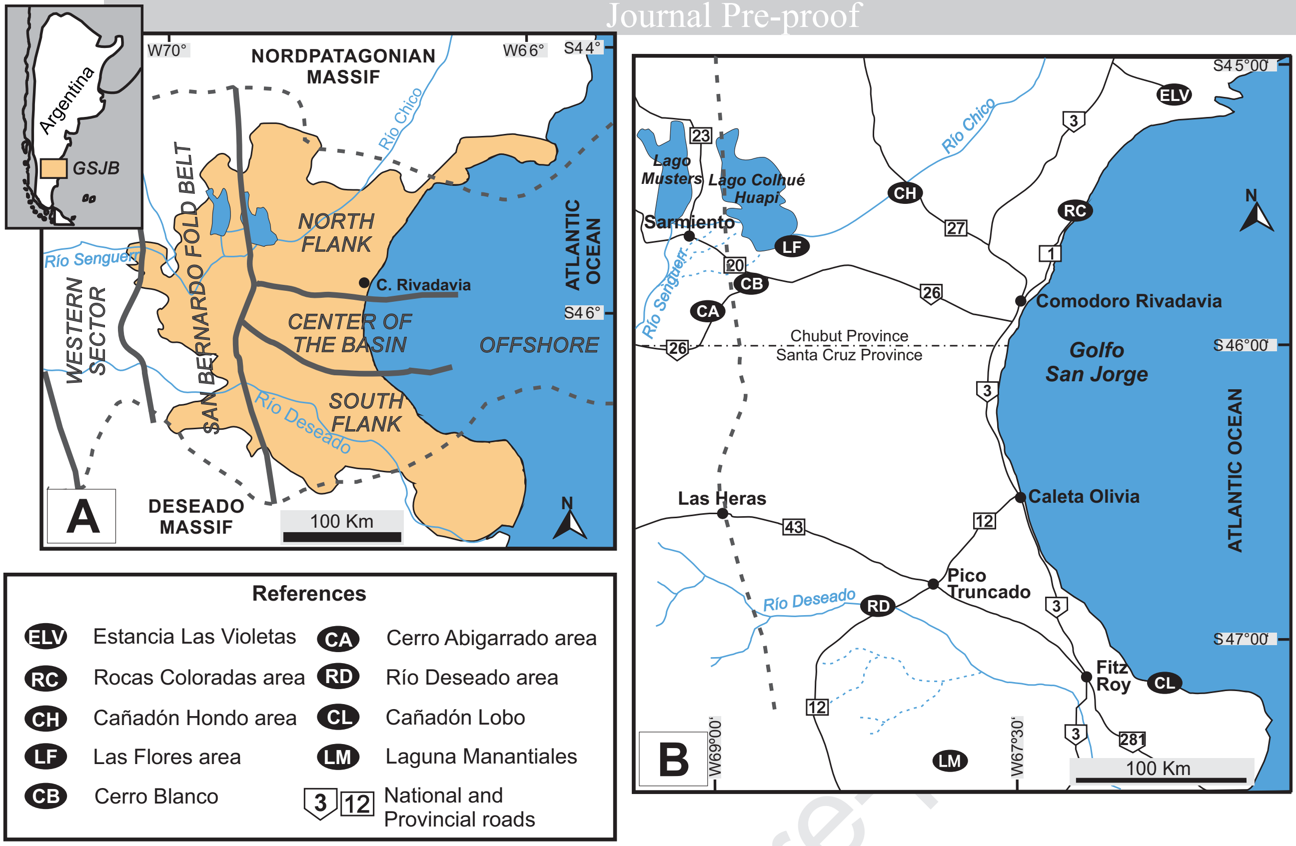
Figure 4. Schematic diagram illustrating systems tract development during the middle Paleocene–middle Eocene in the GSJB. Spatial variations in fluvial architecture and paleosol development between the North Flank and the South Flank are also depicted, as well as the correlation between the lithostratigraphic units and the sequences here-by proposed. In the references box: HAST; high-accommodation systems tract; LAST; low-accommodation systems tract; SB: sequence boundary.

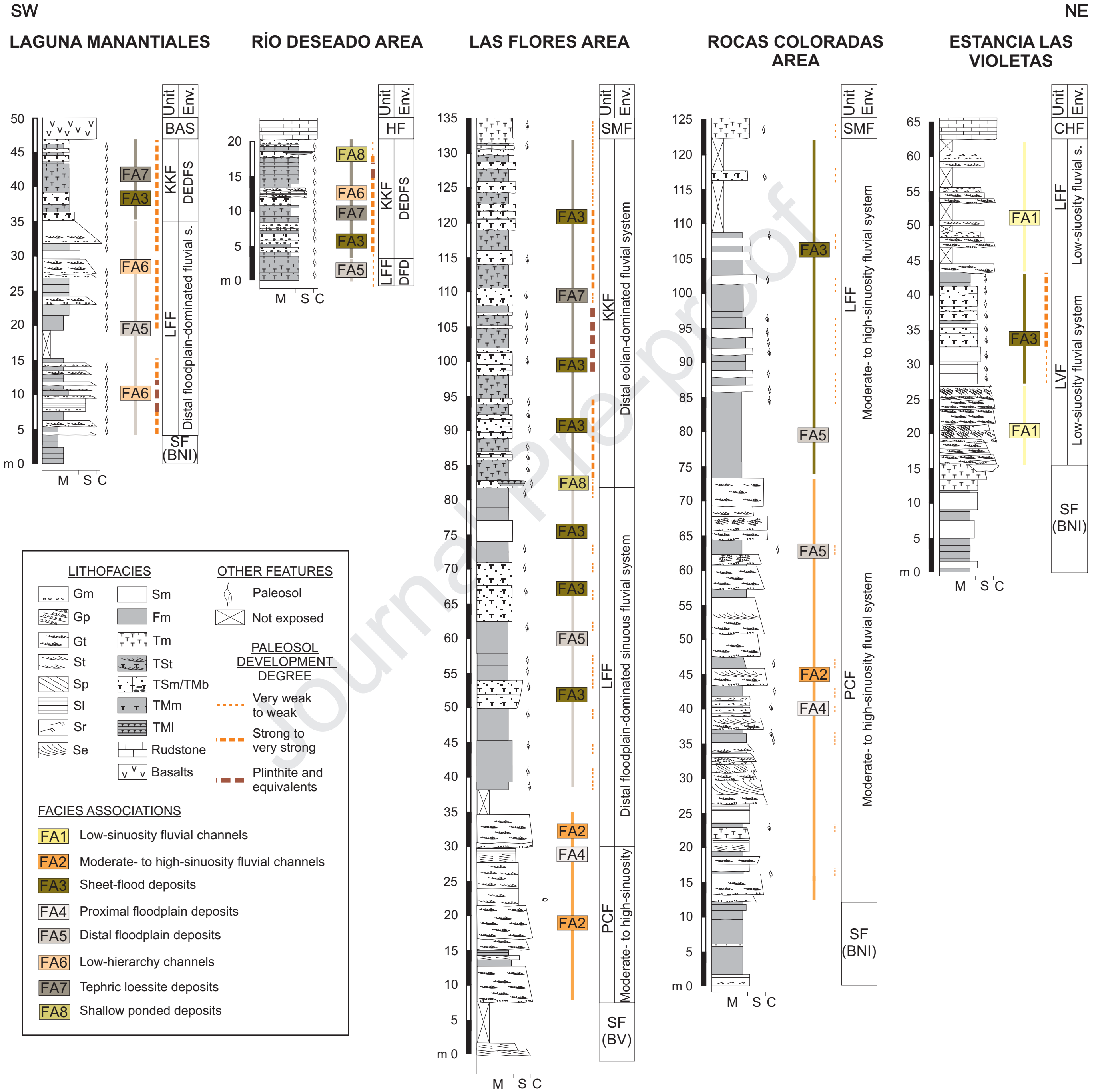
Figure 5. Representative outcrops of the Eastern Golfo San Jorge Basin showing different systems tracts (LAST and HAST) and sequence boundaries (SB). A: SB1 eroded upper deposits of the Salamanca Formation (SF), followed by the LAST1 and the HAST1 (LVF: Las Violetas Formation) at Estancia Las Violetas. The arrow marks the beginning of the HAST1, and the thin white line signals the contact with the Chenque Formation. B: SB1 developed over the upper deposits of the Salamanca Formation (SF) following by the LAST1 and the HAST1 (PCF: Peñas Coloradas Formation) at Cerro Abigarrado area. The arrow marks the beginning of the HAST1. The bar for scale is equivalent to 6 m. C: Irregular and erosional surface (SB2) separating the upper deposits of the Salamanca Formation (SF) from the overlying LAST2 and HST2 pedogenically modified of the Las Flores Formation (LFF), which are followed (SB3) by the pedogenically modified LAST3-HAST3 deposits of the upper Las Flores Formation and Koluel-Kaike Formation (KKF) at Laguna Manantiales. The gray

arrow indicated the position of the very strongly developed paleosols that defined the position of the SB3, and the thin white line indicates the contact with overlying late Eocene basalts. The person as scale in the circle is ~1.60 m height. D: Erosive and irregular surface (SB2) separating HAST1 deposits of the Peñas Coloradas Formation (PCF) from the LAST2 deposits of the Las Flores Formation (LFF) at Rocas Coloradas area. The bar for scale is equivalent to 10 m. E: Highly irregular and erosive surface (SB2) between the HAST1 (PCF: Peñas Coloradas Formation) and the LAST2 (LFF: Las Flores Formation) at Las Flores area. The person as scale, in the upper-left corner, is ~1.80 m height. F: HAST2 deposits of the Las Flores Formation (LFF) with very weak to weak developed paleosols and pedogenically modified lower Koluel-Kaike Formation (KKF), LAST3–HAST3 deposits of the middle-upper KKF represented by strongly-developed stacking paleosols that upwards changes to weakly developed ones, and the Sequence Boundary 3 (SB3) at the top of laterite-like paleosols (lower KKF) at Las Flores area. SMF: Sarmiento Formation. The bar for scale is equivalent to ~50 m.

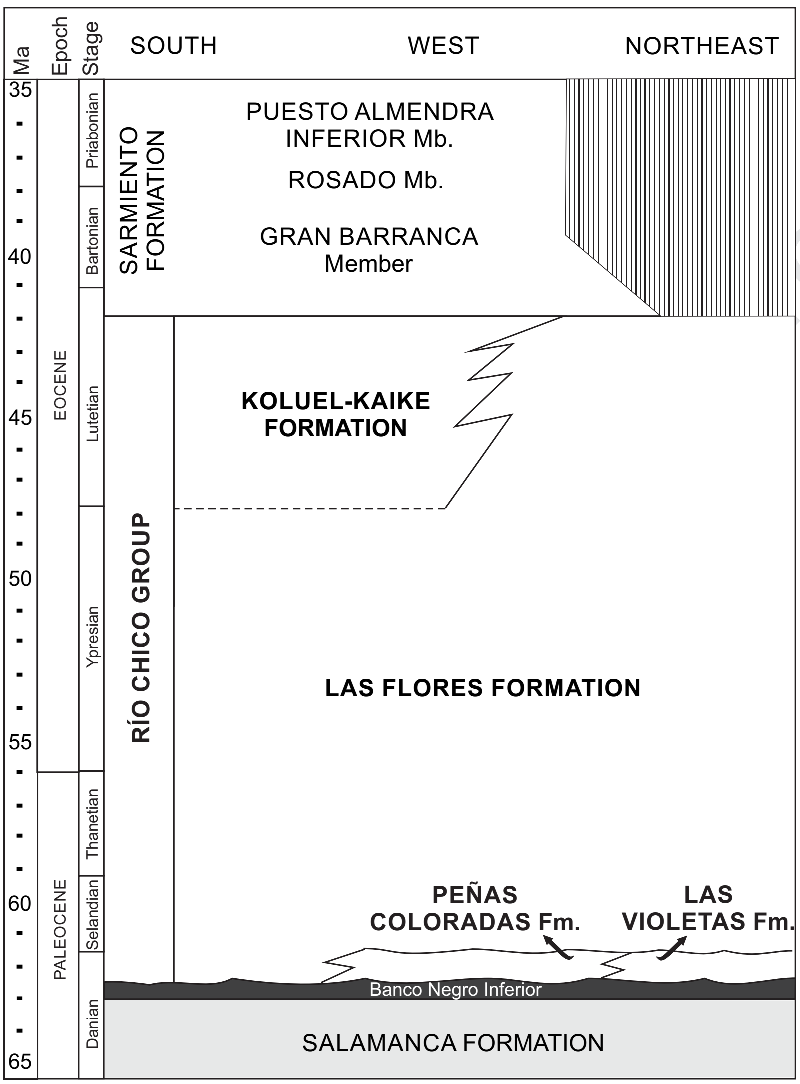
Figure 6. Characteristic paleosol types, considering their degree of development, at the Eastern Golfo San Jorge Basin. A: Stacking of weakly to strong developed paleosols (Inceptisol-like and Alfisol-like paleosols) in the HAST 1 (Las Violetas Formation) at Estancia Las Violetas. B: Very weakly developed paleosol (Entisol-like) in the HAST1 (Peñas Coloradas Formation) at Rocas Coloradas area. C: Paleosol with weak degree of development (Inceptisol-like) at HAST2 (Las Flores Formation) at Las Flores area. D: Very strongly developed paleosols at the middle-upper Las Flores Formation (LFF)

that defined the Sequence Boundary 3 (SB3) at Cerro Blanco. SB4 is at the top of very strongly developed paleosols, signed with an arrow at the lower Koluel-Kaike Formation (KKF). Persons as scale in the circle are ~1.80 and 1.60 m height, respectively. E: Strongly developed paleosols (Ultisol-like) in the HAST2 (Las Flores Formation) at Laguna Manantiales. F: Very strongly developed paleosols (Plinthite-like) of the Sequence Boundary 4 (Koluel-Kaike Formation) at the Río Deseado area. The person as scale is ~1.70 m height.

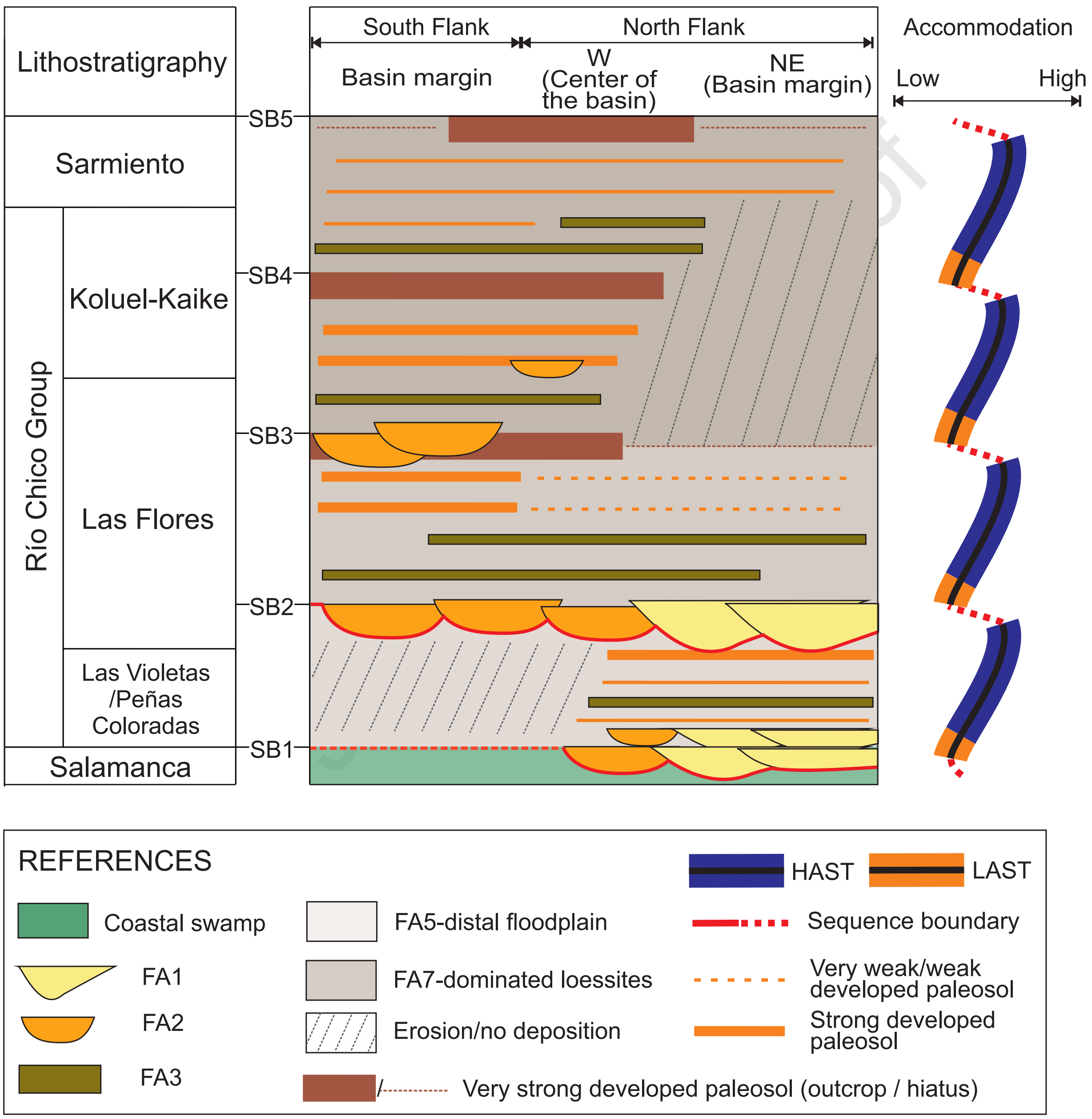

Argentina
GSJB
W70°
W66°
S44°
S46°
NORDPATAGONIAN MASSIF
Río Chico
Río Senguerr
NORTH FLANK
C. Rivadavia
ATLANTIC OCEAN
CENTER OF THE BASIN
OFFSHORE
SOUTH FLANK
Río Deseado
SAN BERNARDO FOLD BELT
WESTERN SECTOR
DESEADO MASSIF
100 Km
N
A
References
ELV Estancia Las Violetas
RC Rocas Coloradas area
CH Cañadón Hondo area
LF Las Flores area
CB Cerro Blanco
CA Cerro Abigarrado area
RD Río Deseado area
CL Cañadón Lobo
LM Laguna Manantiales
3 12 National and Provincial roads
S45°00'
S46°00'
S47°00'
W69°00'
W67°30'
Lago Musters
Lago Colhué Huapi
Sarmiento
Río Chico
Río Senguerr
Comodoro Rivadavia
Golfo San Jorge
Chubut Province
Santa Cruz Province
Las Heras
Caleta Olivia
Pico Truncado
Río Deseado
Fitz Roy
ATLANTIC OCEAN
100 Km
B



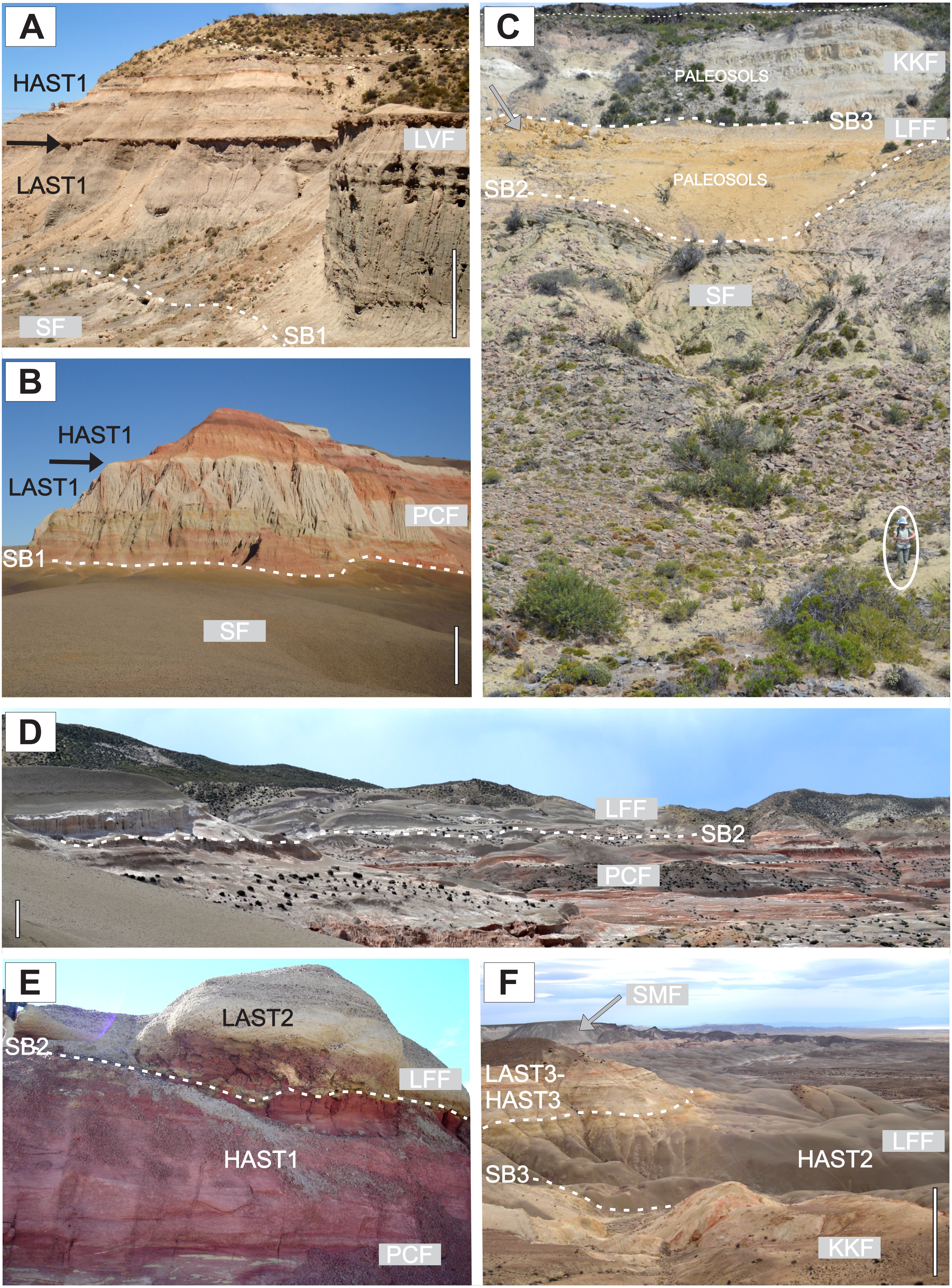
SW
NE
LAGUNA MANANTIALES
RÍO DESEADO AREA
LAS FLORES AREA
ROCAS COLORADAS AREA
ESTANCIA LAS VIOLETAS
Unit
Env.
BAS
KKF
DEDFS
LFF
Distal floodplain-dominated fluvial s.
SF (BNI)
HF
DFD
SMF
Distal eolian-dominated fluvial system
Distal floodplain-dominated sinuous fluvial system
PCF
Moderate- to high-sinuosity
SF (BV)
Moderate- to high-sinuosity fluvial system
CHF
Low-sinuosity fluvial s.
LVF
Low-siuosity fluvial system
FA1
FA2
FA3
FA4
FA5
FA6
FA7
FA8
m 0
M
S
C
LITHOFACIES
Gm
Gp
Gt
St
Sp
Sl
Sr
Se
Sm
Fm
Tm
TSt
TSm/TMb
TMm
TMl
Rudstone
Basalts
OTHER FEATURES
Paleosol
Not exposed
PALEOSOL DEVELOPMENT DEGREE
Very weak to weak
Strong to very strong
Plinthite and equivalents
FACIES ASSOCIATIONS
FA1 Low-sinuosity fluvial channels
FA2 Moderate- to high-sinuosity fluvial channels
FA3 Sheet-flood deposits
FA4 Proximal floodplain deposits
FA5 Distal floodplain deposits
FA6 Low-hierarchy channels
FA7 Tephric loessite deposits
FA8 Shallow ponded deposits

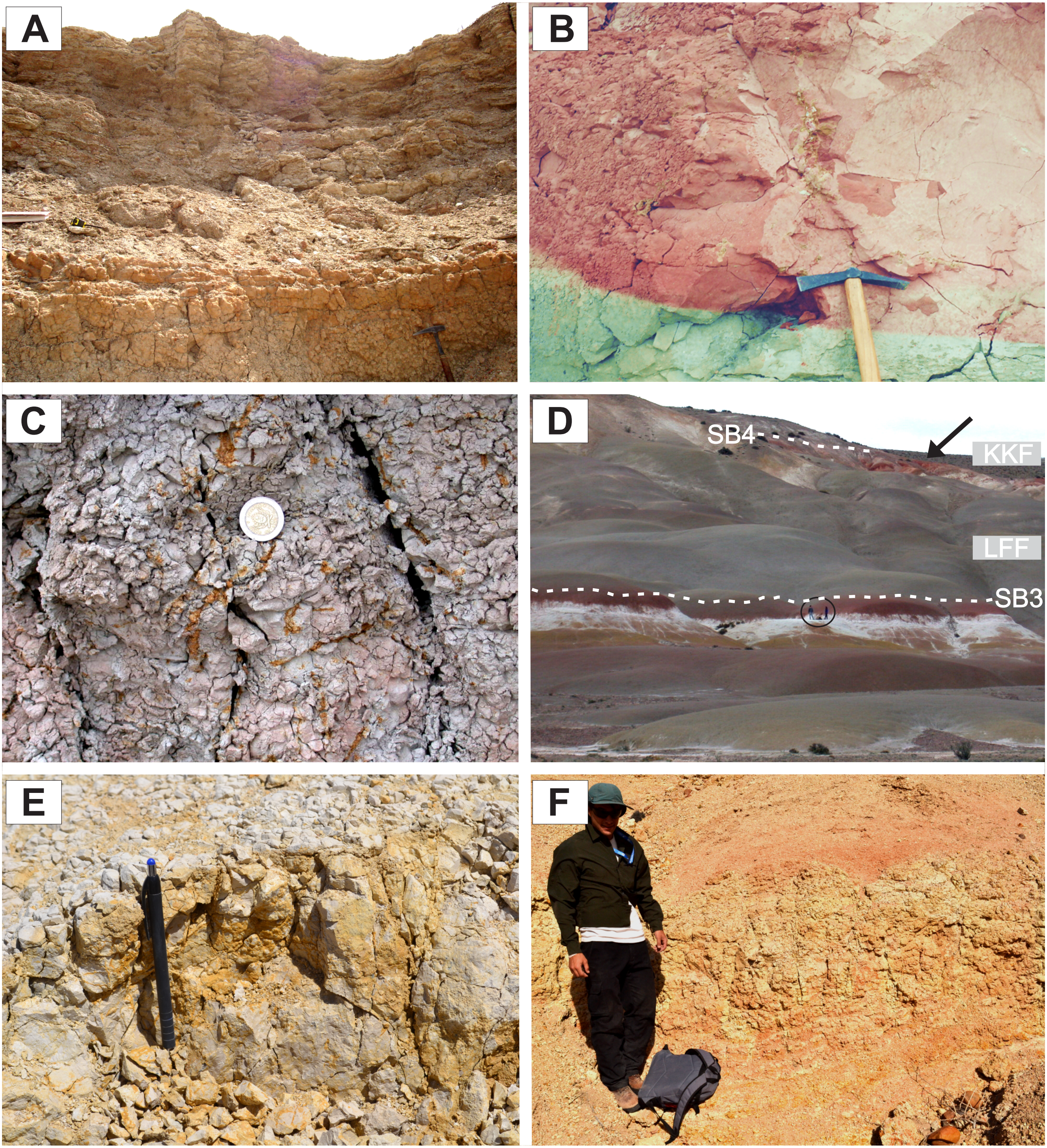


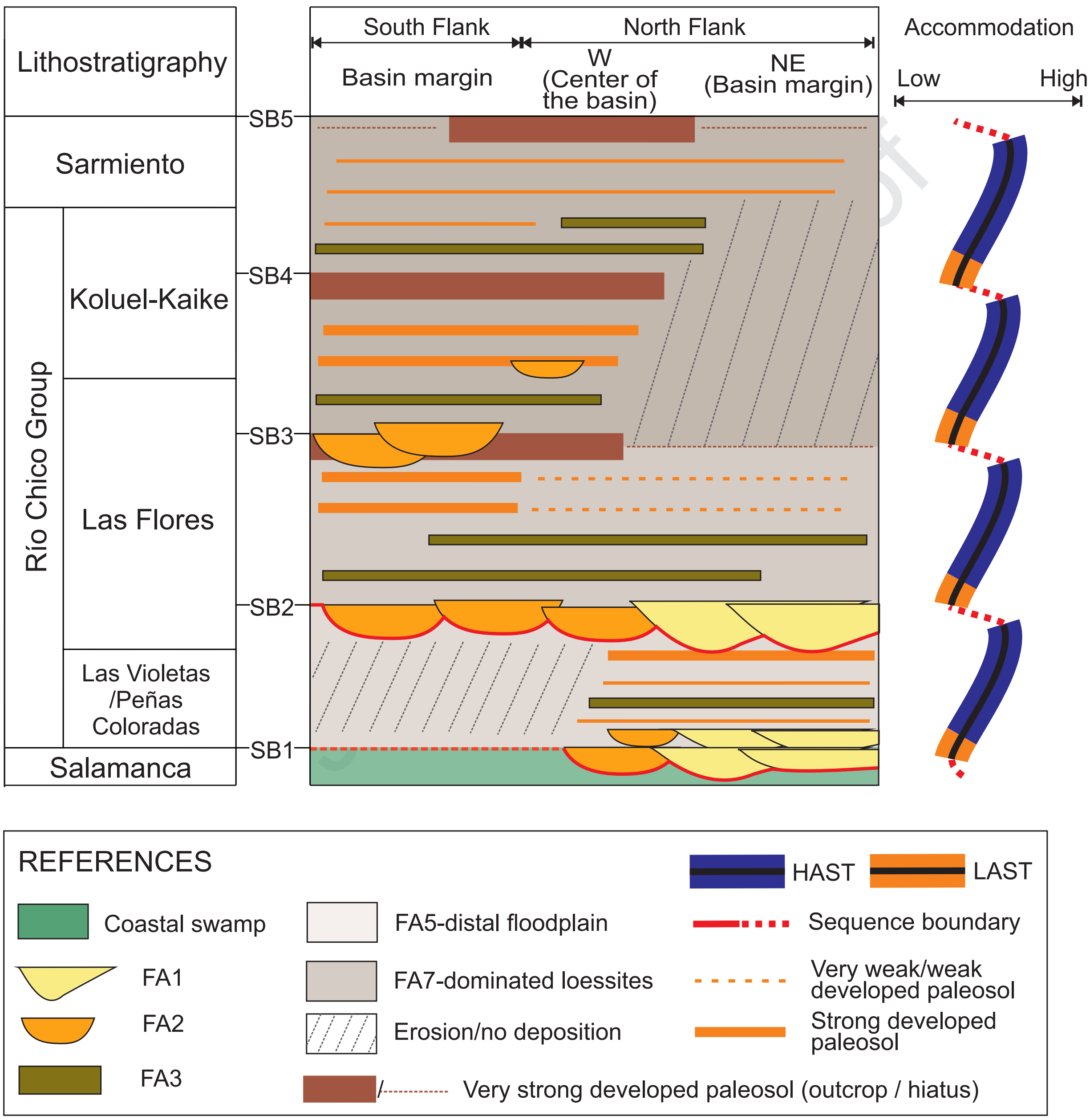
Ma
Epoch
Stage
SOUTH
WEST
NORTHEAST
35
40
45
50
55
60
65
EOCENE
PALEOCENE
Priabonian
Bartonian
Lutetian
Ypresian
Thanetian
Selandian
Danian
SARMIENTO FORMATION
PUESTO ALMENDRA INFERIOR Mb.
ROSADO Mb.
GRAN BARRANCA Member
RÍO CHICO GROUP
KOLUEL-KAIKE FORMATION
LAS FLORES FORMATION
PEÑAS COLORADAS Fm.
LAS VIOLETAS Fm.
Banco Negro Inferior
SALAMANCA FORMATION



Lithostratigraphy
Sarmiento
Río Chico Group
Koluel-Kaike
Las Flores
Las Violetas /Peñas Coloradas
Salamanca
SB5
SB4
SB3
SB2
SB1
South Flank
North Flank
Basin margin
W (Center of the basin)
NE (Basin margin)
Accommodation
Low
High
REFERENCES
Coastal swamp
FA1
FA2
FA3
FA5-distal floodplain
FA7-dominated loessites
Erosion/no deposition
HAST
LAST
Sequence boundary
Very weak/weak developed paleosol
Strong developed paleosol
Very strong developed paleosol (outcrop / hiatus)


A
HAST1
LAST1
LVF
SF
SB1
B
HAST1
LAST1
PCF
SB1
SF
C
KKF
PALEOSOLS
SB3
LFF
PALEOSOLS
SB2
SF
D
LFF
SB2
PCF
E
LAST2
SB2
LFF
HAST1
PCF
F
SMF
LAST3-
HAST3
LFF
HAST2
SB3
KKF


A
B
C
D
SB4
KKF
LFF
SB3
E
F



Lithostratigraphy
Sarmiento
Río Chico Group
Koluel-Kaike
Las Flores
Las Violetas /Peñas Coloradas
Salamanca
SB5
SB4
SB3
SB2
SB1
South Flank
North Flank
Basin margin
W (Center of the basin)
NE (Basin margin)
Accommodation
Low
High
REFERENCES
Coastal swamp
FA1
FA2
FA3
FA5-distal floodplain
FA7-dominated loessites
Erosion/no deposition
Very strong developed paleosol (outcrop / hiatus)
HAST
LAST
Sequence boundary
Very weak/weak developed paleosol
Strong developed paleosol

Highlights

- Paleogene infill of the GSJB can be divided into 4 sequences.
- Sequence boundaries are related to fluvial incision or to mature paleosols.
- Mature paleosols reflect the transition from greenhouse to icehouse world.
- Accommodation space, base level and climate controlled system tracts evolution.
- Subsidence rates controlled fluvial architecture spatial variability.

Table 1: Sumary chart of the facies associations identified in the Río Chico Group

Facies Association (FA)	Facies	Lithology	Color	Sedimentary features and paleosol type
Low-sinuosity fluvial channels (FA1)	Gm , Gt, Gp, Sm, St, Sp	Massive (Gm), trough cross-stratified (Gt) and planar cross stratified (Gp) tuffaceous conglomerates; and massive (Sm), trough cross-stratified (St) and planar cross stratified (Sp) coarse-grained to medium-grained sandstones with pumiceous clasts or intraclast	Greenish to grayish	Multiple and mobile channels
Moderate- to high-sinuosity fluvial channels (FA2)	Gm, Gt, St, Sp, Se, Sl	Massive (Gm) and trough cross-stratified (Gt) conglomerates; and trough cross-stratified (St), planar cross-stratified (Sp), epsilon cross-bedding (Se) and low-angle cross-stratified (Sl) coarse to medium-grained sandstones	Whitish or grayish to yellowish and pinky	Lateral and vertical amalgamation, large-scale inclined surfaces
Sheet-flood deposits (FA3)	Sm, Fm, TSm, TMb, TMm	Massive fine-grained sandstones (Sm), massive mudstones (Fm), massive tuffaceous sandstones (TSm), massive tuffaceous mudstones with intraclast at the base (TMb) and massive tuffaceous mudstones (TMm)	Gray to yellowish-orangy	Tabular bodies, internally ungraded, erosive bases. Entisol-, Andisol-, Inceptisol-, Alfisol-, Ultisol, Ultisol-like paleosols with plinthitic horizon
Proximal floodplain deposits (FA4)	St, Sm, Sr, Sl	Trough cross-stratified (St), massive (Sm), ripple cross stratification (Sr) and laminated (Sl) medium- to fine-grained sandstones	Pinky to reddish	Crevasse splays and channel deposits. Entisol-like paleosols
Distal floodplain deposits (FA5)	Fm, Fl, TMm, Tm	Massive (Fm) and laminated (Fl) very fine-grained sandstones to mudstones, and massive to laminated very fine-grained tuffaceous sandstones to mudstones (TMm), massivevery fine-grained tuffs (Tm)	Gray and white to pinky	Tabular bodies, great lateral extension. Entisol-, Andisol-, Inceptisol-, Ultisol-like paleosols
Low-hierarchy fluvial channels (FA-6)	TSt	Very poorly-preserved trough cross-bedding very fine-to fine-grained tuffaceous sandstones with intraclasts at the base (TSt)	White and light brown	Ribbon shaped bodies, single and low-sinusity channels, laterally stables. Ultisol-, Ultisol-like paleosols with plinthitic horizon
Loessites (FA7)	TMm	Massive tuffaceous siltstones (TMm)	White, light gray and pale brown	Massive, broad sheets. Entisol-, Andisol-, Ultisol-, Ultisol-like paleosols with plinthitic horizon
Shallow ponded areas (FA8)	TMl	Poorly-preserved plane-parallel lamination to laminated tuffaceous siltstones-mudstones (TMl)	White to very pale brown	Narrow lenticular bodies. Andisol-, Inceptisol-like paleosols

Table 2: Summary of the most distinctive pedogenic features within the paleosol in the study area

Degree of development	Paleosol type	Main pedofeatures	Lithostratigraphyc unit and Locality of occurrence	Author
Very weak and weak	Entisol-like	[1,2]Rhizoliths, burrows, Fe-nodules, mottles, slickensides; [3]Burrows, relict primary stratification	LFF (Rocas Coloradas area)[1,2]; KKF (Río Deseado area)[3]	[1,2]Raigemborn et al. (2009b) and Krause and Piña (2012); [3]Raigemborn et al. (2018a)
	Andisol-like	[1]Rhizoliths, burrows, granular structure, Mn-nodules	KKF (Las Flores area)[1]	[1]Krause et al. (2010a)
	Inceptisol-like	[1]Rhizoliths, Fe-nodules, mottles; [2,3]Rhizoliths, Fe-nodules, mottles, slickensides; [4]Blocky structure, rhizoliths, slickensides; [5]Rhizoliths, slickensides, Fe-nodules, Mn-nodules, platy structure	LVF (Estancia Las Violetas)[1]; PCF and LFF (Cerro Abigarrado and Las Flores area)[2,3]; LFF (Cerro Blanco)[4]; KKF (Río Deseado area)[5]	[1]Krause et al. (2010b); [2,3]Raigemborn et al. (2009a and b); [4]Krause et al. (2017); [5]Raigemborn et al. (2018a)
Strong and very strong	Alfisol-like	[1]Rhizoliths, blocky and granular structures	LVF (Estancia Las Violetas)[1]	[1]Krause et al. (2010b)
	Ultisol-like	[1]Blocky structure, slickensides, Fe-nodules; [2]Rhizoliths, Fe-nodules, irregular mottles, Fe-cutans, slickensides, blocky structure; [3,4]Rhizoliths, slickensides, Fe-nodules, irregular mottles, Fe-cutans, blocky structure	KKF (Las Flores area)[1]; KKF (Río Deseado area)[2]; LFF and KKF (Laguna Manantiales)[3,4]	[1]Krause et al. (2010); [2]Raigemborn et al. (2018a); [3,4]Lizzoli et al. (2018) and Raigemborn et al. (2018b)
	[1,2]Oxisol-like? [3]Laterite-like [4]Plinthite-like or Ultisols with plinthitic horizon	[1,2]Rhizoliths, Fe-reticulatedl mottles, blocky structure; [3]Fe-nodules, Fe-mottles, slickensides; [4]Rhizoliths, blocky and prismatic structures, Fe/Mn-noules, slickensides, Fe-irregular and reticulated mottles	LFF (Laguna Manantiales)[1,2]; KKF (Las Flores area)[3]; KKF (Río Deseado area)[4]	[1,2]Lizzoli et al. (2018) and Raigemborn et al. (2018b); [3]Krause et al. (2010); [4]Raigemborn et al. (2018a)
	[1]Calcrete or Aridisol-like with calcrete horizon	[1]Petrocalcic horizons, rhizoliths, burrows	RM (Las Flores area)[1]	[1]Bellosi and González (2010)