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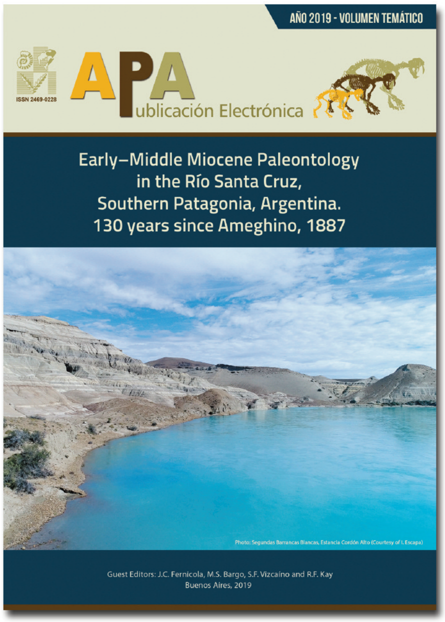

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS OF THE SANTA CRUZ FORMATION (EARLY–MIDDLE MIOCENE) ALONG THE RÍO SANTA CRUZ, SOUTHERN PATAGONIA, ARGENTINA

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Abstract. The Santa Cruz Formation is an Early–Middle Miocene terrestrial sedimentary succession widely distributed in southern Patagonia. Particularly, it is exposed along the southern margin of the Río Santa Cruz valley where the sedimentological and stratigraphical features are described for three localities. From east to west these localities are: Barrancas Blancas, Segundas Barrancas Blancas and Yaten Huageno. The facies analysis permits us to identify three associations, representing deposition in 1) low-energy floodplains; 2) crevasse splays and sheet floods; and 3) fluvial channels. The three localities are chronologically equivalent and represent accumulation in an aggradational low-gradient fluvial system that drained towards the east and northeast from the Patagonian Andes to the Atlantic sea. Abundant pedogenic features and some trace fossils are consistent with a temperate subhumid climate and in part, a grassland environment.

Key words. Burdigalian. Sedimentology. Fluvial system. Paleosol. Austral Basin.

Resumen. ESTRATIGRAFÍA Y AMBIENTES DE SEDIMENTACIÓN DE LA FORMACIÓN SANTA CRUZ (MIOCENO TEMPRANO–MEDIO) EN EL RÍO SANTA CRUZ, PATAGONIA AUSTRAL, ARGENTINA. La Formación Santa Cruz consiste en una sucesión de sedimentos continentales del Mioceno Temprano–Medio que se encuentran ampliamente distribuidos en la Patagonia austral. Se describen los atributos sedimentológicos y estratigráficos de tres localidades a lo largo del Río Santa Cruz. De este a oeste estas localidades son: Barrancas Blancas, Segundas Barrancas Blancas y Yaten Huageno. El análisis de facies permitió definir tres Asociaciones que representan acumulación en 1) planicies de inundación; 2) lóbulos de desbordamiento y crecidas en manto; y 3) canales fluviales. Las tres localidades son cronológicamente equivalentes y representan acumulación en un sistema fluvial de bajo gradiente con alta agradación, el cual drenaba hacia el este y noreste desde los Andes Patagónicos hasta la plataforma. Los rasgos de los paleosuelos, más algunas trazas fósiles reconocidas, sugieren un clima templado subhúmedo y en parte, una planicie herbácea.

Palabras clave. Burdigaliense. Sedimentología. Sistema fluvial. Paleosuelo. Cuenca Austral.

The Santa Cruz Formation (SCF) is an Early–Middle Miocene continental sedimentary succession that is distributed in a large area of southern Patagonia within the Austral-Magallanes Basin. This unit represents an important record for Burdigalian–early Langhian high-latitude paleoenvironments, paleoclimates, and terrestrial ecosystems of the Southern Hemisphere (*e.g.*, Vizcaíno *et al.*, 2012; Cuitiño *et al.*, 2019). Early expeditions along the Río Santa Cruz valley summarized by Vizcaíno *et al.* (2013) and Fernicola *et al.* (2019a) noted the abundance and diversity of terrestrial fossil vertebrates from the sedimentary strata of the valley margins; the rich collections formed the basis for the Santacrucian South American Land Mammal Age (SALMA; Pascual *et al.*, 1965; Marshall *et al.*, 1983; Fernicola *et al.*, 2014 and references therein). Currently, the stratigraphy, chronology, sedimentology and paleontology of the SCF is best known for its exposures along the Atlantic coast of southeast of the Province of Santa Cruz (*e.g.*, Tauber, 1999; Vizcaíno *et al.*, 2012; Raigemborn *et al.*, 2018a,b; Zapata, 2018; Trayler *et al.*, 2019). Only recently has interest in the SCF of the Río Santa Cruz area increased, in part prompted by the beginning of a project for the construction of two dams in the Río Santa Cruz valley and the threat of subsequent flooding of fossiliferous outcrops. This resulted in some recent scientific contributions (Fernicola *et al.*, 2014; Cuitiño *et al.*, 2016) as well as the geology, stratigraphy, taxonomy, systematics, biostratigraphy, and paleoecology results presented in this Thematic Volume.

In this contribution we present new sedimentological and stratigraphic data obtained after revisiting some of the best exposures of the SCF along the southern margin of the Río Santa Cruz valley, with two main objectives. First, we aim to reconstruct the general depositional environment for the SCF in the Río Santa Cruz valley, and to compare it to other better known exposures of the unit. Second, we aim to provide a detailed stratigraphic context for the large number of fossils collected in this area.

GEOLOGIC SETTING

The Austral-Magallanes Basin is the southernmost basin of South America (Fig. 1.1) and its sedimentary record starts in the Early Cretaceous. Three main tectonic phases can be recognized for this basin: 1) a synrift phase occurred during the Late Jurassic–Early Cretaceous; 2) a sag phase occurred during the Early Cretaceous; and 3) a retroarc foreland stage occurred during the latest Cretaceous to Cenozoic (*e.g.*, Biddle *et al.*, 1986; Sachse *et al.*, 2016). The sedimentary units outcropping in the Río Santa Cruz valley correspond to the younger part of the foreland stage and are thought to be strongly controlled by the Andean tectonics and arc volcanism (Fosdick *et al.*, 2013; Cuitiño *et al.*, 2016; Ghiglione *et al.*, 2016; Parras and Cuitiño, 2018).

The Río Santa Cruz is one of the largest rivers of Patagonia. It flows through an incised deep and broad valley stretching 230 km from west to east, which was excavated during a relative sea level fall in the Quaternary. The river originates close to the Andean foothills in the eastern margin of Lago Argentino and ends in the Río Santa Cruz estuary that discharges in the Atlantic Ocean (Fig. 1.2–3). Along the valley margins, three Miocene sedimentary units of the Austral Basin can be recognized: (1) the shallow marine Early Miocene Estancia 25 de Mayo –previously named as Centinela Formation; Cuitiño and Scasso (2010)–, (2) the Monte León Formation (Sacomani and Panza, 2011; Parras and Cuitiño, 2018), and (3) the terrestrial Early–Middle Miocene Santa Cruz Formation (Tauber *et al.*, 2008; Sacomani and Panza, 2011; Cobos *et al.*, 2014; Fernicola *et al.*, 2014; Cuitiño *et al.*, 2016). A thin veneer of terrace conglomerates of Late Miocene to Quaternary age covers most of the study area (Sacomani and Panza, 2011; Cobos *et al.*, 2014; Fig. 1).

The age of the SCF is well dated radiometrically. For the coastal zone of southeast of the Province of Santa Cruz the age of the unit is bracketed by means of Ar^{39}/Ar^{40}, high precision zircon U/Pb, and sedimentation rate estimations between ~17.8 and 16 Ma (Burdigalian; Tejedor *et al.*, 2006; Perkins *et al.*, 2012; Trayler *et al.*, 2019), whereas in the Río Santa Cruz valley the unit is dated by means of U/Pb on zircons and sedimentation rate estimations between ~17.45 and 15.6 Ma (Burdigalian–early Langhian; Cuitiño *et al.*, 2016).

Beyond the Río Santa Cruz valley, the SCF and equivalent units are distributed in a wide area within the Austral-Magallanes Basin (Fernicola *et al.*, 2014, fig. 1; Fig. 1.2). It crops out along the foothills of the Andes from the Meseta Cosmelli in Aysén (Chile) (Ugalde *et al.*, 2015; Encinas *et al.*, 2019) and Lago Posadas regions (~400 and ~300 km to the northwest, respectively), where it is time equivalent to the Río Zeballos Group (Cuitiño *et al.*, 2019; Aramendía *et al.*, in press), and south of this area up to the Río Turbio region (~200 km to the southwest; Fig. 1.2). It is also present in the central Santa Cruz Province near Gobernador Gregores and Lago Cardiel (~150 km to the north). Several good exposures occur in the southern of the Province of Santa Cruz (Fig. 1.2), including the Río Chalía (= Sheuhen) (Vizcaíno *et al.*, 2018) and the coastal zone between the Monte León National Park and the Río Gallegos estuary (Bown and Fleagle, 1993; Tauber, 1999; Matheos and Raigemborn, 2012; Raigemborn *et al.*, 2015, 2018a,b; Zapata, 2018). The southernmost counterpart for the SCF is the Cullen Formation, located

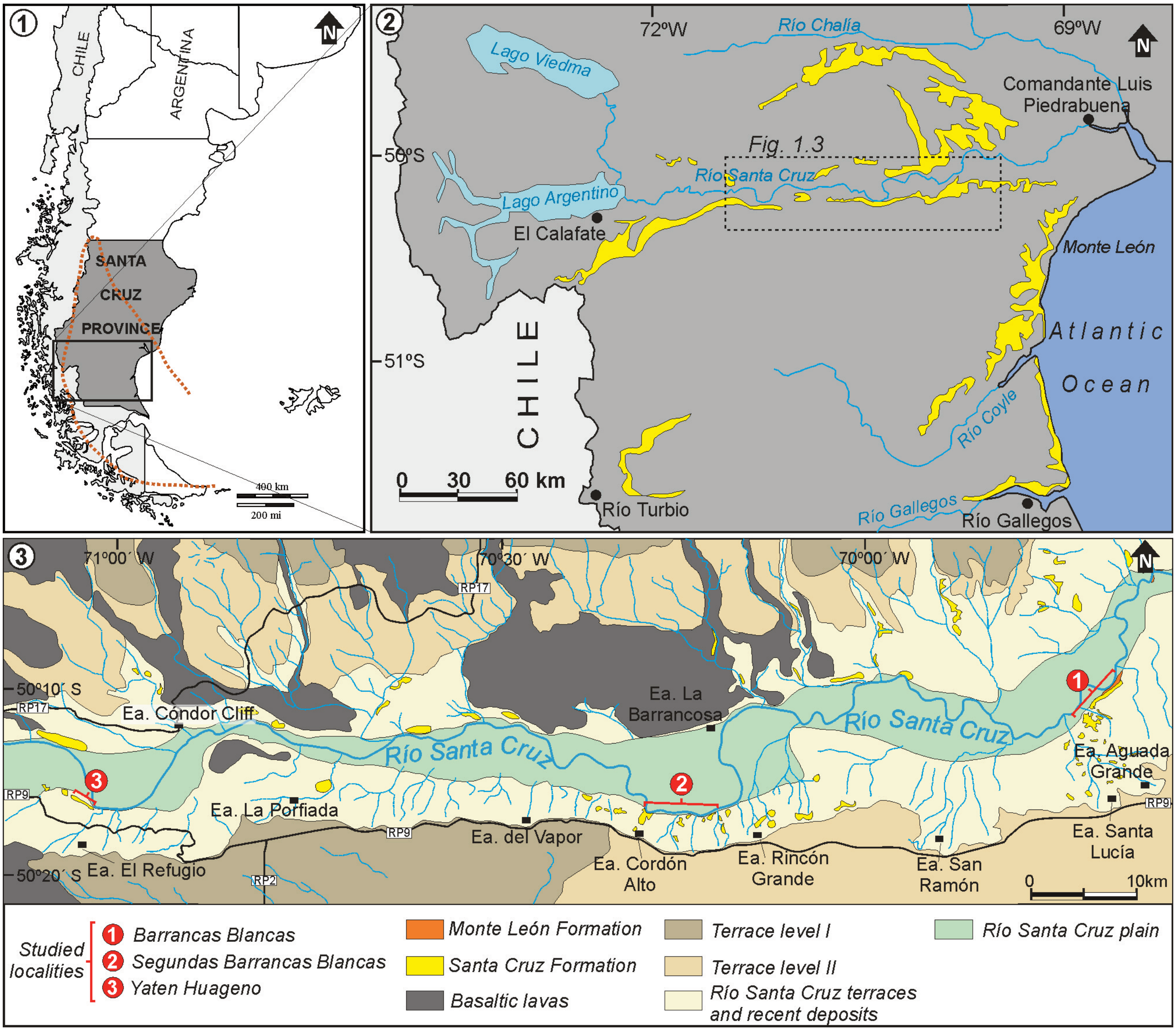

Figure 1. Geographic and geologic context for the studied outcrops. **1,** regional location map showing the position of the study area. The boundary of the Austral-Magallanes Basin is highlighted in dotted red line. **2,** Map of southern Santa Cruz province showing the distribution of the SCF outcrops (in yellow). The dashed-lined box indicates the location of the studied localities. **3,** Detailed geologic map of the Río Santa Cruz valley and the localities studied in this work. Modified after Sacomani and Panza (2011) and Cobos *et al.* (2014).

~300 km to the southeast in the northern part of the Tierra del Fuego Island (Olivero *et al.*, 2015; Bargo *et al.*, 2018).

METHODS

This work is based on data collected in the field, including stratigraphic, sedimentological, macropedological and ichnological observations. The SCF crops out in both the north and south margins of the Río Santa Cruz valley. The three main localities of the southern margin are here described, which correspond to those visited in 1887 by Carlos Ameghino, and recently revisited, as described in Fernicola *et al.* (2014), with new dates presented in Cuitiño *et al.* (2016). From east to west they are (Fig. 1.3): Barrancas Blancas, within the boundaries of the Estancia Aguada Grande (EAG) and Estancia Santa Lucía (ESL); Segundas Barrancas Blancas, in the Estancia Cordón Alto (ECA) and

Estancia El Tordillo (EET); and Yatén Huageno, in the Estancia El Refugio (Fig. 1.3).

The base and top of SCF exposures, as well as guide level elevations, were measured with conventional GPS devices taking care of recording only with the maximum available altitude accuracy. When possible, guide levels such as tuffs or distinctive yellow layers were followed in the field for several kilometers to check their validity as correlation horizons. We logged each outcrop using a Jacob Staff. Sedimentological descriptions include grain-size, primary sedimentary structures, bed thickness and geometry were noted. Paleosol macro pedofeatures noted include structure, mottles, nodules, color, slickensides, root traces, as well as body and other trace fossils (following Retallack, 2001). Colors were described according to the Geological Rock Color Chart (2009). Ages for the base and top of exposures were estimated using the available U/Pb ages and a sedimentation rate of 150 m/Ma estimated by Cuitiño *et al.* (2016), which is roughly coincident with average sedimentation rates of 158 m/Ma obtained by Trayler *et al.* (2019) for the SCF in the coastal zone by means of high precision geochronology. In addition, these values are very close to the sedimentation rate calculated by Sachse *et al.* (2016) for the times of deposition of the SCF in all the Austral Basin (170 m/Ma). Names and numerical ages for formal chronostratigraphic stages are taken from the International Chronostratigraphic Chart 2018/07.

DEPOSITIONAL ENVIRONMENTS

The sedimentological descriptions of the SCF in all the studied sections were the basis for defining a set of facies representing the main depositional processes (Tab. 1). These were grouped in Facies Associations (FAs) representing depositional sub-environments.

Table 1 – List of sedimentary facies defined in this work with their distinctive features

Facies Code	*Lithology*	*Physical Sedimentary Structures*	*Other features*	*Depositional process*
Sh	*Fine to medium sandstones, well sorted. Gray to light gray. Intraclasts and pumice common*	*Plane-parallel and low-angle lamination*	-	*Tractive deposits formed through upper flow regime plane bed*
St	*Medium to coarse sandstones*	*Trough cross-bedding. Occasionally with pumice or intraclast particles on the foresets*	*Common reddish to brownish carbonate concretions*	*Migration of 3D subaqueous dunes within fluvial channels*
Sp	*Medium to coarse sandstones*	*Planar cross-bedding.*	-	*Migration of 2D subaqueous dunes*
Sm	*Very fine to medium sandstones. Abundant pyroclastic material*	*Structureless*	*Common root traces. Occasional decapod burrows.*	*Tractive deposits subsequently modified by soil forming processes*
Sr	*Fine sandstones*	*Ripple lamination. Usually observed climbing ripples*	-	*Deposition by tractive currents by current ripple migration*
Fp	*Siltstone and mudstone, with subordinate fine sandstone. Usually greenish or gray*	*Structureless. Remains of plane-parallel or current ripple lamination.*	*Common root traces. Scarce mottles, slickensides, nodules, cutans, peds, rhizoconcretions, organic matter remains. Scarce invertebrate trace fossils and coprolites.*	*Settling from suspension of fine sediments in low energy environments and subsequent modification by soil processes*
Fl	*Silt and clay*	*Plane-parallel lamination*	*Scarce leaf remains.*	*Settling from suspension of fine sediments in low energy environments. Lamination produced by fluctuating energy conditions*
Tm	*Medium to very fine tuffs. White to light yellow or light pink*	*Structureless*	*Abundant in-situ fossil vertebrates. Scarce root traces*	*Ash fallout deposits with subsequent reworking by fluvial and pedogenic processes.*

FA1- Floodplain deposits with paleosols

Description. FA1 is dominant throughout the SCF and is composed of grayish yellow (5Y 8/4), light greenish gray (5GY 8/1) and yellowish gray (5Y 7/2) mudstones, siltstones and light gray very fine to fine sandstones usually lacking any primary sedimentary structure (facies Fp, Sm; Fig. 2.1). A variable degree of intermingled tuffaceous material (facies Tm) like sparse white (N9) to very light gray (N8) thin tuff layers are also observed (Fig. 2.1). Tabular beds of different colorations show large lateral extension, giving the stratified aspect to the unit. Although some layers show delicate parallel laminations (facies Fl; Fig. 2.2), other primary sedimentary structures are hardly observed. In some cases laminated mudstones show poorly preserved oxidized

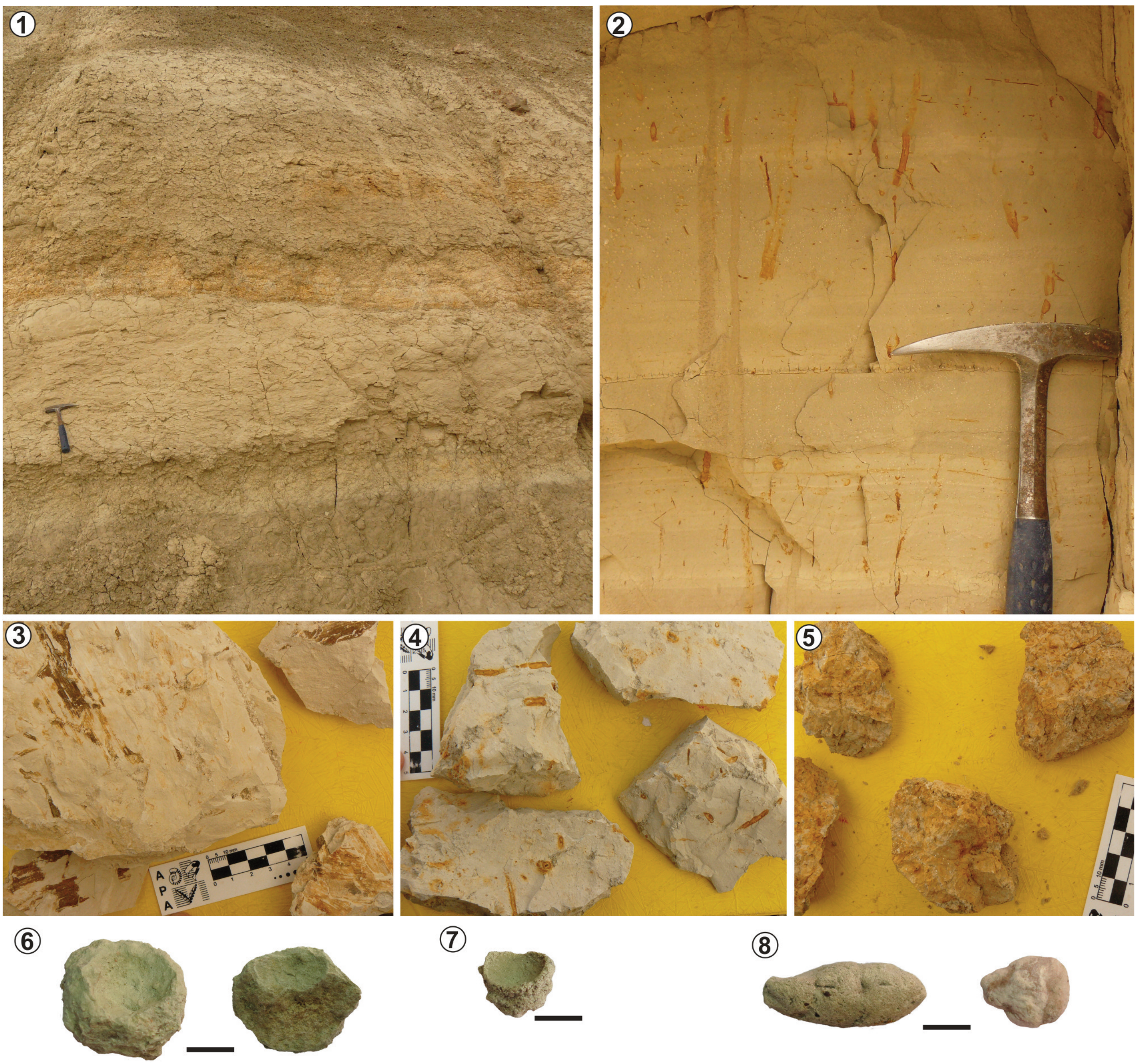

Figure 2. Different features of Facies Association 1 deposits. **1,** succession of structureless strata composed of pedogenically-modified fine tuffaceous sandstones and mudstones. **2,** Detail of laminated siltstones and mudstones with different types of orange-colored root traces. **3,** Plant remains preserved on lamination planes of mudstone. **4,** Detail of angular to subangular blocky peds with ferric delicate and haloed root traces. **5,** Detail of subangular blocky to granular peds with abundant root traces and mottles. **6,** Fragments of ***Coprinisphaera*** isp. **7,** ***Feoichnus challa***. **8,** Coprolites. Scale bars for 6, 7 and 8= 1 cm.

leaf impressions on the lamination planes (Fig. 2.3), some of them tentatively assigned to *Nothofagus* Blume (1851) (Roberto Pujana, personal communication 2018). Pedogenic features are abundant in this FA (Fig. 2.2, 2.4–5), being dominated by very pale brown (10YR 8/2) to moderate yellowish brown (10YR 5/4) ferric and delicate root traces –following the classification of Krapovickas (2012)–. Usually these root traces show dark yellowish orange (10YR 6/6) to light brown (5YR 5/6) haloes –*i.e.*, haloed-root traces *sensu* Krapovickas (2012)– (Fig. 2.4–5). Scarce trace fossils, such as *Feoichnus challa* Krause *et al.*, 2008 (Fig. 2.7) and fragments of *Coprinisphaera* isp. (Fig. 2.6), and scarce coprolites (Fig. 2.8) are recorded. Organic matter, slickensides, ferrous and calcareous nodules, calcareous rhizoconcretions, and mottling are also observed (Fig. 2.5). In general, these pedogenically-modified beds show no evidence of soil horizonation and peds. However, occasionally soil horizons are recognized showing cutans, and a blocky to granular structures (Fig. 2.4–5).

Interpretation. The fine-grained nature of these deposits suggests low-energy environments of deposition. Abundant rhizoliths and other pedogenic features suggest subaerial exposure followed by plant colonization during periods of relative landscape stability that allowed pedogenesis. This is typical of distal fluvial floodplains, which receive sporadic influxes of sediment during flooding episodes with subsequent periods of non-deposition and soil development. Laminated mudstones are interpreted to be deposited in small ponds in the floodplain in which the preservation of leaf impressions took place under acid and oxidizing conditions.

The abundance of small diameter root traces would suggest colonization of the substrate by grasses, herbs, and shrubs (Retallack, 2001; Catena *et al.*, 2016; Raigemborn *et al.*, 2018b). However, we do not rule out the coexistence of this plant community with trees (based on the presence of leaves of *Nothofagus* in this FA) and/or palms indicating mixed environments involving open areas and patches of trees/palms, as has been described in similar paleosols of the SCF southeast of the study area (*e.g.*, Raigemborn *et al.*, 2018a,b). In this context, the record of *Coprinisphaera* and *Feoichnus* are frequently but not exclusively preserved on grassland environments. These features are typical of open vegetated grassland-like soils, which could develop under subhumid to semiarid climates (Retallack, 2001; Catena *et al.*, 2016; Raigemborn *et al.*, 2018b). Particularly, granular structures are typically seen in wooded grassland soils (Retallack, 2001; Stoops *et al.*, 2010). Reduced hues in the matrix paleosols indicate iron-depletion (*e.g.*, Kraus and Hasiotis, 2006). However, the red and brown colors of the ferric root traces result from iron oxides, probably hematite, and represent better-oxidized areas where the Fe was reprecipitated (*e.g.*, Kraus and Hasiotis, 2006). Fe-nodules indicate redox-cycles; haloed root traces, slickensides, mottling and calcareous features suggest well-drained conditions and seasonal rainfall. Remains of organic matter in paleosols could be preserved under wet conditions (Buol *et al.*, 2011), and cutans (*i.e.*, clay-coatings) are signs of improved soil-drainage (Ashley and Driese, 2000). In combination, these features are evidence of fluctuating soil moisture. Paleosols with lack of horizonation and peds, and preservation of relict sedimentary structures as those of the SCF, are considered as very weakly/weakly-developed paleosols, which resemble paleo-Entisols and -Inceptisols present in other sections of the SCF outside the study area (Raigemborn *et al.*, 2018b). However, paleosols with defined horizons, peds, and cutans are compatible with relatively more developed soils (*e.g.*, Retallack, 2001) that probably could be interpreted as Alfisol-like paleosols. The studied paleosol types refer to very short-to-short–moderate pedogenesis, and probably they involved tens, hundreds to more than thousand years of soil formation (*e.g.*, Retallack *et al.*, 2000; Retallack, 2001). Consequently, pauses in sedimentation/erosion or stability of the landscape that allowed pedogenesis in FA1 of the SCF were relatively short (10^1–10^3 yr). The very low/low to moderate degree of paleosol development under the warm-temperate and seasonally humid-to-subhumid environment that prevailed during the Early–Middle Miocene in southern Patagonia (Kay *et al.*, 2012; Raigemborn *et al.*, 2018a,b) is likely the consequence of elevated aggradation rates.

FA2- Sheet flood – crevasse splay deposits

Description. FA2 is composed of centimeter-thick tabular beds of yellowish gray (5Y 8/1) to pale yellowish brown

(10YR 6/2) fine to medium sandstones. Also, up to 1 meter thick, light colored (N9 and N8) tuffaceous horizons show a fining upward trend are present in low proportion (Fig. 3.1). These beds form a distinctive feature of the SCF in the region. They are usually structureless (facies Sm; Tm) although occasionally they show parallel lamination (facies Sh) or ripple lamination (facies Sr), and show sharp bases and gradational tops to fine-grained beds of FA1, producing finning upward successions at the bed-scale. In minor proportion, some small lenticular bodies with planar base and convex tops were observed (Fig. 3.2), showing internal tractive sedimentary structures such as plane-parallel laminations (facies Sh) or small scale cross-bedding (facies St).

At Barrancas Blancas (EAG2), this facies association hosts an extensive burrow system conforming horizontal and vertical networks (Fig. 4.1–3). The individual branches are subcircular in cross section (2–3 cm in diameter) and are passively filled by the overlaying sandstones. The network is composed by burrows of horizontal disposition interconnected to vertical elements. Upward Y-branching and T-branching are commonly recorded (Fig. 4.5). The burrow lining is usually obscured by an external halo conformed by the host rock (Fig. 4.4), even though when visible, are smooth and structureless.

Interpretation. The dominance of relatively thin tabular sandstone deposits suggest accumulation by tractive currents produced by unconfined flows on the floodplain. These flows are interpreted as the result of fluvial flooding episodes when the flow overtopped the channel levees (Burns *et al.*, 2017). In some cases, the repetitive alternation of muddy and sandy tabular layers suggests accumulation confined within levees. Although occasionally observed in our survey, excepting for the Yaten Huageno locality (Fig. 3), lobe-shaped sandy beds are interpreted as crevasse-

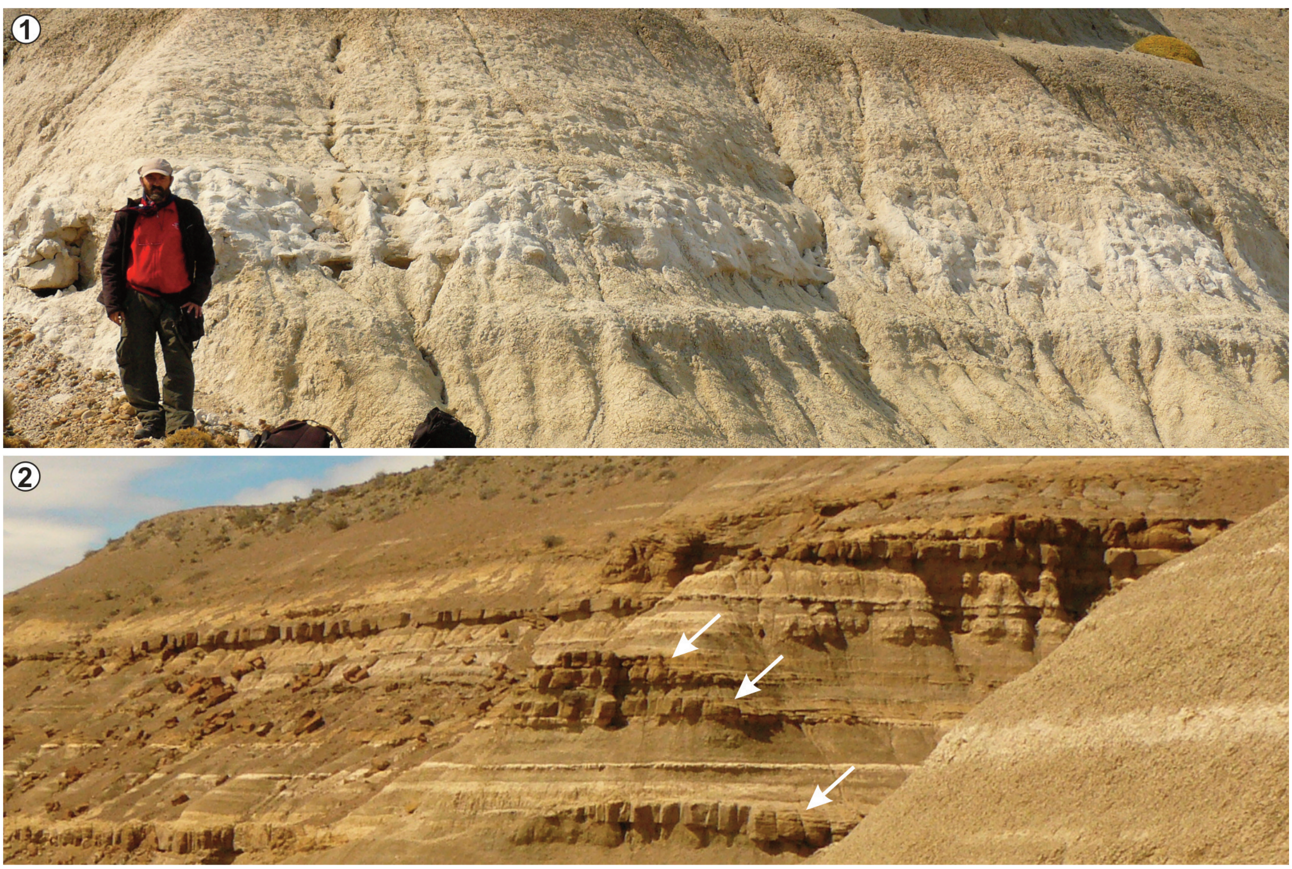

Figure 3. Outcrop views of different features assigned to Facies Association 2. **1,** A ~1 m-thick, tabular whitish tuff horizon showing fining upward trend, interpreted as a sheet flow deposit. **2,** Succession with abundant convex sandstone bodies (arrows), interpreted as lobes formed during crevasse splay events intercalated with floodplain deposits of FA1.

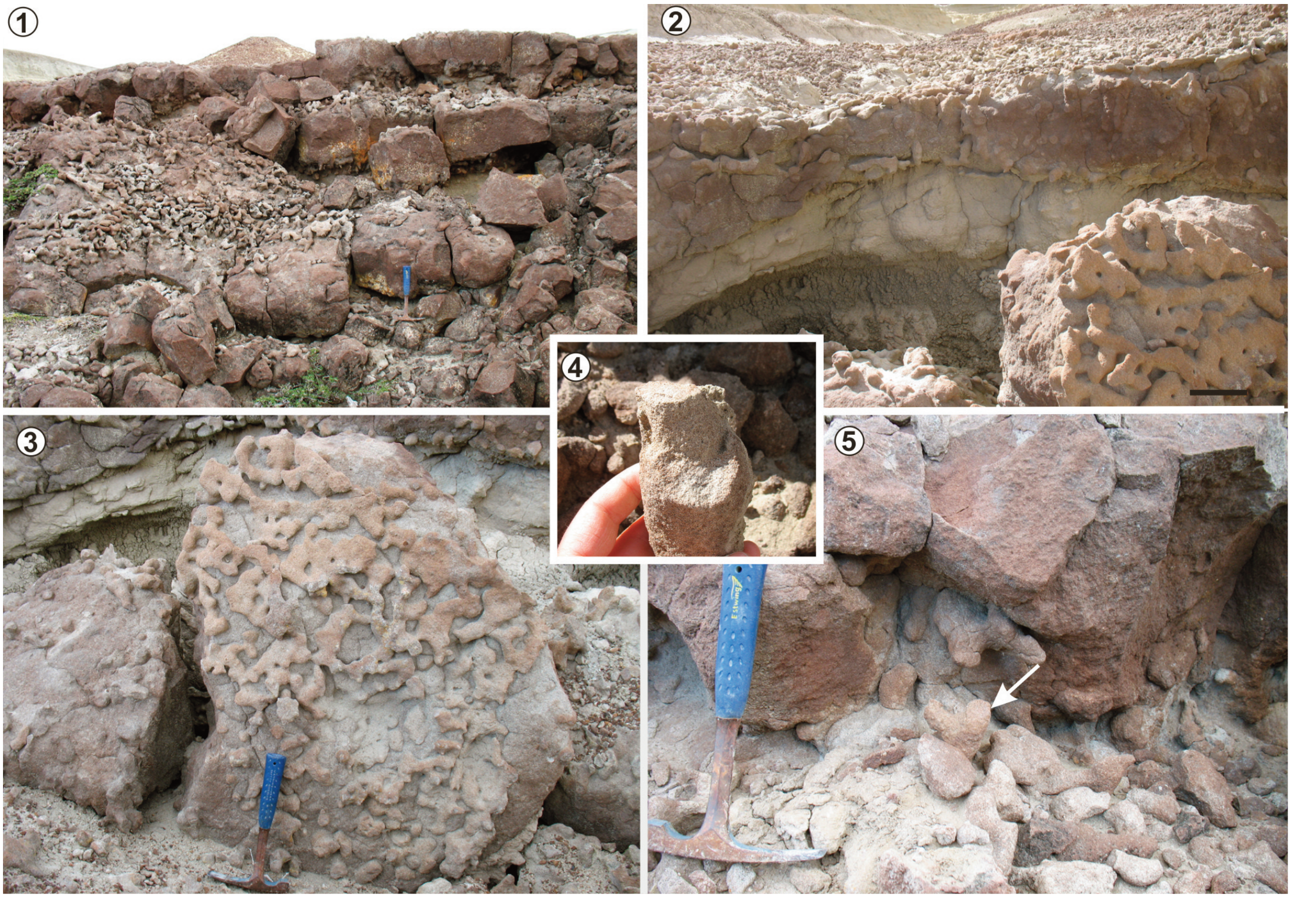

Figure 4. Burrow system described for Facies Association 2. **1–2,** General view of the burrow system and the host medium sandstones. Scale bar in 2= 10 cm. **3,** Detail of the burrows system of horizontal disposition interconnected to vertical elements. **4,** Burrow lining obscured by an external layer. **5,** Detail of an upward Y-branching burrow (indicated by arrow).

splay deposits. These types of sedimentary bodies are a common element in other SCF localities (Zapata, 2018; Cuitiño *et al.*, 2019). The lack of primary sedimentary structures in the m-thick, tabular tuff beds makes their interpretation difficult. Some cm-thick tuff layers can be interpreted as primary ash fall deposits. However, considering the distance from the Andes, thin-to-thick tuffs are interpreted as the product of reworking of primary volcanic ash fall deposits either by unconfined flows on the floodplains, aeolian processes, or a combination of both. The occurrence of rhizoliths restricted to the upper part of these tuff beds suggests fast accumulation of the tuffaceous material followed by stable conditions and pedogenic modification.

The architecture of the described burrow systems shows a close morphological resemblance to other burrow systems produced by terrestrial and marginal marine decapod, such as *Camborygma* Hasiotis and Mitchell, 1993, *Lunulichnus* Zonneveld *et al.*, 2006, *Loloichnus* Bedatou *et al.*, 2008 and *Psilonichnus* Fürsich, 1981. They differ from the first three mentioned in this list in lacking vertically dominated structure and differs from *Psilonichnus* by the absence of branches with J and U shape (Fürsich, 1981; Frey *et al.*, 1984; Hasiotis and Mitchell, 1993; Zonneveld *et al.*, 2006; Bedatou *et al.*, 2008). For this reason and until we are able to gather more diagnostic information, we prefer to leave the burrow network without any formal nomenclature.

FA3- Fluvial channel deposits

Description. FA3 is composed essentially by lenticular sandstone deposits with a sharp, concave base and planar top (Fig. 5.1), sometimes grading upwards to fine-grained deposits of FA1 or FA2. Grain sizes vary between fine and coarse sandstone, with subordinate fine gravels. Color ranges from dark gray, grayish yellow (5Y 8/4) to yellowish gray (5Y 7/2). Primary sedimentary structures such as planar and trough cross bedding (facies Sp and St, respectively), as well as plane parallel lamination (facies Sh) are common, forming sets that vary between 0.2 and 1.5 m

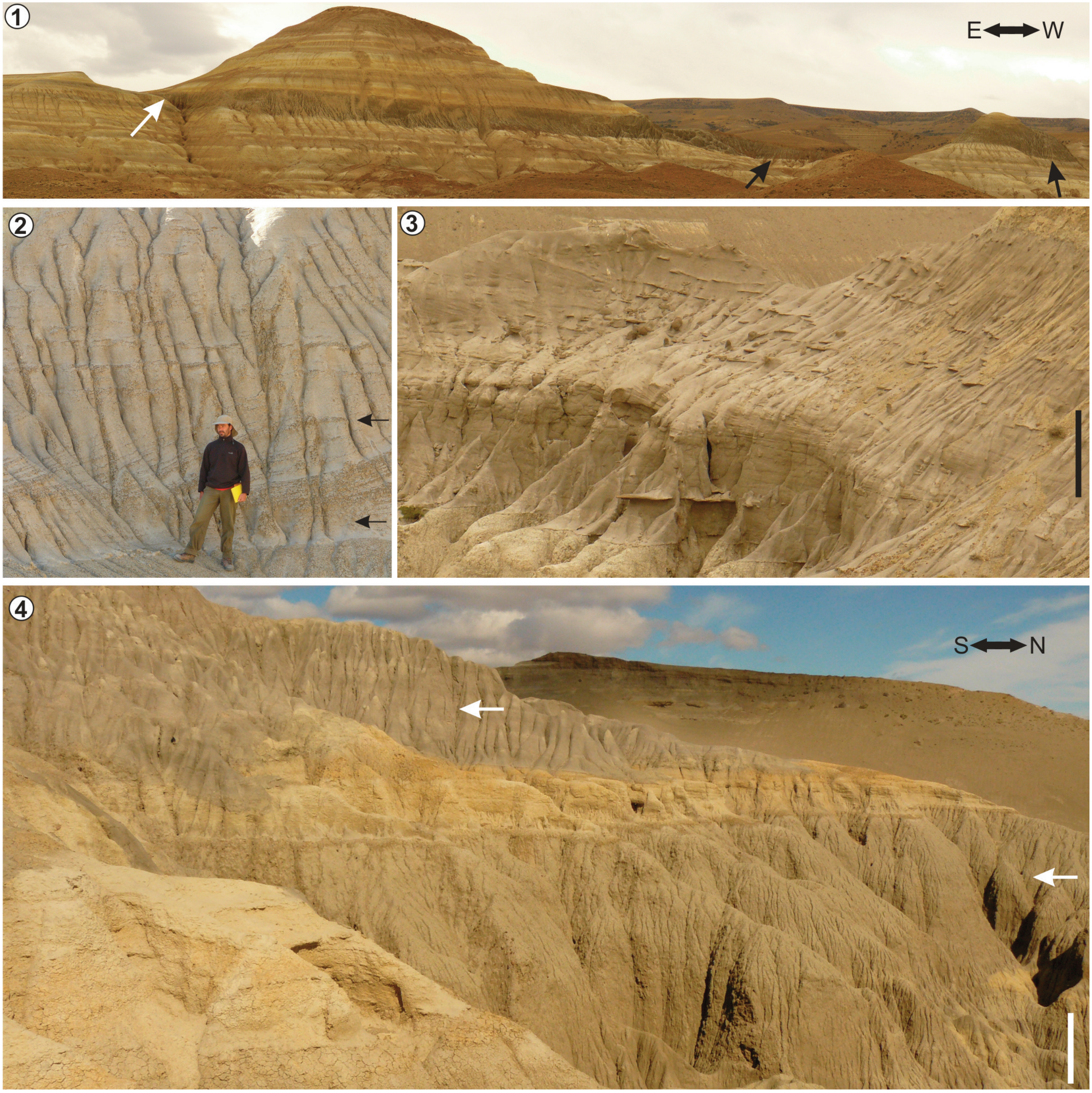

Figure 5. Field photographs of channel deposits of Facies Association 3. **1,** Lenticular dark gray sandstone body with irregular, concave base and planar top. The white arrow points to the lateral pinch-out of the body, whereas the black arrows point to the irregular bottom surface close to the thalweg of the channel. The visible lateral extension of this channel is about 150 m. **2,** Large-scale cross-bedded set (between arrows; 1.1 m) at the base of a thick channel deposit. Upward the sets are no thicker than 0.3 m. **3,** Gray sandstone with trough cross stratification in sets of about 0.5 m thick. Scale bar=1 m. **4,** Two thick channel gray sandstones showing organ pipe weathering (white arrows). Primary sedimentary structures are hardly observed in these bodies, although some relict stratification can be observed for the upper one. Scale bar= 1 m.

thick (Fig. 5.2 and 5.3). The thicker cross-bedded sets are usually observed at the base of these bodies (Fig. 5.2). Due to the poor lithification, many bodies show "organ pipe" weathering patterns without visible structure (Fig. 5.4). Thickness of individual bodies varies between 1 and 7.5 m, whereas apparent width reaches up to 300 m. Some caution on this measurement must be taken because of the limited lateral extension of the exposures and the common lack of paleocurrent indicators useful to locate the cross-current orientation of the bodies. Few paleocurrent measurements from cross bedding show E and NE directions.

Interpretation. Lenticular bodies with erosive bases, infilled with cross bedded sandstones and showing fining upward trends, are interpreted as produced by confined flows typical of fluvial channels (Miall, 2014). They are interbedded within fine-grained deposits of FA1 and FA2. Given the simple infill of the channels and the general reduced thickness of individual bodies, most are interpreted as shallow, single story channels. The lack of evidence for lateral accretion suggests these were fixed channels in a low sinuosity fluvial system (Miall, 2014). In accordance to our interpretation, for the coastal cliff exposures of the SCF, Zapata (2018) also concluded that the most common type of channel for the SCF is the confined, single story channel.

STRATIGRAPHY AND SPATIAL FACIES TRENDS

The SCF along the southern margin of the Río Santa Cruz valley is exposed in a series of isolated small hills and cliffs located near the valley bottom (Fig. 1.2–3). These were exposed by the erosion of ephemeral streams that transect the valley margin or by the cut bank of the Río Santa Cruz. Most of the area is covered by Miocene–Quaternary terrace fluvial conglomerates or recent alluvial deposits (Fig. 1.2–3). For these reasons, plus the large distances between the exposures (tens of kilometers), a field-based physical correlation scheme based on guide levels at the regional scale was not feasible.

The SCF strata are subhorizontal, with local dips no higher than 3° and few normal faults with no more than 10 m of throw. The maximum measured thickness for the SCF in the study area is 167 m corresponding to Segundas Barrancas Blancas; 142 m and 80 m were measured for Barrancas Blancas and Yaten Huageno, respectively.

The base of the SCF, defined as just above the uppermost oyster shell bed recognized in the underlying marine deposits is only visible in Barrancas Blancas, where one can observe the transition with the underlying Monte Observación Member of the Monte León Formation (Parras and Cuitiño, 2018). For the remaining localities, the base of the unit is covered.

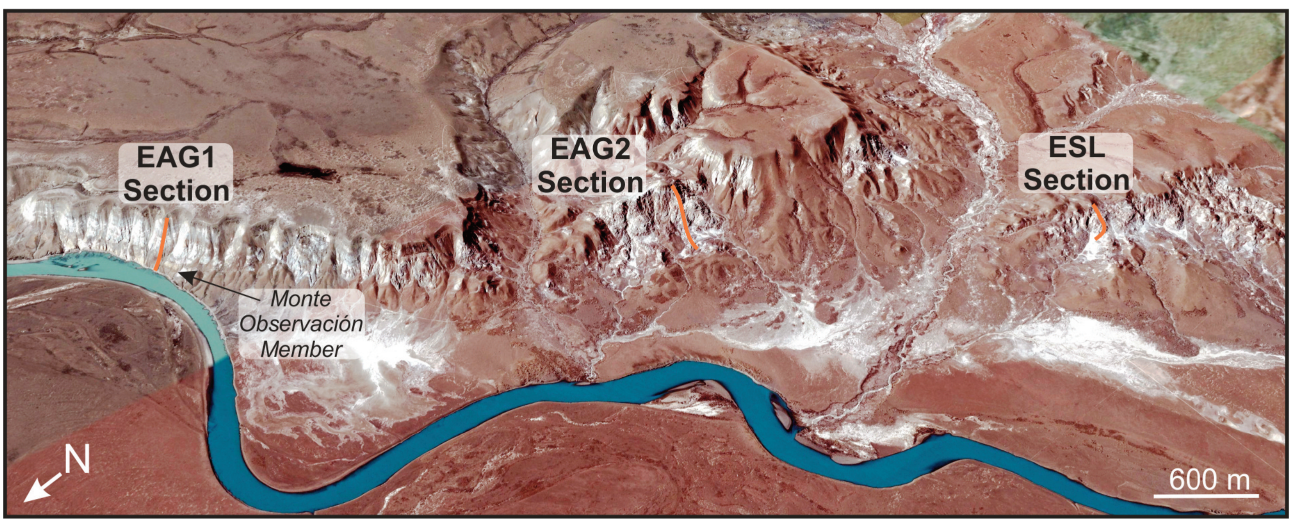

Figure 6. Oblique satellite image (Google Earth TM; 2002) of the Barrancas Blancas locality showing the position of the three measured sections just south of the Río Santa Cruz. In the lower part of the EAG1 Section the brownish strata of the Monte Observación Member of the Monte León Formation is highlighted.

Several small outcrops of poor quality record the SCF in higher topographic elevations, up to few meters below the uppermost conglomerate of the Terrace II of Pampa de Monte León (Sacomani and Panza, 2011; Cobos *et al.*, 2014) (*e.g.*, Estancia Santa Lucía, Estancia Rincón Grande; Fig. 1.3), which is estimated to be no more than 10 m thick. Thus, we estimate the thickness of the SCF including covered intervals is about 267 m for Barrancas Blancas, at least 288 m for Segundas Barrancas Blancas and at least 380 m for Yaten Huageno. This westward increase in thickness is consistent with regional trends observed elsewhere for the SCF in southern of the Province of Santa Cruz (Cuitiño *et al.*, 2016).

Considering only the measured thicknesses of the well-exposed stratigraphic intervals studied here, together with the available ages and using a sedimentation rate of 150 m/Ma (Cuitiño *et al.*, 2016), the estimated time span for the SCF in the studied localities is 17.21–16.3 Ma (Burdigalian)

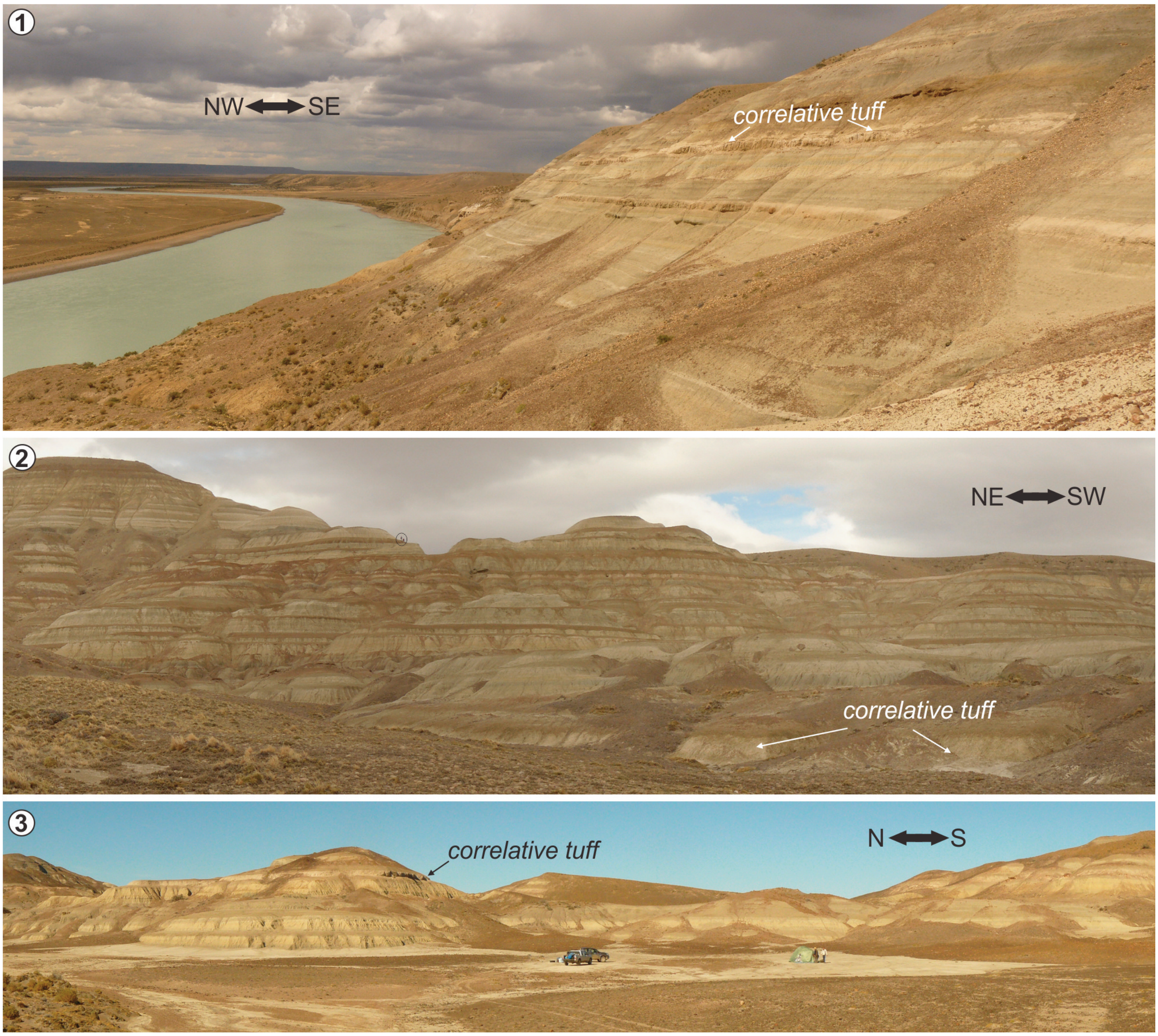

Figure 7. Field panoramic photographs of the three exposures from which sections were measured. **1,** Section EAG1 with the correlative tuff highlighted. **2,** A thick exposure from Section EAG2. The same correlative tuff of Section EAG1 is highlighted. **3,** The small exposure of Section ESL and its correlative tuff. Photographs 1 and 2 taken in December 2012; photograph 3 taken in February 2014.

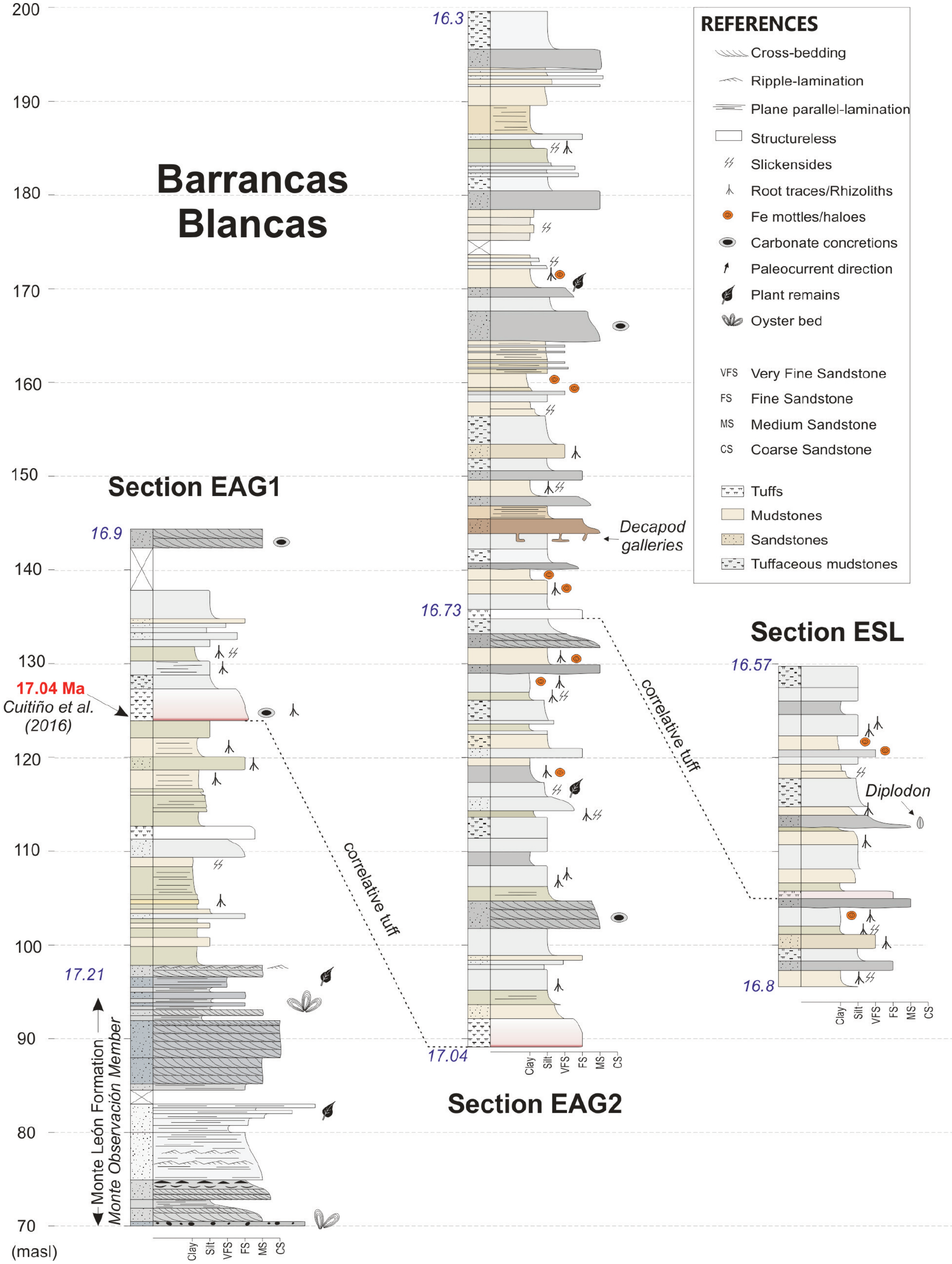

Figure 8. Sedimentary sections measured in Barrancas Blancas locality, showing local correlative horizons. The red number indicates the position of the U-Pb age (Cuitiño *et al.*, 2016) whereas the blue numbers are ages estimated upon sedimentation rates.

for Barrancas Blancas; 16.47–15.3 Ma (Burdigalian–early Langhian) for Segundas Barrancas Blancas; and 17.21–16.68 Ma (Burdigalian) for Yaten Huageno. In addition, it is noted that if the isolated high elevation exposures of the SCF lying just below the Terrace II of Pampa de Monte León conglomerates (see above) are considered in this analysis, the age of the SCF in the Río Santa Cruz should be extended somewhat younger than estimated here and certainly it should comprise part of the Langhian stage.

Barrancas Blancas

This is the easternmost locality of the study area (Fig. 1) and corresponds to a belt of exposures oriented NE-SW in which we measured three sections: Estancia Aguada Grande 1 (EAG1), Estancia Aguada Grande 2 (EAG2) and Estancia Santa Lucía (ESL) (Figs. 6, 7, 8).

Section EAG1 (S 50° 09' 47.6"; W 69° 41' 02.2") begins at the Río Santa Cruz level (Fig. 7.1), and is the only one in the study area where the underlying shallow marine to transitional deposits of the Monte Observación Member of the Monte León Formation can be observed (Figs. 6 and 8). Following the criteria of Parras and Cuitiño (2018) the boundary of this member with the overlying SCF is arbitrarily located in the uppermost *Crassostrea orbignyi* Ihering, 1897 shell bed. Above this contact is a 50 m thick succession of the lower beds of the SCF composed of deposits assigned mostly to FA1 and FA2, with a conspicuous 3 m thick tuff bed located 30 m above the base of the unit (Figs. 7.1 and 8). This tuff was dated in 17.04 ± 0.55 by means of U/Pb on zircons (Cuitiño *et al.*, 2016), and it is used as a marker bed to correlate with Section EAG2 (Fig. 8). In this part of the SCF no terrestrial fossil vertebrates were recovered.

Section EAG2 is 4 km southwest of EAG1 (Fig. 6), it is the thickest and most extensive exposure within Barrancas Blancas (Figs. 7.2 and 8). It is the site of a significant vertebrate fossils collection (Fernicola *et al.*, 2019b) and contains a horizon rich in decapod burrows (Fig. 8). It is mostly composed of floodplain deposits of FAs 1 and 2.

Finally, the ESL Section is a small exposure located 3 km southwest of EAG2 (Figs. 6 and 7.3). The correlation of this section with EAG2 is performed using a local tuff layer (Fig. 8). In this locality, besides the fossil vertebrate collection (Fernicola *et al.*, 2019b), a level bearing the freshwater bivalve *Diplodon* sp. was found (Pérez *et al.*, 2019).

Segundas Barrancas Blancas

This is a belt of 9 km of exposures composed of several isolated outcrops that lie close to the Río Santa Cruz in Es-

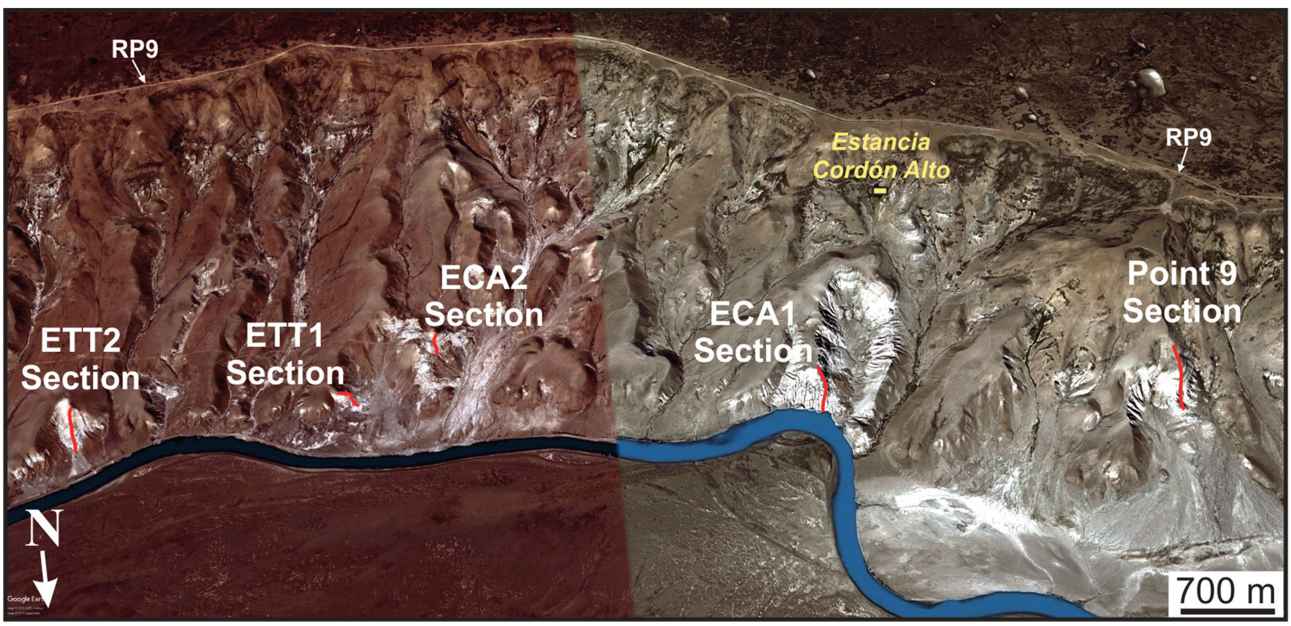

Figure 9. Oblique satellite image of Segundas Barrancas Blancas (from Google Earth TM; 2001), showing the position of the five measured sections.

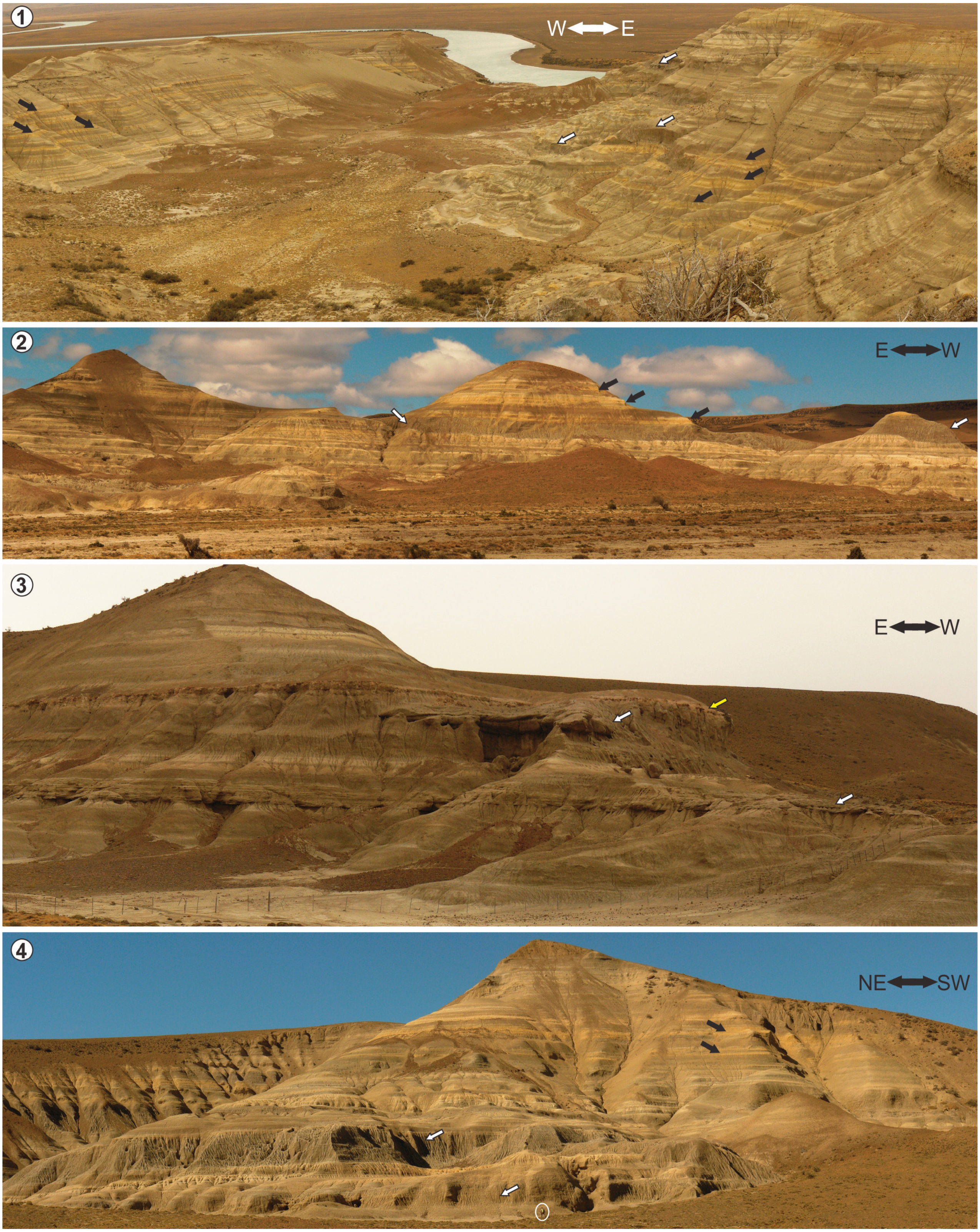

Figure 10. Panoramic photographs of Segundas Barrancas Blancas most representative exposures. In all cases white arrows indicate thick lenticular channel sandstones whereas black arrows point to the yellow beds that were used for correlation. **1,** ECA Section viewed from above. **2,** ECA2 Section. **3,** EET1 Section showing the CECA-2 tuff layer dated by Cuitiño *et al.* (2016) (yellow arrow). **4,** EET2 Section. A person (encircled) as scale. All photographs taken in February 2014.

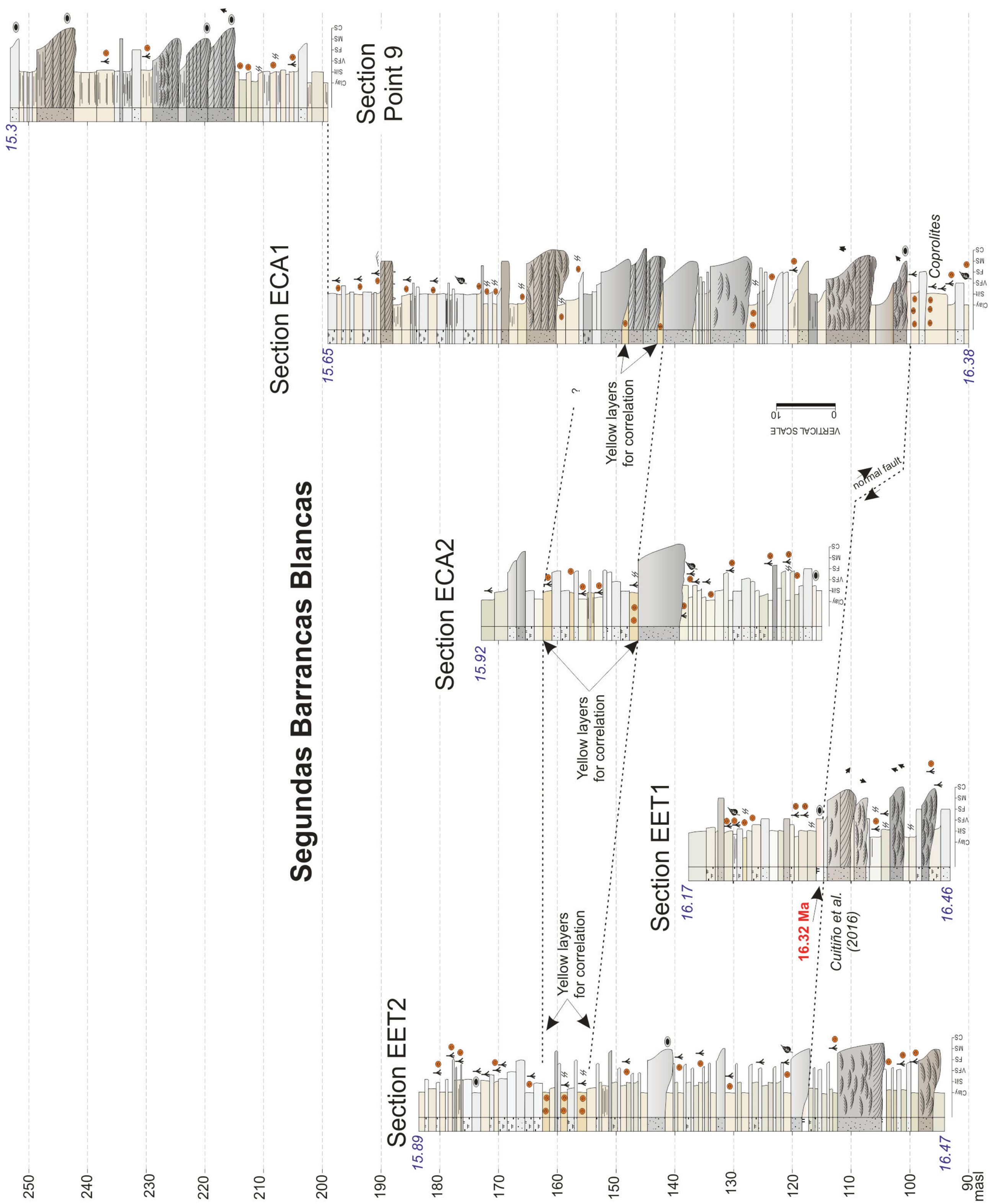

Figure 11. Sections measured for Segundas Barrancas Blancas locality, showing their correlative horizons. All sections are positioned in relation to the altitude above sea-level. The red number indicates the U/Pb age (Cuitiño *et al.*, 2016), whereas the blue numbers are estimated upon sedimentation rates. For references see Figure 8.

tancia Cordón Alto and Estancia El Tordillo (Figs. 1, 9, and 10). Here we measured five sections (Fig. 11), which from east to west are: Estancia El Tordillo 2 (EET2; S 50° 16′ 39.08″; W 70° 13′ 26.18″), Estancia El Tordillo 1 (EET1; S50° 16′ 43.00″; W 70° 15′ 9.90″), Estancia Cordón Alto 2 (ECA2; S 50° 16′ 55.96″; W 70° 15′ 47.33″), Estancia Cordón Alto 1 (ECA1; S 50° 16′ 25.56″; W 70° 18′ 24.74″), and Point 9 (S 50° 16′ 16.30″; W 70° 20′ 48.60″) (Figs. 9 and 11). In each of these sections vertebrate fossils were recovered (Fernicola *et al.*, 2019b).

The SCF here is composed of fine-grained sediments of FAs 1 and 2, although conspicuous lenticular sandstone bodies of FA3 are observed (Fig. 10). The sections are locally correlated using a tuff layer (CECA-2 tuff; Cuitiño *et al.*, 2016) and tabular, laterally extensive and distinctive yellow beds (Figs. 10 and 11). The CECA-2 tuff layer is about 1 m thick (Fig. 10.3) and was dated at the EET1 Section by Cuitiño *et al.* (2016) with an age of 16.32 ± 0.62 Ma. This tuff allows the correlation of Section EET1 with Section ECA1 (Fig. 11) 3.5 km away. Conspicuous yellow beds also used for correlation are a package of about 10 m of fine-grained sediments assigned to FA1 that contains two or three layers that contrast in color with the remaining beds of the SCF (Fig. 10). These beds were used to correlate sections EET2, ECA2 and ECA1 (Fig. 11). Although present in Section ECA, the yellow layers are barely visible due to the presence of thick lenticular sandstone deposits that partly erode them (Figs. 10.1 and 11). Finally, due to the lack of guide levels, Section Point 9 was located in the correlation scheme according to its elevation above sea level (Fig. 11).

Yaten Huageno

This locality has a single section (Fig. 12; S 50° 15′ 40.74; W 71° 3′ 48.81″) in which vertebrate fossils were recovered (Fernicola *et al.*, 2019b). Due to the geographic isolation of this section, physical correlation to other sections is nearly impossible to perform. Here, the SCF is composed of a mixture of fine-grained deposits of FA1 and lenticular to tabular sandy deposits of FA2 and FA3 (Figs. 12 and 13). For this section, a tuff layer has been dated in 16.88 ± 0.65 Ma (Cuitiño *et al.*, 2016).

OVERVIEW AND CONCLUDING REMARKS

Overall, the SCF in the study area is composed of bioturbated and pedogenized poorly consolidated fine-grained sediments with abundant tuffaceous material, mostly represented by floodplain deposits of FA1 and sheet flood to crevasse splay deposits of FA2. Lenticular, cross-bedded sandstone bodies deposited by fluvial channels of FA3 are a minor component of the unit. Conglomerates are only observed as layers of granule to fine-gravel intercalated within sandstone deposits or forming lags at the base of channel sandstone beds. The vertical proportion of the three FAs here defined remains homogeneous for all the studied sections, suggesting an aggradational stacking pattern for the SCF in this region.

The three studied localities of the SCF could not be physically correlated because of the large distances between them and the absence of regional guide levels. However, based on the available U-Pb ages and the estimated sedimentation rates (Cuitiño *et al.*, 2016), they can be

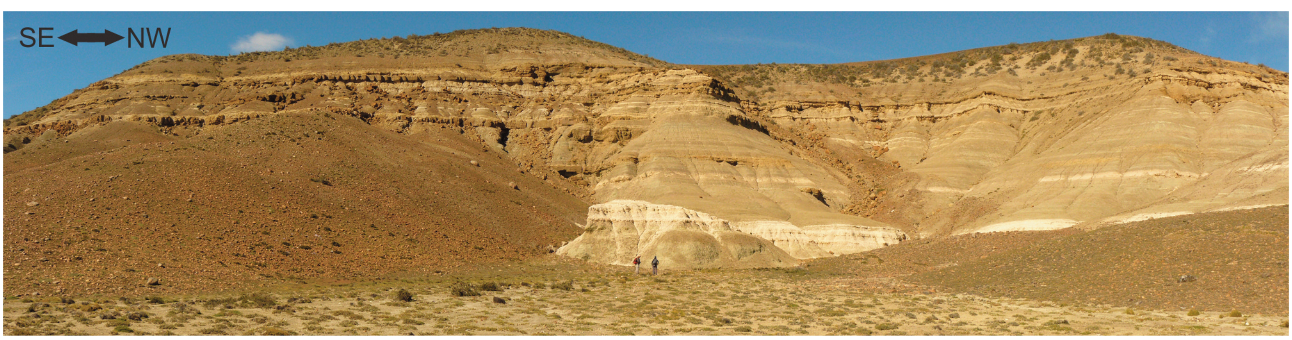

Figure 12. Panoramic photographs of the exposure where the Yaten Huageno section was measured. The whitish strata correspond to tuffs whereas the beds projecting off the exposure are sandstone bodies. Note two persons at the base of the outcrop as scale. Photographs taken in December 2012.

chronologically correlated, being deposited in a time interval between 17.2 and 15.3 Ma (Burdigalian–early Langhian).

Paleocurrent data is scarce because of the poor preservation of primary sedimentary structures. Some isolated measurements point to N, NE and E paleoflows, but this must be taken with caution since the channel sinuosity was not evaluated. The studied exposures of the SCF are arranged in a west to east trend, *i.e.*, approximately parallel to the paleoflow. This is based on the assumption that the Southern Patagonian Andes were a high topographic feature that produced the drainage network to flow eastward, as presently occurs. This is supported by the paleocurrent data and fluvial channel architecture from the coastal localities that show a main paleoflow to the east (Zapata, 2018). This, together with the synchronicity of the SCF among localities of the Río Santa Cruz, implies that Yaten Huageno represents sedimentation roughly 140 km upstream in relation to Barrancas Blancas. In Yaten Huageno several sandstone channels are composed of coarse-sandstones and some reach up to granule-size deposits (Fig. 13), whereas in Barrancas Blancas the sandstone deposits are mostly composed of fine to medium sandstones, with few thin coarse sandstone levels (Fig. 8). This eastward finning grain size trend observed among the channel sandstones in the studied localities supports the idea of a West to East drainage pattern.

The Decapod burrow system recorded at Barrancas Blancas has a strong horizontal component, differing from what has been described until now for crayfish burrows, dominated by vertically components (*e.g.*, Hasiotis and Mitchells, 1993; Bedatou *et al.*, 2008). On the other hand, land crabs as Gecarcinidae and Coenobitidae (Brachyura) typically produce extensive burrow systems along riverbanks, within several kilometers from the sea, where they leave their marine larvae (Maitland and Maitland, 1985; Vannini *et al.*, 2003).The South American freshwater crab Trichodactylidae (Brachyura) excavate along ditches, river banks or wetlands; while the freshwater crayfish Parastacidae excavates burrows not necessary connected to water courses, mostly in soils where they reach the water table (Genise, 2017). Therefore, even though the Barrancas Blancas burrows were found at the easternmost locality, based on the sedimentological evidence for the corresponding terrestrial horizons, the idea of a coastal-influenced paleoenvironment is discounted: freshwater crabs or crayfish could have produced the Barrancas Blancas burrows.

Paleosols developed in the SCF along the Río Santa Cruz valley are abundant although all show an overall very poor/poor to moderate degree of development, which would be assigned to paleo-Entisols, -Inceptisols, and Alfisol-like paleosols. They occur mostly on fine-grained deposits interpreted as distal floodplain deposits (FA1).

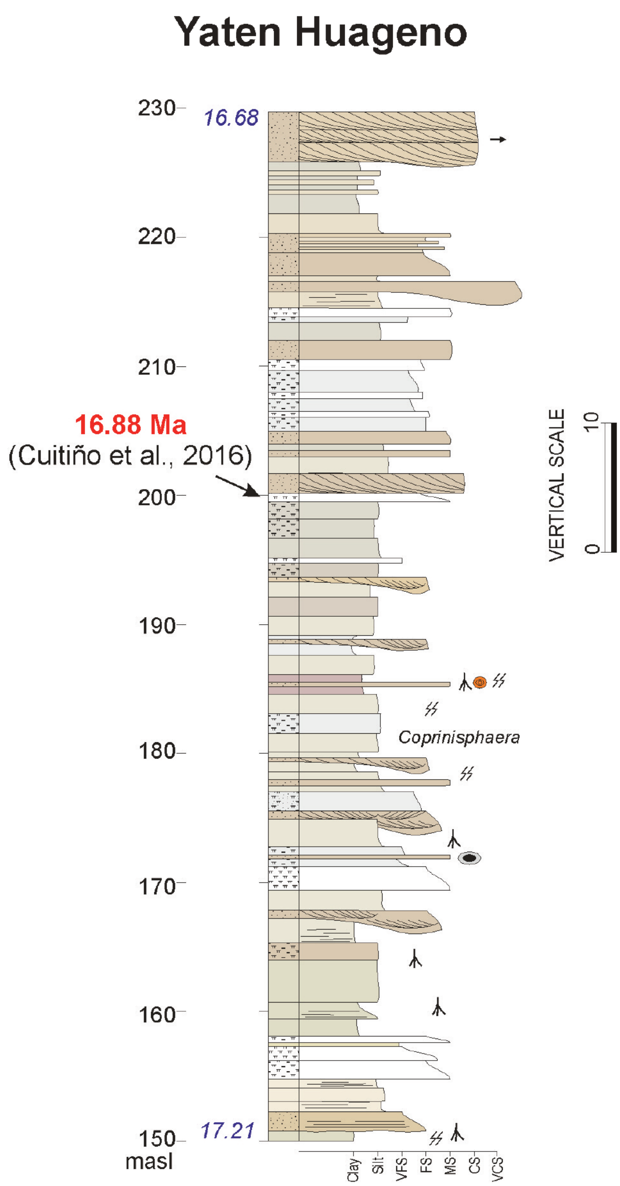

Figure 13. Sedimentary section measured for Yaten Huageno locality showing the dated horizon. The red number indicates the U/Pb age whereas the blue numbers are estimated upon sedimentation rates. For references see Figure 8.

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