

SEDIMENTOLOGY OF THE SHALLOW MARINE DEPOSITS OF THE CALAFATE FORMATION DURING THE MAASTRICHTIAN TRANSGRESSION AT LAGO ARGENTINO, AUSTRAL-MAGALLANES BASIN, ARGENTINA

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ABSTRACT

The Maastrichtian shallow marine deposits exposed at the south margin of the Lago Argentino within the Austral-Magallanes Basin are known as the Calafate Formation. In order to interpret the depositional systems and reconstruct the sequence stratigraphic architecture for this unit at its type locality (Cerro Calafate), we acquire new data from seven stratigraphic sections. We recognized six facies associations (FA-1 to FA-6) corresponding to shallow marine deposits, which are organized vertically displaying a transition from shallower to deeper conditions, representing a ~90 m thick transgressive succession. The Calafate Formation deposits are differentiated into a lower wave-dominated coast (FA1, FA2 and FA3) and an upper tide-dominated coast (FA4, FA5 and FA6), each marked by the dominance of wave and tidal sedimentary processes, respectively. The Calafate Formation overlies the fluvial deposits of the Chorrillo Formation by a transgressive surface (TS), which is overlaid by a transgressive marine succession characterized by a retrogradational stacking pattern. The latter is finally covered by offshore transition marine deposits marking a progressive deepening of the depositional system that culminates with the maximum flooding surface (MFS). From here, an aggradational stacking pattern dominates the upper sandstones of the unit representing the highstand systems tract (HST), which is interpreted to be the cause of short-term periods when the accommodation space rate was nearly equaled to the sediment supply rate during the Maastrichtian.

INTRODUCTION

The Calafate Formation is part of the foreland phase sedimentary infill of the Austral-Magallanes Basin deposited during the Maastrichtian (Fig. 1a, d).

This unit was previously and informally defined as the “Estratos de Calafate” by Feruglio (1938) south of the Lago Argentino and then assigned to the Maastrichtian-Paleocene (Nullo *et al.*, 1981; Macellari *et al.*, 1989; Marenssi *et al.*, 2004; Gonzalez Estebenet

et al., in press). The unit under study was described as green sandstones and grey conglomerates that occur as tabular and massive beds with planar and sigmoidal cross stratification, reaching up to 250 m of thickness. By means of sedimentological and palynological analysis, Marensi *et al.* (2004) interpreted the Calafate Formation as deposited under marine nearshore depositional conditions. The authors described three facies associations, comprising 1) tidal flats (5–50 m thick); 2) sub-tidal main channels (4–11 m thick); and 3) sandy tidal waves (8–20 m thick), interpreted as the product of short-lived transgressive-regressive events in which the coarsening upward part represents sedimentary aggradation with a stable or lowering sea level. Later, Poiré and Franzese (2010) described the Calafate Formation as a green glauconitic sandstone succession with *Lahillia luisa* and *Trigonias* fauna and with abundant trace fossils related to a marine shelf environment.

Up to date, a detailed analysis of the stratigraphic architecture, with special focus on key stratigraphic surfaces, is still missing for the Calafate Formation. These aspects are needed in order to better understand the origin of these deposits and their importance as reservoir rocks. Transgressive deposits as those described for the Calafate Formation are highly variable in thickness and facies but can be texturally and compositionally mature making them excellent oil/gas reservoirs in some cases (Posamentier, 2002; Cattaneo and Steel, 2003). The high volume and lower degree of heterogeneity of ancient regressive deposits in comparison with transgressive ones, have made them historically the primary target for the oil and gas industry. Consequently, ancient regressive shorelines are not only well documented, but their processes are better understood than their transgressive counterparts (Cattaneo and Steel, 2003). The main goals of this contribution are: i) to determine in detail the bed-scale to bedset-scale stratigraphic architecture of the Calafate Formation in order to reconstruct the different depositional settings during part of the foreland stage of the Austral-Magallanes Basin, and ii) to propose a depositional system based on the analysis and interpretation of lithofacies, differentiating wave from tidal processes during sedimentation and considering the associated relative sea level changes. Therefore, original sedimentological information is presented, with a degree of resolution not yet reached for the Calafate

Formation at its locality type.

GEOLOGICAL SETTING

The Austral-Magallanes Basin is located on the southwestern portion of the South American plate encompassing south Patagonia, Tierra del Fuego Island and the adjacent continental shelf of Argentina (Biddle *et al.*, 1986; Nullo *et al.*, 1999; Malumián, 1999). The basin is elongated following an NNW-SSE axis and is bounded by the Deseado Massif and Río Chico High to the northeast and by the Patagonian-Fuegian Andes to the west and south (Fig. 1a). The Austral-Magallanes Basin covers an area of approximately 230.000 km² with a maximum thickness of 8 km in the subsurface, constituting one of the most important oil-basins in Argentina, owing to the excellent thermal maturity of its sedimentary infill (Biddle *et al.*, 1986; Rodríguez and Miller, 2005). Based on the proposal of Ghiglione *et al.* (2010), the tectonic history of the Austral-Magallanes Basin involves: (1) Triassic to Early Cretaceous rifting during the break-up of Gondwana; (2) thermal subsidence, followed by (3) development of a retro-foreland basin in response to Late Cretaceous-Paleogene compression linked to subduction of Pacific plates (Farallon-Aluk-Nazca-Antarctic) beneath the South American plate; and (4) contractional deformation being replaced during the Oligocene by regional wrench-style deformation driven by left-lateral motion across the South American-Antarctica plate boundary, a process that had begun by nearly 50 Ma. The deposition of the Calafate Formation occurred during the foreland stage (Arbe, 1989) (Fig. 1d). The Calafate Formation shows excellent exposures at the northern and southern margins of Lago Argentino (Fig. 1b, c) and it is easily recognizable due to its greenish sandstones and conglomerate strata. The focus of this study is on those outcrops located south of the Lago Argentino and El Calafate city, where the Calafate Formation extends laterally for approximately 30 km in a northeast-southwest direction, from the Cerro Calafate to the Barrancas de La Anita (Fig. 1b, c). The Cerro Calafate is the type locality of the Calafate Formation where it discordantly overlies the continental deposits of the Chorrillo Formation (Maastrichtian) (Arbe and Hechem, 1984; Tettamanti *et al.*, 2019). In turn, it is unconformably overlain by the marine deposits of the Man Aike Formation (middle to upper Eocene)

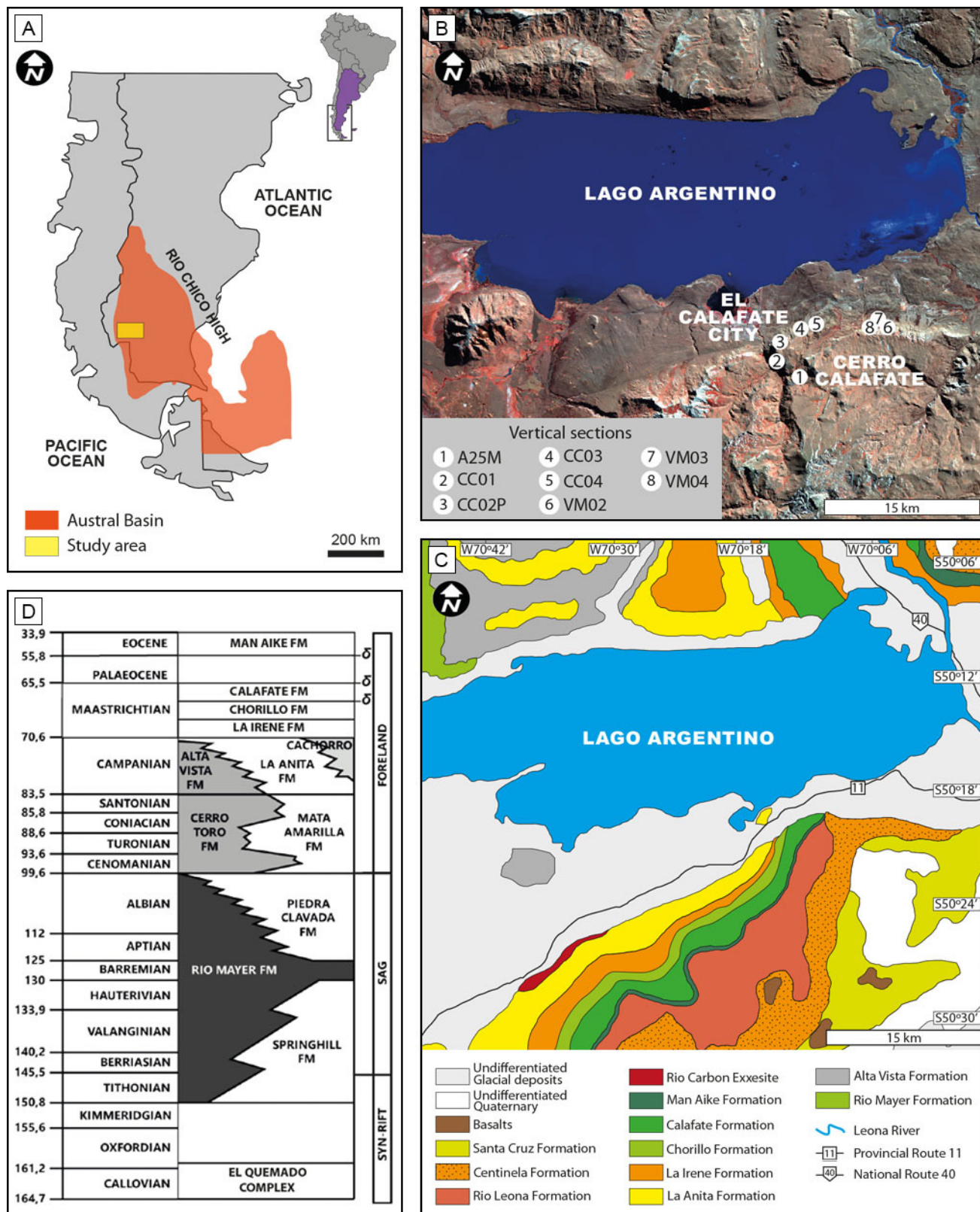


Figure 1. a) Geographic location and geological setting of the Austral-Magallanes Basin at the southern Patagonian region (adapted from Richiano *et al.*, 2012). The study area is outlined by the yellow box. b) Satellite image of the Cerro Calafate area, south of Lago Argentino, where the measured sections are shown and numbered. c) Geological map of the Cerro Calafate area, showing the different sedimentary units of the Austral-Magallanes Basin. d) Generalized stratigraphic column for the Austral-Magallanes Basin in the Lago Argentino region (modified from Varela *et al.*, 2013). References for 1b: A25M=Arroyo 25 de Mayo (25 de Mayo Creek); CC=Cerro Calafate (Calafate Hill); VM=Vertedero Municipal (Municipal dumpsite).

(Marensi et al., 2002; Casadío et al., 2009) (Fig. 1d).

METHODOLOGY

Data acquisition was obtained during fieldwork from the outcrops of the Calafate Formation in the Cerro Calafate area (Fig.1b). Over 1.5 km of stratigraphic thickness of the Calafate Formation strata (cumulative) were measured at the centimeter scale and a ca. 14 km lateral extension of the outcrops. The stratigraphic sections analyzed were four at the Cerro Calafate (CC01, CC02P, CC03, CC04), three at the Vertedero Municipal (VM02, VM03, VM04), and one at the Arroyo 25 de Mayo (A25M) (Fig. 1b, 2). These localities were selected because they expose entirely and partially the thickness of the Calafate Formation and they exhibit lateral variability in depositional facies.

The stratigraphic sections were divided into sedimentary facies (SF) based on bed or set thickness, grain size, sedimentary structures and trace fossils, which allowed the recognition of depositional processes (Table 1). The genetically related SFs were grouped in facies associations (FA) (Table 2), where each FA represents a distinct part of a depositional system. For every FA, ichnoassociations were documented considering main ichnotaxobases, as proposed by Bromley (1990, 1996). Palaeocurrents were measured using a Brunton® compass mostly in cross-bedded facies and occasionally in ripple crests and imbricated clasts. The data were appropriately corrected for tilt (Potter and Pettijohn, 1963) and for magnetic declination.

The measured sections were correlated at the meter scale based on the lateral continuity of FAs and using the first prominent sandstone succession of the Man Aike Formation as the guide level for correlation given that it is laterally continuous and traceable across the length of the outcrop extension. Correlations included the identification of architectural elements, which were distinguished by a variety of characteristics, including bounding surfaces, lithofacies composition, geometry, as well as vertical and lateral associations (Allen and Fielding, 2007).

FACIES ANALYSIS

Fourteen sedimentary facies were recognized within the Calafate Formation and their characteristics

are summarized in Table 1 and Figures 3 and 4. Then, these sedimentary facies were grouped into six facies associations (FAs). Table 2 summarizes the characteristics and interpretations of the facies associations and ascribed to different depositional environments for the Calafate Formation. The FAs described below were organized in a stratigraphic order from base to top (Table 2).

Facies association 1 (FA1): foreshore to upper shoreface deposits

Description. This FA is characterized by sandstone bodies with an external tabular geometry, reaching up to 15 m thick and 5-10 km of lateral extension (Fig. 5a). Internally, it is defined by tabular strata delimited by irregular bases and undulated tops and displaying a coarsening and thickening upward arrangement. Individual tabular strata are up to 30-40 cm thick and consists of fine to medium bioturbated sandstones (Sb), sandstones with parallel lamination and sandstones with low angle cross-lamination (Sl). The trace fossil assemblage is characterized by *Skolithos*, *Arenicolites* and *Ophiomorpha nodosa*, intercalating with *Macaronichnus*. At the base of the association the *Ophiomorpha* burrows have mud linings that are replaced upward by sand linings. Some levels of sandstones with *Ophiomorpha* are recognized due to very large galleries (Fig. 5a, b) and some other levels present a very high density of *Ophiomorpha nodosa* with a lateral variation of bioturbation intensity (Fig. 5c).

Interpretation. The texture, sedimentary structures and the general arrangement of the sandstones suggest deposition in high-energy settings, well above fair-weather wave base. The trace fossil assemblage reflects a predominance of vertical over horizontal components indicating relatively high energy conditions (Howard and Frey, 1984; Anderson and Droser, 1998). Additionally, the low ichnodiversity recorded by the monospecific *Ophiomorpha* association and the size and lining of the pellets, supports the stressful conditions related to relatively high energy (Buatois and Mángano, 2011), common in shallow coastal environment (Daly, 1997). Moreover, the assemblage dominated by the ichnogenus *Macaronichnus* is reflecting conditions of very high energy, given that the archetypal *Skolithos* ichnofacies has been replaced

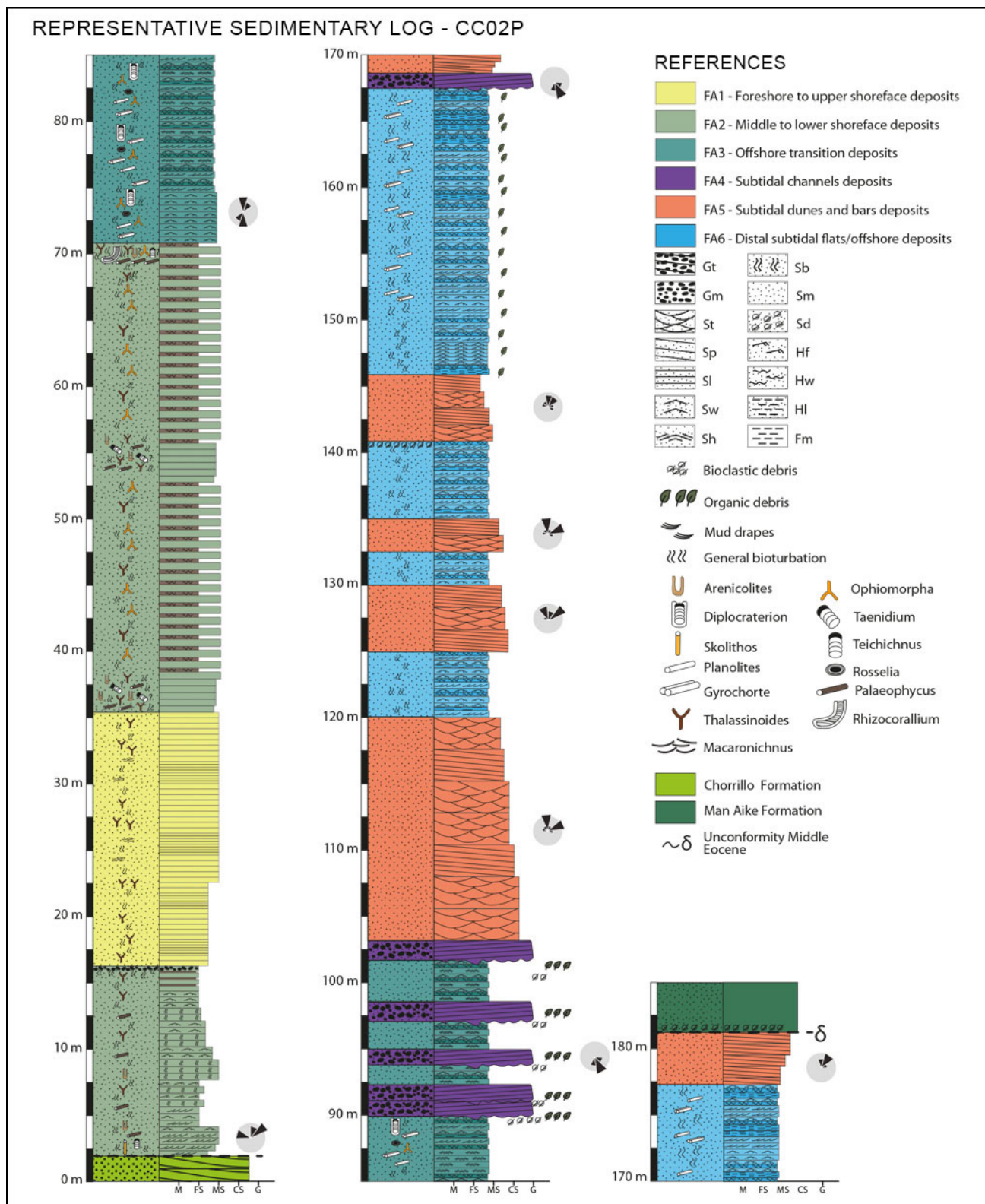


Figure 2. Detailed representative vertical section of the Calafate Formation at the type locality Cerro Calafate. References: CC=Cerro Calafate (Calafate Hill); M=mudstones; FS= fine sandstone; MS=medium sandstone; CS=coarse sandstone; G=gravel; Gt= conglomerate with planar to tangential cross-stratification; Gm= massive conglomerate; St=sandstone with trough cross-lamination/cross-stratification; Sp=sandstone with planar to cross-lamination/cross-stratification; Sl=sandstone with parallel lamination; Sw=sandstone with ripple lamination; Sh= sandstone with hummocky cross-stratification; Sb=bioturbated sandstone; Sm=massive sandstone; Sd= bioclastic sandstone; Hf= flaser bedding; Hw= wavy bedding; HI= lenticular bedding; Fm= massive mudstone.

SF	Lithofacies	Texture	Bed / set (cm)	Sedimentary structures	Trace and body fossils I	Interpretation
Gt	Fine to medium conglomerate	Clast-supported, moderate sorting	50 - 100	Planar to trough cross-stratification, mud rip-up clasts	<i>Ophiomorpha nodosa</i> , <i>Ophiomorpha</i> isp.	Downstream migration of bi- to three-dimensional dunes
Gm	Fine to medium conglomerate	Matrix-supported, poor sorting	10 - 100	Structureless	Absent	Rapid deceleration of a concentrated flow
St	Medium to coarse sandstone	Clast-supported, moderate to well sorting	20 - 100	Trough cross-lamination, trough cross-stratification, frequently with inner reactivation surfaces and mud drapes	<i>Ophiomorpha nodosa</i> , <i>Ophiomorpha</i> isp.	Downstream migration of three-dimensional ripples and dunes, with periods of suspension settling and some degree of tidal reworking
Sp	Fine to coarse sandstone	Clast-supported, moderate to well sorting	10 - 30	Planar to cross-lamination, planar to cross-stratification, frequently with mud drapes	Absent	Downstream migration of bi-dimensional ripples and dunes, with periods of suspension settling
Sl	Fine to medium sandstone	Clast-supported, moderate to well sorting	10 - 40	Parallel lamination, low angle cross-lamination	Absent	Upper flow regime (unidirectional)
Sh	Medium sandstone	Clast-supported, moderate sorting	25 - 45	Hummocky cross-stratification	Absent	Aggradation of sand originated by a combination of oscillatory and combined flow
Sw	Medium to coarse sandstone	Clast-supported, moderate to well sorting	2 - 3; 20 - 40	Ripple lamination, symmetric to moderately asymmetric ripples with mud drapes	Absent	Low to moderate energy of oscillatory flow and suspension settling episodes
Sb	Very fine to coarse sandstone	Clast-supported, moderate sorting	30 - 40	Structureless, symmetric ripples to the tops	<i>Skolithos</i> and <i>Cruziana ichnofacies</i>	Loss of primary structure due to bioturbation, oscillatory flow
Sm	Medium to coarse sandstone	Clast-supported, moderate sorting	5 - 15	Structureless	Absent	Rapid deceleration of a hyperconcentrated flow (high-sedimentation rate)
Sd	Medium to coarse sandstone	Matrix to clast-supported, poor to moderate sorting	15 - 20	Structureless	Fragments of marine invertebrates	Rapid deceleration of a hyperconcentrated flow (high-sedimentation rate)
Hf	Fine to coarse sandstone and siltstone	Clast-supported, moderate sorting	10 - 15 / 100	Tangential cross-lamination	<i>Skolithos</i> and <i>Cruziana ichnofacies</i>	Bedload (sand) > suspension settling (mud) deposition during fluctuating flow energy
Hw	Very fine to coarse sandstone and mudstone	Clast-supported, moderate sorting	5 - 15 / 100	Tangential cross-lamination	<i>Skolithos</i> and <i>Cruziana ichnofacies</i>	Fluctuating periods of suspension settling (mud) and bedload (sand) deposition during fluctuating flow energy
HI	Mudstone and very fine sandstone	Matrix-supported, poor sorting	10 - 15 / 400	Tangential cross-lamination	Absent	Suspension settling (mud) > bedload (sand) deposition during fluctuating flow energy
Fm	Mudstone	Moderate sorting	5 - 10 / 400	Structureless	Absent	Suspension settling in subaqueous conditions

Table 1. Descriptions and interpretations of sedimentary facies (SF) for the Calafate Formation.

FA	Sed. facies	Sedimentary characteristics	Architectural elements	Trace fossil assemblage	Mean palaeoflow direction	Interpretation
FA1	Sb, SI	Sandstone dominated. Bioturbated sandstones. Medium-scale sets, planar to irregular bases, undulated tops (symmetric to slightly asymmetric ripples). Coarsening and thickening upward arrangement	Tabular, large lateral continuity (> 10 km)	<i>Ophiomorpha</i> isp., <i>Ophiomorpha nodosa</i> , <i>Skolithos</i> , <i>Arenicolites</i> , <i>Macaronichmus</i> . (<i>Skolithos</i> ichnofacies)	-	Foreshore to upper shoreface deposits
FA2	St, Sb, Sw, Sh, Hf, Hw, Gm	Sandstone dominated. Tabular strata, planar bases and undulated tops, displaying a fining and thinning upward arrangement	Tabular, large lateral continuity (> 10 km)	<i>Ophiomorpha</i> isp., <i>Ophiomorpha nodosa</i> , <i>Skolithos</i> , <i>Arenicolites</i> , <i>Planolites</i> , <i>Palaeophycus</i> , <i>Taenidium</i> , <i>Phycosiphon incertum</i> , <i>Diplocraterion</i> , <i>Rhizocorallium</i> , <i>Rosselia</i> , <i>Thalassinoides</i> isp., <i>Protovirgularia</i> (?). (<i>Skolithos</i> ichnofacies; <i>Cruziana</i> ichnofacies; and <i>Glossifungites</i> ichnofacies)	NE (W)	Middle to lower shoreface deposits
FA3	Sw, Sb, Sh, Hw, Fm	Sandstone dominated. Tabular to irregular strata, mud laminae preserved at the tops. Rhythmic intercalation. Bioturbated sandstones. Fining and thinning upward arrangement	Tabular, large lateral continuity (> 10 km). Top of the succession is truncated by large-scale erosive surfaces linked to FA4 and FA5	<i>Skolithos</i> , <i>Planolites</i> , <i>Palaeophycus</i> , <i>Thalassinoides</i> , <i>Arenicolites</i> , <i>Taenidium</i> , <i>Rosselia</i> , <i>Gyrochorte</i> , <i>Bergaueria</i> and <i>Diplocraterion</i> . (<i>Cruziana</i> ichnofacies)	N (landward); S (seaward) (bi-modal)	Offshore transition deposits
FA4	Gm, Gt	Conglomerate dominated. Amalgamated lenticular bodies, concave-up medium-scale erosive bases, planar tops. Mud drapes. Mud clast, plant debris and ostrea valves remains at the bases. Mud clast host borings of undetermined trace fossils	Tabular to lenticular, large lateral continuity (> 10 km). Large-scale erosional surface	<i>Ophiomorpha nodosa</i> , <i>Ophiomorpha</i> isp.	S, SE (seaward)	Subtidal channels deposits
FA5	St, Sp, Sd	Sandstone dominated. Tabular to lenticular strata, slightly planar erosional bases and planar tops, displaying a fining and thinning upward arrangement. Internally mud drapes, reactivation surfaces, scarce mud rip-up clast at the bases	Tabular, large lateral continuity (> 10 km). Large-scale inclined surfaces (accretion). Top of the succession is truncated by large scale erosive surface (middle Eocene unconformity)	<i>Ophiomorpha nodosa</i> , <i>Ophiomorpha</i> isp.	N-NE	Subtidal dunes and bars deposits
FA6	Hw, Hf, Hl, Sb, Sw, St, Fm	Mixed dominated. Tabular to irregular strata. Internally with mud drapes, reactivation surfaces (?). Sand/mud rhythmites. Bioturbated sandstones	Tabular, large lateral continuity (> 10 km)	<i>Skolithos</i> , <i>Arenicolites</i> , <i>Planolites</i>	-	Distal subtidal flats/offshore deposits

Table 2. Description and interpretations of facies associations (FA) for the Calafate Formation.

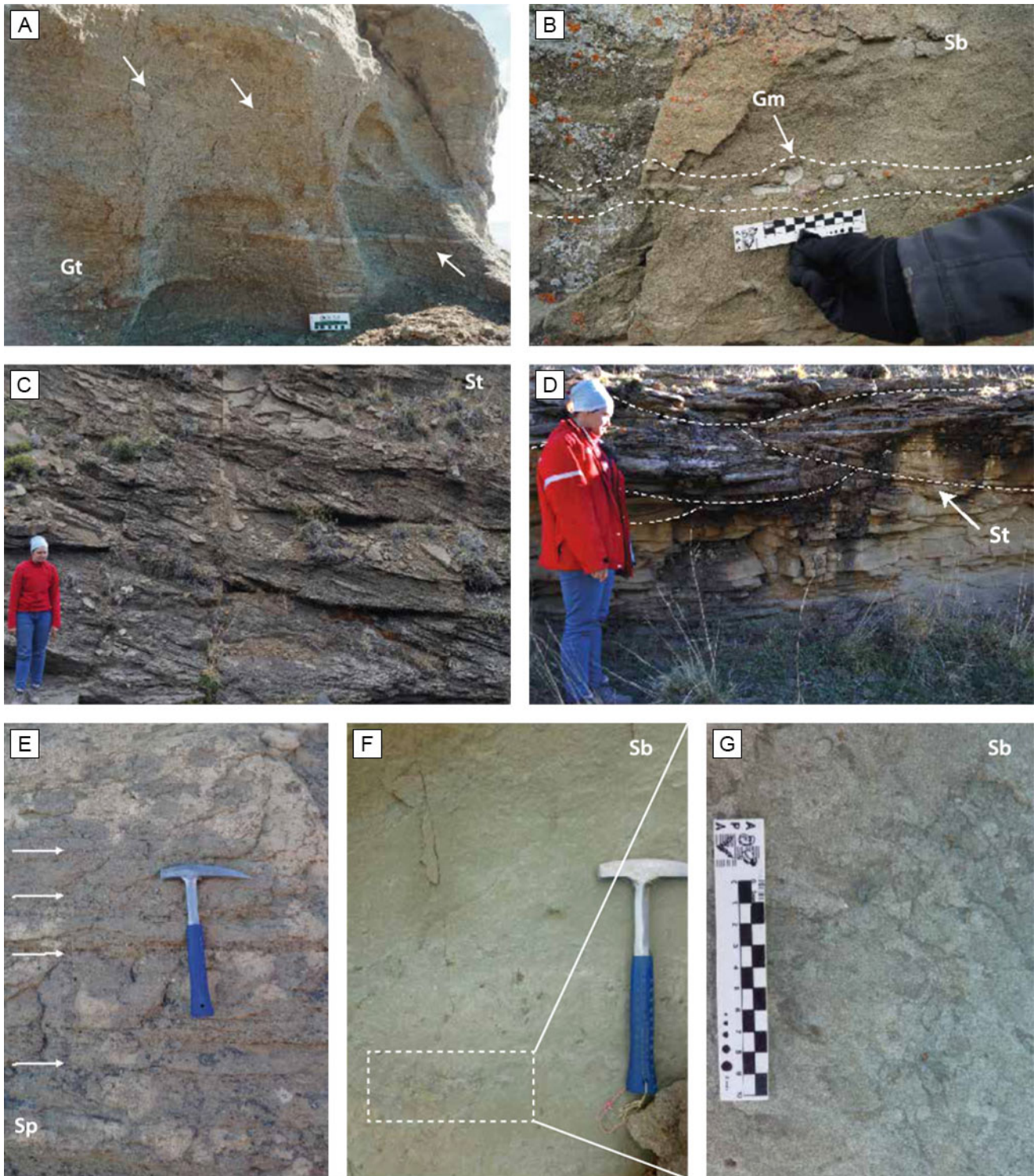


Figure 3. Field photographs of representative sedimentary facies of the Calafate Formation. **a)** General view of conglomerate deposits with trough cross-stratification (Gt) and mud drapes (white arrows). **b)** Laminae of structureless, matrix-supported fine to medium conglomerates (Gm) (dotted white lines), recognized within the cross-stratified sandstones (St). **c)** Medium-scale co-sets of sandstones with trough cross-stratification (St). **d)** Sandstones with trough cross-stratification (St) showing well developed troughs. Dotted white lines are pointing out different sets. **e)** Sandstones with parallel cross-stratification (Sp), internally with cross-beds displaying grain size variations (white arrows). **f)** Common aspect of bioturbated sandstones (Sb). **g)** Close up of bioturbated sandstones (Sb); the primary sedimentary structures of these sandstones are completely obliterated due to the high degree of bioturbation.

by this ichnogenus (Pemberton *et al.*, 2001). The lithological characteristics of the sandstones and the *Skolithos* ichnofacies interpretations suggest that this association deposited between foreshore to upper shoreface environments.

Facies association 2 (FA2): middle to lower shoreface deposits

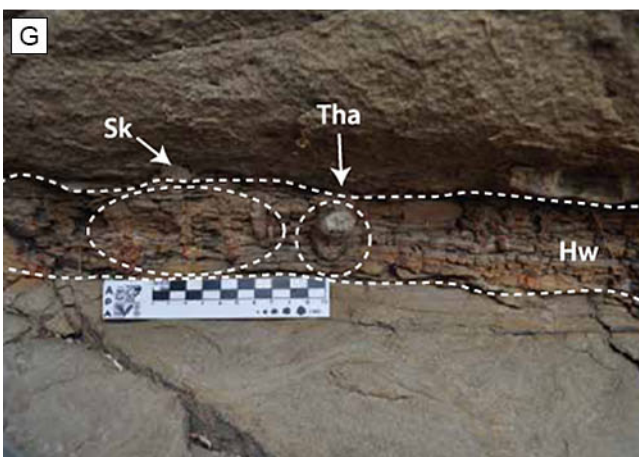
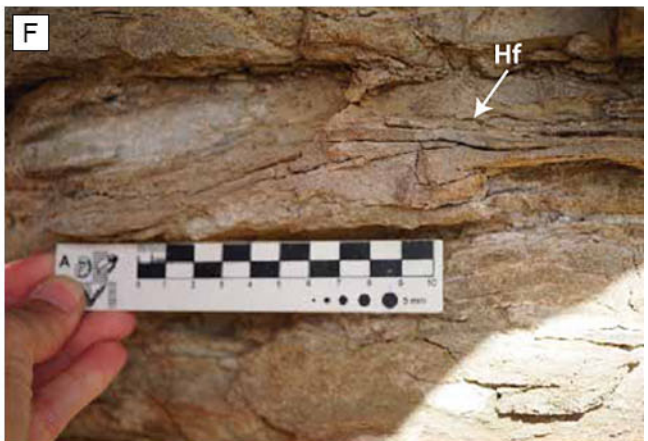
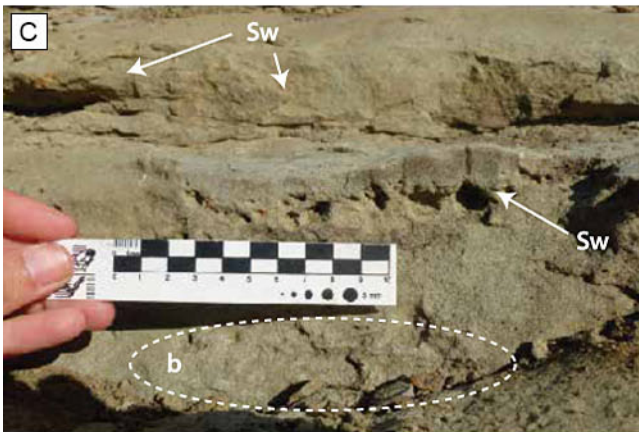
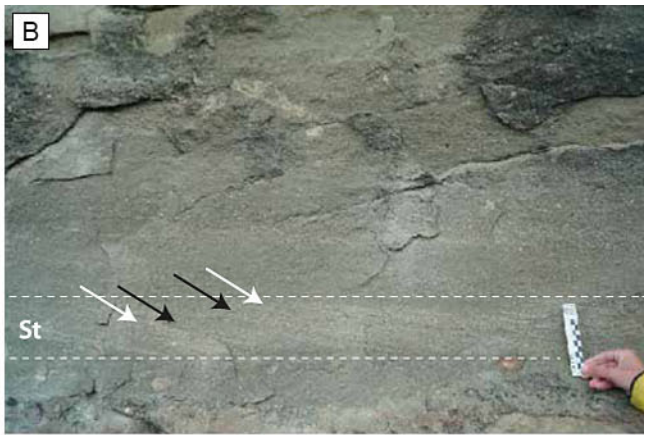
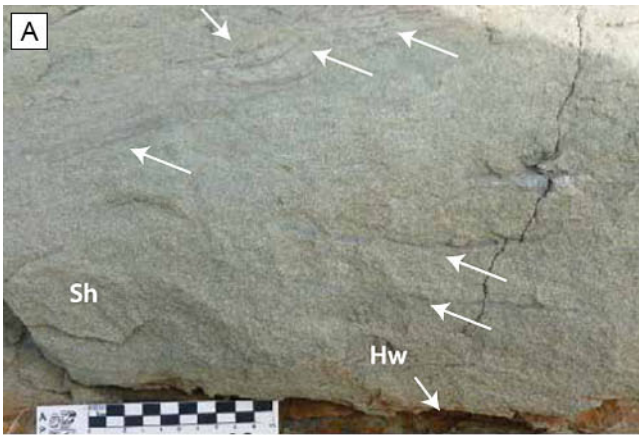
Description. Deposits of FA2 form tabular packages up to 40.5 m thick, which are laterally continuous for several kilometers (Fig. 5a). The packages are composed of sandstone-dominated tabular strata, delimited by irregular to planar bases and undulated tops, displaying a fining and thinning upward arrangement (Fig. 5e, f). They initiate with amalgamated tabular sets of 30-50 cm thick, composed of coarse sandstones with trough tangential cross-lamination (St), covered by bioturbated medium sandstones (Sb) up to 20 cm thick, and interbedded with ripple lamination (Sw) (3-5 cm thick). The association culminates with hummocky cross-stratified (Sh) beds and with symmetric ripples preserved at the tops, interbedded with flaser (Hf) to wavy bedding (Hw). Occasionally, thin levels of massive medium conglomerates (Gm) occur as tabular and horizontal to sub-horizontal strata in these upper sandstones. Bioturbation and ichnodiversity range from moderate to high and vary vertically throughout the FA2. The lower sandstones exhibit *Ophiomorpha* isp., *Skolithos* and *Arenicolites*, while the middle to upper sandstones are characterized by ichnogenera of the *Cruziana* ichnofacies, such as *Planolites*, *Palaeophycus*, *Taenidium*, *Phycosiphon incertum*, *Diplocraterion*, *Rhizocorallium*, *Rosselia*, *Thalassinoides*, *Ophiomorpha nodosa*, *Ophiomorpha* isp., and *Protovirgularia* (?). Some levels of sandstones with *Ophiomorpha* are recognized due to very large galleries such as those in FA1 (Fig. 5a). The trace fossil assemblage culminates with *Glossifungites* ichnofacies, where vertical and unlined shafts of *Thalassinoides* penetrate fine sandstones, and the passive burrow fill has been partially eroded by modern weathering (Fig. 5d). Palaeocurrent data collected at the Cerro Calafate locality, from the cross-laminated sandstones, indicate directions mainly to the northeast and yield a dispersion to the west.

Interpretation. This facies association is interpreted as the result of three-dimensional subaqueous

dunes migration during high-energy conditions dominated by wave action and associated currents. Upwards, the energy conditions were moderate to low, evidenced by the deposition of sandstones by the migration of subaqueous ripples, which intercalate with mud suspension settling events. The medium and coarse sandstones (St, Sb, Sw) and the interbedded layers of silt and mud reflect deposition between fair-weather wave base and storm wave base. Lithological variability induced by alternating storm and fair-weather conditions is typical for shallow marine strata (Bhattacharyya *et al.*, 1980). In addition, due to the geometry, extension and sporadic appearance, the conglomeratic intercalations are interpreted as lags formed during maximum storm intensity. The degree of bioturbation displayed by the *Skolithos* ichnofacies also indicates high-energy and reflects high abundance of organic particles kept in suspension in the well-oxygenated water column dominated by waves and currents. The *Cruziana* ichnofacies reflect overall environmental stability and low to moderate sedimentation rates. In turn, the *Glossifungites* ichnofacies recognized at the top of the association depicts colonization by suspension feeders or passive predators in a stable and cohesive substrate (firmgrounds) (Buatois and Mángano, 2011). The vertical variations described throughout FA2 deposits suggest that this association deposited between the middle to lower shoreface environment.

Facies association 3 (FA3): offshore transition deposits

Description. FA3 presents a tabular external geometry, with 21.5 m thick and 5-10 km of lateral extension (Fig. 5a, g). Typically, the association consists of sandstone-dominated packages with a higher mud proportion in comparison with FA1 and FA2. The FA3 is delimited by planar to irregular base and top and displaying a fining and thinning upward arrangement (Fig. 5g). The packages are organized as tabular strata with ripple stratification (Sw) in the lower part and bioturbated sandstones (Sb) of 2-3 cm thick. In contrast, mud laminae are preserved at the top of the beds (Fig. 5h). These facies are covered by rhythmic intercalations of bioturbated sandstones (Sb), sandstones with hummocky cross-stratification (Sh) and wavy bedding (Hw) (5-10 cm thick) (Fig. 5j). The Sh sandstones are generally unbioturbated and can also be observed as a thick succession of



amalgamated sets of 20-40 cm thick, delimited by Hw sandstones bioturbated by *Planolites*. FA3 culminates with ripple-stratified sandstones (Sw), flaser (Hf) to wavy bedding (Hw), and mudstones (Fm). The upper beds of FA3 are commonly truncated by large-scale erosive surfaces dividing them from FA4 and FA5 deposits. The succession is commonly bioturbated by ichnogenus such as *Skolithos*, *Planolites*, *Palaeophycus*, *Thalassinoides*, *Arenicolites*, *Taenidium*, *Rosselia*, *Gyrochorte*, *Bergaueria* and *Diplocraterion* (Fig.5i), typical of the *Cruziana* ichnofacies. The palaeocurrent directions obtained from the crests of the symmetric ripples preserved at the top of the strata are mainly towards the north and to the south (Fig. 5g).

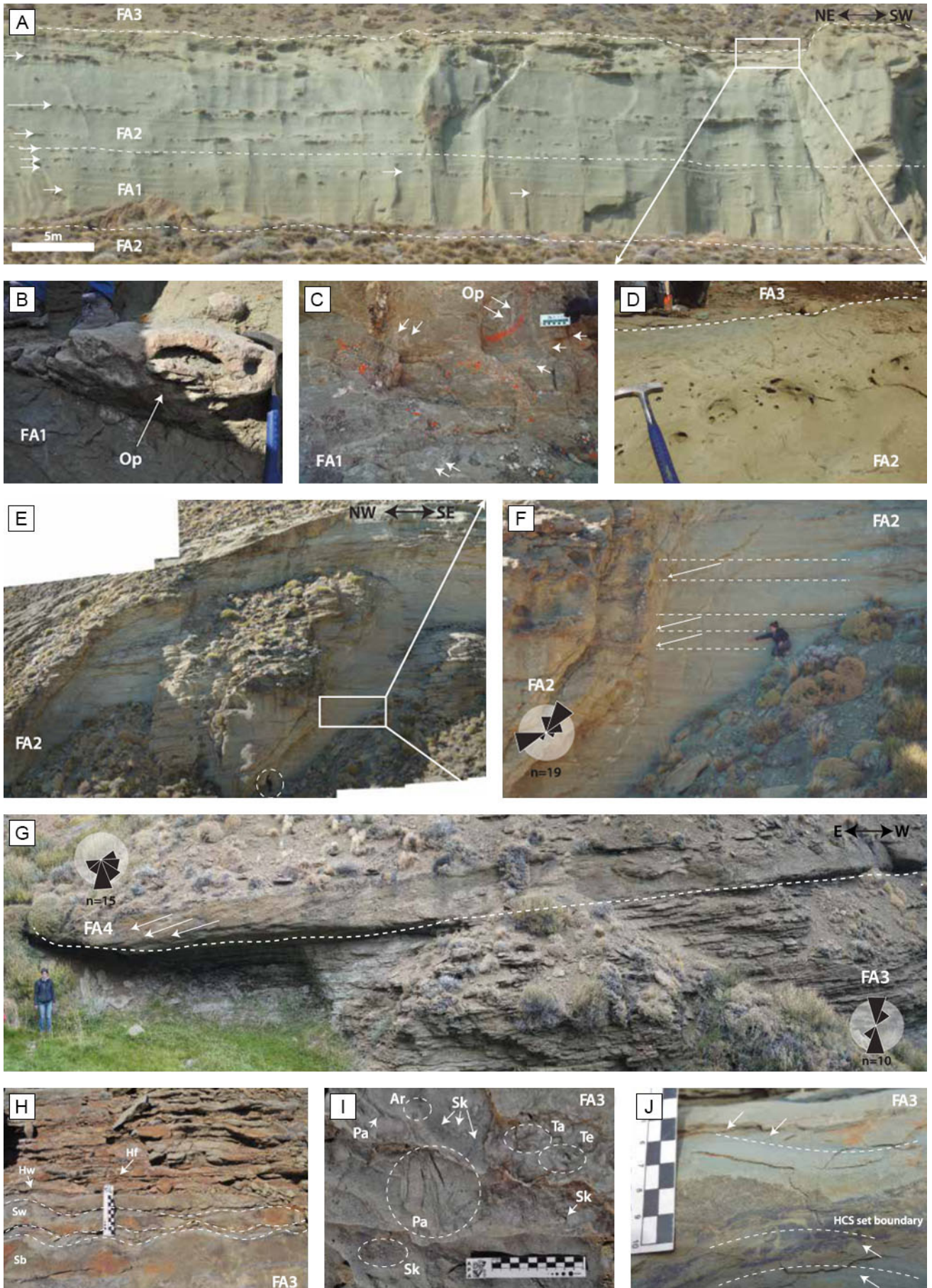
Interpretation. This facies association is interpreted to represent ripple migration processes and settling from suspension during fair-weather conditions, alternating with sand accumulated by oscillatory and combined flows during storm events. The interbedded layers of sandstones and mud forming heterolithic successions favored the preservation of trace fossils due to the lithological contrast. Dominance of horizontal structures reflected by the traces of the *Cruziana* ichnofacies indicates accumulation of organic detritus in sediment under moderate to low energy conditions. In this sense, the ethologies and trophic types represented, and the moderate to high diversity and abundance of biogenic structures, commonly reflect overall environmental stability and low to moderate sedimentation rates (Buatois and Mángano, 2011). The *Cruziana* ichnofacies occurs in a bathymetric range from slightly above the fair-weather wave base to the storm wave base (MacEachern *et al.*, 1999a). The alternation of high-energy storm events and low energy fair-weather mudstone deposition suggest that this association accumulated in the transition between the shoreface and offshore environments.

Facies association 4 (FA4): subtidal channels

Description. This facies association overlies directly through a large-scale erosive contact on top of FA3 deposits (Fig. 5g, 6a, c). This association is characterized by conglomerate bodies with an external tabular to lenticular geometry, up to 4 m thick (2 m on average), and > 10 km of lateral extension (Fig. 6a). Internally, they have a complex organization, defined by the vertical and lateral amalgamation of individual lenticular bodies delimited by concave-up medium-scale erosive bases and planar tops (Fig. 6c). Laterally, towards the west, the conglomeratic levels have a lower degree of amalgamation and are commonly interbedded with heterolithic tabular deposits of FA3. Individual lenticular bodies have on average 1.75 m thick and 60 m wide and are composed of medium to fine conglomerates and coarse sandstones with tangential cross-stratification (Gt, St) (Fig. 6c, d) and displaying a fining upward arrangement (Fig. 6d). Sets are up to 1m-thick with grain-size variations and mud drapes (0.5-1 cm thick) (Fig. 6e). At the bases, plant debris and abundant *Ostrea* shells remains were observed (Fig. 6g), as well as mud clasts which host borings of undetermined trace fossils. Some disperse and isolated trace fossils exclusively of *Ophiomorpha nodosa* and *Ophiomorpha* isp. are distributed randomly at the base or in the middle of the conglomerates (Fig. 6f). The palaeocurrent indicators obtained from the conglomeratic deposits, at CC and A25M vertical sections, indicate directions preferentially towards the south and southeast (paleo-seaward) (Fig. 6c).

Interpretation. This facies association represents the migration of two and three-dimensional dunes during high-energy conditions related to unidirectional tractive currents. The lenticular geometry, the erosive bases, as well as the fining upward arrangement, suggest that these conglomerates were deposited as

Figure 4. Field photographs of representative sedimentary facies of the Calafate Formation. **a)** Sandstones with hummocky cross-stratification (Sh) with mud laminae preserved at the tops of strata (white arrows). Sets are delimited by wavy beddings (Hw). **b)** Sandstones with tangential cross-lamination (St), showing alternated fine (black arrows) and coarse (white arrows) sandstone laminae in the foresets. **c)** Sandstones with ripple lamination (Sw) (white arrows), commonly disturbed by bioturbations (*b*) (white circle) and with ripples preserved on top of the strata. **d)** Massive sandstones (Sm) characterized by the massive aspect and the absence of any primary and biogenic structures. **e)** Massive sandstones (Sd) characterized by abundant gravel clasts and skeletal debris of marine invertebrate fossils randomly distributed. **f), g), h)** Heterolithic deposits (facies H) including flaser (f), wavy (w) and lenticular (l) beddings, respectively. References: *Sk*=*Skolithos*; *Tha*=*Thalassinoides*.



the infill of channels. The mud drapes, attributed to recurring energy variations that allow suspension settling of fine-grained material, together to the outcrop geometry, indicate tidal currents (De Raaf and Boersma 1971; Marensi *et al.*, 2004). Moreover, a subtidal channel complex below the low tide mean level is proposed, considering the different degree of amalgamated channels and the lateral extension registered for this unit. The isolated trace fossils within the coarse material indicate sediment contribution from a shallower sector, as well as the vegetal debris and oyster fragments.

Facies association 5 (FA5): subtidal dunes and bars

Description. The FA5 is composed of sandstone-dominated packages more than 10 km of lateral extension and more than 15 m in thickness, with a tabular external geometry (Fig. 7a-c, 8a-c). Internally, individual bodies are bounded at the base by sharp and slightly planar erosional surfaces, whereas tops are planar (Fig. 7c, 8c). In addition, the individual bodies are delimited by large-scale inclined surfaces (Fig. 7a, b). Individual bodies comprise tabular to lenticular sets up to 1.5 m thick and co-sets up to 3.5 m thick. The association commonly initiates with massive conglomerates (Gm) with mud clasts or bioclastic massive sandstones (Sd), and then is covered by sandstones with planar cross-stratification (Sp), tangential cross-stratification and trough cross-stratification (St), displaying a thinning and finning upward arrangement. Within the sets, thick mud drapes, inner reactivation surfaces and plant debris are observed (Fig. 8c, e, f), as well as some randomly distributed reworked marine fossils such as *Belemnites* and trace fossils of

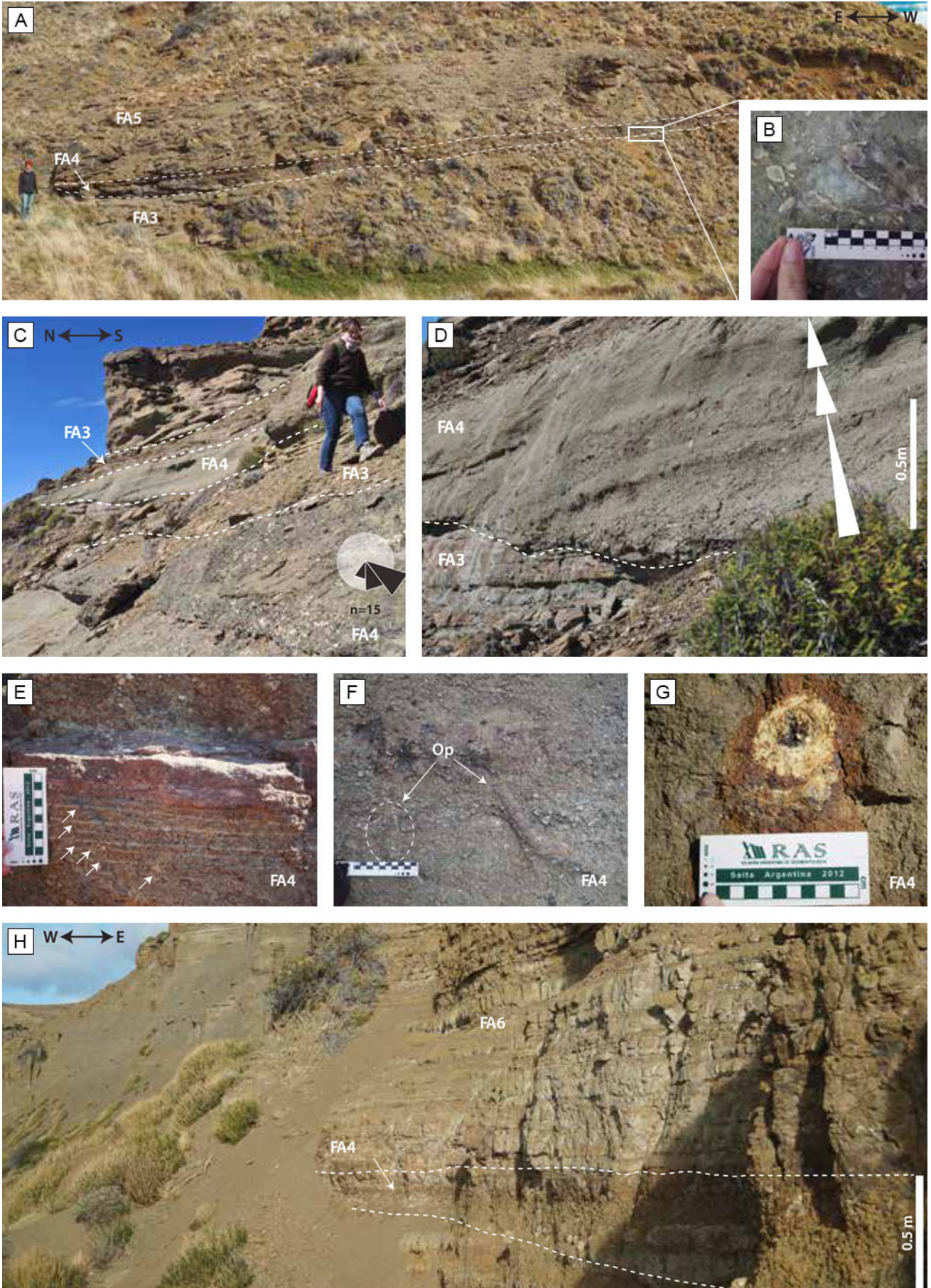
Ophiomorpha nodosa or *Ophiomorpha* isp. Palaeocurrents obtained from tangential cross-stratification at CC and A25M reveal a primary transport direction to the NE and a subordinate transport direction to the north (Fig. 7a, c, 8c).

Interpretation. This facies association is interpreted as the result of two and three-dimensional subaqueous dunes migration. The sedimentary structures and the significant height and length of the sandy bodies suggest deposition in relatively high-energy settings below the low tide mean level. The presence of large-scale inclined surfaces indicates that the sandstone units were deposited as accreted large bars. Additionally, the internal facies trend, the dominantly landward palaeocurrent directions, inner reactivation surfaces, and the mud drapes, indicate the accumulation of these deposits as subtidal dunes (Plink-Björklund, 2005; Pontén and Plink-Björklund, 2009). This type of sandy bodies with large-scale bedforms has been reinterpreted as representing compound dunes (Dalrymple *et al.*, 2003; Dalrymple and Choi, 2007). Levels with thick mud drapes would probably result from the rapid deposition of flocculated material in the most protected areas of the interdunes. The lack of bioturbation in the sandy bodies indicates moderate to high sedimentation rates and erosion resulting from continuous and rapid bedform migration (Desjardins *et al.*, 2012).

Facies association 6 (FA6): distal subtidal flats/offshore

Description. FA6 presents a tabular external geometry, with 20 m thick and more than 10 km of

Figure 5. Outcrop photographs of the facies associations of the Calafate Formation. **a)** Shallow marine deposits of FA1, FA2, FA3 at the Cerro Calafate. Large *Ophiomorpha* isp. galleries are highlighted by white arrows. **b)** Close-up to a large *Ophiomorpha* isp. gallery within foreshore to upper shoreface deposits of FA1. **c)** *Ophiomorpha nodosa* conspicuous ichnofabric displaying an explosion of activity of the organisms within the sandstones of FA1. **d)** Close-up to *Glossifungites* ichnofacies at the top of FA2, covered by FA3 deposits (dotted white line indicates the omission surface). **e)** General view of middle to lower shoreface deposits of FA2; person for scale *ca* 1.7 m tall. FA2 is highlighted by its sandstone-dominated tabular strata and general homogeneity. **f)** Close-up to FA2 deposits (sandstones with trough and planar cross-stratification; St and Sp, respectively). Main palaeocurrent direction towards NE and W (white arrows). **g)** FA3 deposits at the Arroyo 25 de Mayo locality, truncated at the top by the lenticular bodies of FA4 (dotted white line indicates the erosion surface). Note the cross-stratification presented within the FA4 deposits (white arrows). **h)** Offshore transition deposits of FA3, showing interbedded fine- to coarse sandstones and mudstones, displaying rhythmic intercalations of bioturbated sandstones (Sb), sandstones with ripple cross-lamination (Sw) and flaser (Hf) to wavy bedding (Hw). **i)** Bedding-plane view of FA3 deposits with trace fossils of *Arenicolites* (Ar), *Skolithos* (Sk), *Palaeophycus* (Pa), *Taenidium* (Ta), and *Teichichnus* (Te). **j)** Close-up to sandstones with hummocky cross-stratification (HCS), in which the set boundary is highlighted by dotted white lines and white arrows.



lateral extension (Fig. 6h). Typically, the association consists of mixed-dominated (sand and mud) packages, delimited by planar to irregular bases and tops, displaying a fining and thinning upward arrangement. The packages are organized as tabular strata with rhythmic intercalation of wavy (Hw) and flaser (Hf) bedding, and lenticular (Hl) bedding in a lesser proportion (Fig. 7d). These facies are often intercalated with ripple stratification (Sw) and bioturbated sandstones (Sb) of 2-3 cm thick, and less usually with cross-laminated sandstones (St) with scarce reactivation surfaces and mud drapes (Fig. 7e). The sandstone levels of the succession are bioturbated by ichnogenus such as *Skolithos* and *Arenicolites*, while *Planolites* is recognized within the heterolithic deposits.

Interpretation. This facies association is interpreted to represent tractive (bedload sedimentation) and suspensive (fallout of suspended sediment) processes of moderate frequency, suggesting periodically fluctuating currents. The heterolithic intervals, mud drapes, and reactivation surfaces are indicative of tidal currents (*c.f.* Reineck and Singh, 1980). The sedimentary facies and related processes, together with the lack of evidence for subaerial exposure, allude to deposition as flats in the subtidal zone corresponding to the outermost region of the influence of tides (*c.f.* Desjardins *et al.*, 2012; Fan, 2012). Moreover, the diversity assemblages reflected by the traces of *Skolithos* and *Cruziana* ichnofacies suggests an increase of the faunal diversity from the subtidal sand bodies towards the outer shelf (*c.f.* Buatois and Mángano, 2011).

DISCUSSION

Evolution of depositional systems

The Calafate Formation deposits have been previously

described as high-energy estuarine deposits (Arbe and Hechem, 1984) and as an estuarine system with inter- and sub-tidal flats, sub-tidal channels and tidal sandy bars (Marenssi *et al.*, 2004). Based on a general characterization of the sediments, Marenssi *et al.* (2004) proposed for this unit a sub-tidal environment and stated that an estuary or incised valley is the most likely palaeogeographical context, even though the geometry of the basin has not been recorded. In view of the new data and results presented herein, we have attempted an alternative reconstruction of the depositional system that can explain the architecture and the facies features recorded in the Calafate Formation at the study area. The reconstruction represents a challenge itself, because although excellent, the exposures of the Calafate Formation present vertical cliffs that preclude further detailed analysis that the one presented here.

The facies analysis for the Calafate Formation at the Cerro Calafate suggests it accumulated in a shallow-marine depositional system (Fig 9). The shallow-marine strata initiate with the FA1 overlying the fluvial deposits of the Chorrillo Formation. FA1 represents conditions of very high-energy, related to the shallowest part of the depositional system, replaced transitionally upwards by medium sandstones of FA2 deposited above fair-weather wave base. FA3 covers FA2 through a sharp contact, and it is dominated by low-energy conditions alternating with high-energy storm episodes, which represent the offshore transition part of the depositional system. The contact between FA2 and FA3 is recognizable as a surface marked by the *Glossifungites* ichnofacies. Given its distribution throughout the outcrops and its stratigraphic position, it is interpreted to represent the hardening of the substrate during transgression of the shallow-marine depositional system.

Channelized conglomeratic bodies of FA4, which lo-

Figure 6. Outcrop photographs of the facies associations of the Calafate Formation. **a)** Arroyo 25 de Mayo locality illustrating the lateral continuity of the exposure and the relationships between FA3, FA4 and FA5 deposits; person for scale *ca* 1.7 m tall. **b)** Example of skeletal fragments (*Ostrea*) on the basal erosional surface of FA4; bedding-plane view. **c)** Exposure showing the relationships between FA4 and FA3 deposits at the Cerro Calafate locality. **d)** Close-up to the upward-fining arrangement within the cross-stratified conglomerates and channel-like geometry bodies of FA4. Dotted white line shows FA4 deposits commonly eroding and covering offshore transition deposits (FA3). **e)** Sets with grain size variation and mud drapes within the FA4 deposits (white arrows). **f)** *Ophiomorpha nodosa* (left, white dotted circle) and *Ophiomorpha* isp., (Op) (right, with poorly developed pelletoidal exteriors) located at the base of FA4 deposits. **g)** Vegetal debris (trunk piece) contained within the FA4 deposits. **h)** Exposure of FA6 deposits showing the intercalation of a lenticular body of FA4 towards the upper section of the unit.

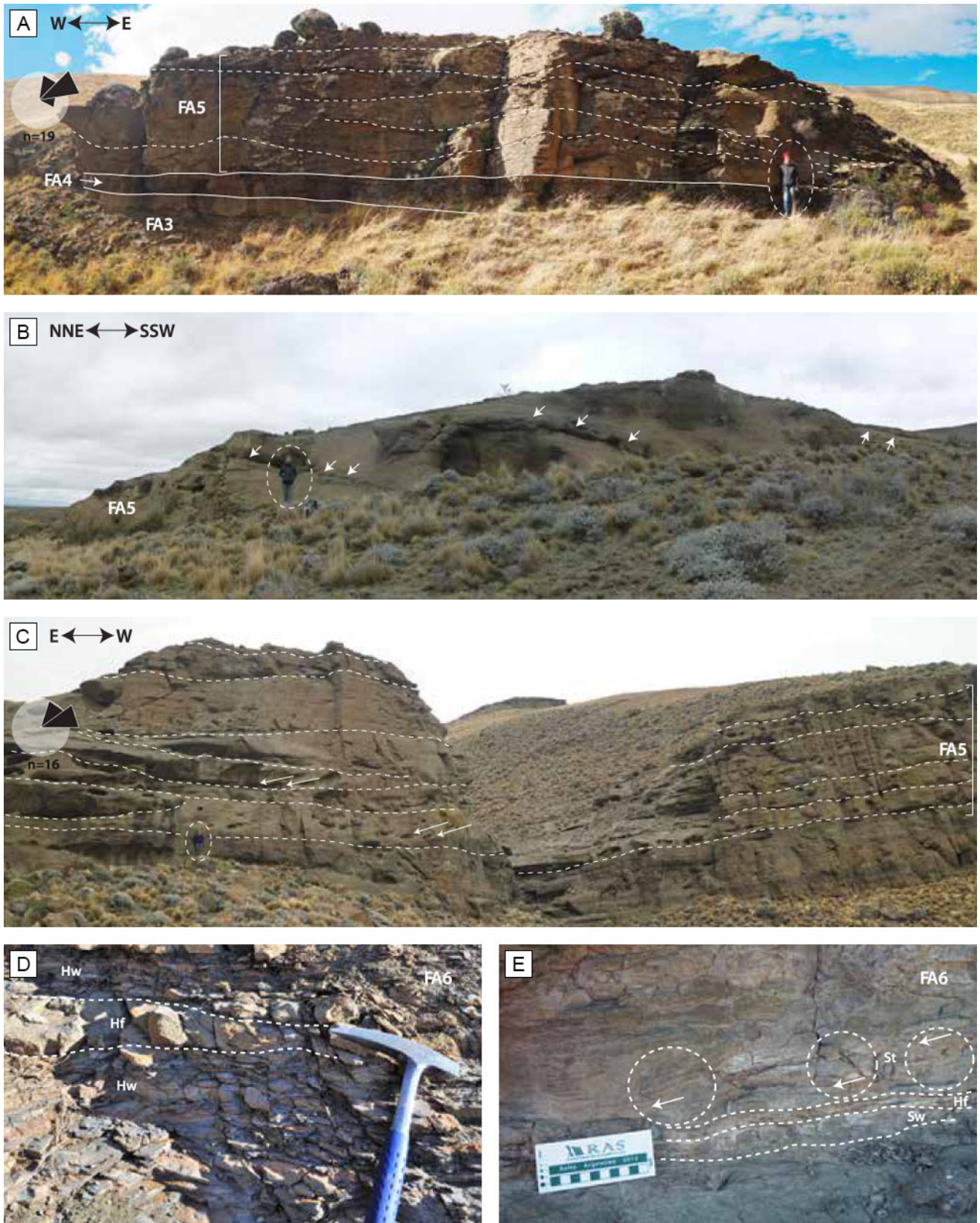


Figure 7. Outcrop photographs of the facies associations of the Calafate Formation. Person for scale *ca.* 1.7 m tall. **a)** Exposures at Arroyo 25 de Mayo locality showing FA5 deposits as a tabular to lenticular unit of brown coarse sandstones that overlies FA4 deposits through a planar and sharp contact (white line). Medium-scale co-sets of FA5 deposits conform the unit (dotted white lines). **b)** Exposure at Vertedero Municipal where the FA5 deposits are delimited by large-scale inclined surfaces (white arrows) related to accreted bars. **c)** Exposure at Cerro Calafate locality of FA5 deposits. Subtidal dunes and bars with large-scale cross-

cally incise over FA3 deposits through a sharp and concave-up contact, are interpreted to reflect deposition in high-energy conditions below low tide mean level. The external tabular geometry and the orientation of palaeocurrents mainly to the south and southeast suggest that they were developed as a channel belt. The strongly erosive base of FA4 indicates the action of currents with high velocities on steep slopes that consequently supplied mud clasts from finer-grained sediments that flanked these channels. The presence of shell fragments of *Ostrea*, vegetal debris and isolated trace fossils of *Ophiomorpha* that constitute patches within FA4 deposits, indicate material contribution from a shallower sector of the depositional system. This interpretation is further supported by the abrupt change in the composition of sandstones recorded within FA4 deposits, which are characterized by a very scarce monocrystalline quartz (~3%), abundant plagioclase (>35%), and a noticeable increment in the feldspar content (petrofacies B; Odino *et al.*, 2017).

The stratigraphic succession continues with the deposition of FA5 over FA4 through a sharp contact, which depicts the initiation of three fining-upward cycles represented by FA5 with vertical intercalation of FA6 (Fig. 10). Each fining-upward cycle begins with tidal dunes and bars deposits (FA5) accumulated in a high-energy environment that is replaced upwards by sandstones and mudstones deposited in a distal subtidal flats/offshore environment (FA6). In this sense, these tidal dunes (FA5) were transgressed and they were ultimately replaced by distal subtidal flats/offshore deposits (FA6). Condensed shell beds recognized at the base of FA5 deposits are interpreted as the result of low net deposition due to sediment bypass during coastal retreat.

At the top of the studied unit the stacking pattern changes reflecting a coarsening-upward arrangement. Here, the tidal dune deposits dominate the upper part of the Calafate Formation and the FA6 deposits are replaced gradually, becoming thinner and less representative. The uppermost part of the depositional system for the Calafate Formation has

been eliminated due to an erosive event after the accumulation of the unit, hence it is not entirely represented (Fig. 8a, b, g, Fig. 9).

Based on the predominance of either wave or tidal processes, the depositional system proposed here for the Calafate Formation can be differentiated into a wave-dominated coast and a tidally dominated coast). The wave-dominated coast is represented by FA1, FA2 and FA3 deposits, where the predictable shore-normal zonation is observed. The FA4 deposits mark an important change in the Calafate Formation, and probably represent a major event in the basin that needs to be farther investigated. Since the accumulation of the amalgamated channels of FA4 (Fig. 9), a tide-dominated coast is emplaced, represented by the alternation of FA4, FA5 and FA6 deposits, where direct tidal effects imparted on sediments by tidal energy are preserved (*e.g.* the subtidal channels, subtidal dunes and bars, reactivation surfaces and mud drapes).

Previous studies (Arbe and Hechem, 1984; Marensi *et al.*, 2004) for the Calafate Formation showed that tidal processes had a significant impact on the sedimentological character of these deposits that resembles an estuarine or an incised valley depositional model. Nevertheless, the results presented in this contribution indicate that the predictable spatial distribution of facies and the stratigraphic organization of deposits for these depositional models are not recorded (*cf.* Dalrymple *et al.*, 1992; Zaitlin *et al.*, 1994). In addition, the sedimentological and architectural characterization of the unit is not compatible with just one depositional system model, in which the sedimentation is controlled by wave, tidal processes, or both, such as barrier island (*cf.* Hayes, 1979), open-coast tidal flats (*cf.* Yang *et al.*, 2005), shoreface with tidal effects (*cf.* Dashtgard *et al.*, 2012) and tidal flats (*cf.* Desjardins *et al.*, 2012). Additional research is necessary to assess the variation in the coast configuration, fair-weather wave, storm wave and tidal flux within these deposits to correctly constrain the shallow-marine depositional systems

stratified sandstones (white arrows) are highlighted with dotted white lines. **d**) Distal subtidal flats/offshore deposits of FA6, showing heterolithic tidal bedding represented mostly by sand/mud rhythmites and flaser (Hf) or wave (Hw) bedding (white dotted lines separating facies). Hammer is *ca.* 28 cm long. **e**) Distal subtidal flats/offshore deposits (FA6) variation displaying trough cross-bedded coarse-to medium grained sandstones (St) (white dotted circles), current-rippled medium-grained sandstones (Sw) and thin levels of flaser bedding (Hf).

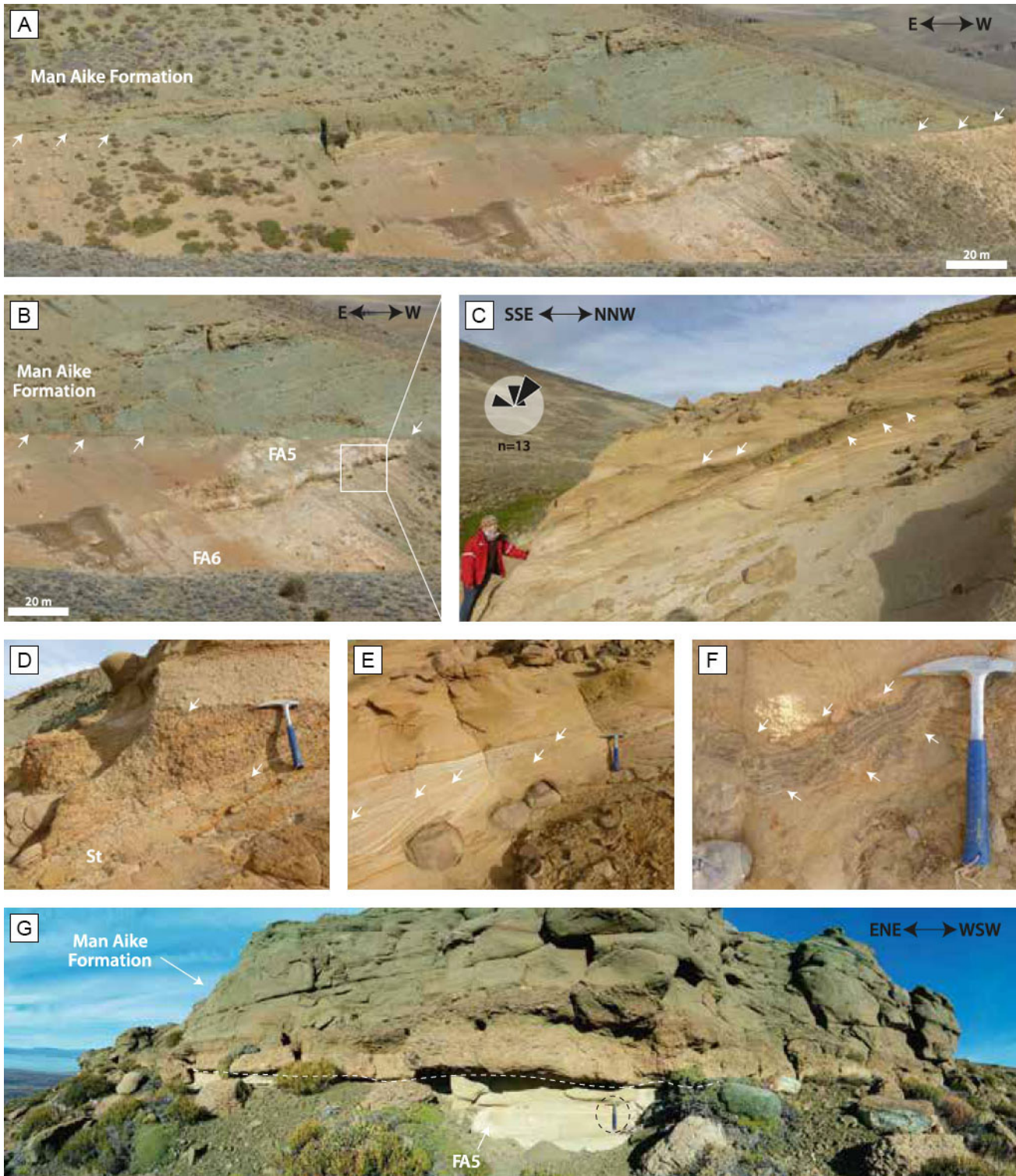


Figure 8. Outcrop photographs of the facies association of the Calafate Formation. **a), b)** Exposure at Arroyo 25 de Mayo locality where the uppermost beds of the Calafate Formation, composed of FA5 deposits, are unconformably overlain through an irregular surface by the marine Man Aike Formation deposits (white arrows). **c)** Close-up view of large-scale sets with tangential cross-stratification or trough cross-stratification within the FA5 sandy and pebbly sandstones deposits. These deposits exhibit several tidally influenced features as the thick mud drapes (white arrows). **d)** Trough cross-stratified pebbly sandstones, internally with foresets displaying grain size variation (white arrows). **e)** Cross-stratified sandstones with internal inner reactivation surfaces (white arrows). **f)** Abundant plant debris following the stratification planes within these deposits (white arrows). **g)** Exposure at Cerro Calafate locality where the uppermost beds of the Calafate Formation (FA5) are unconformably overlain, through a planar surface (dotted white lines), by the marine deposits of the Man Aike Formation. Hammer is ca. 28 cm long.

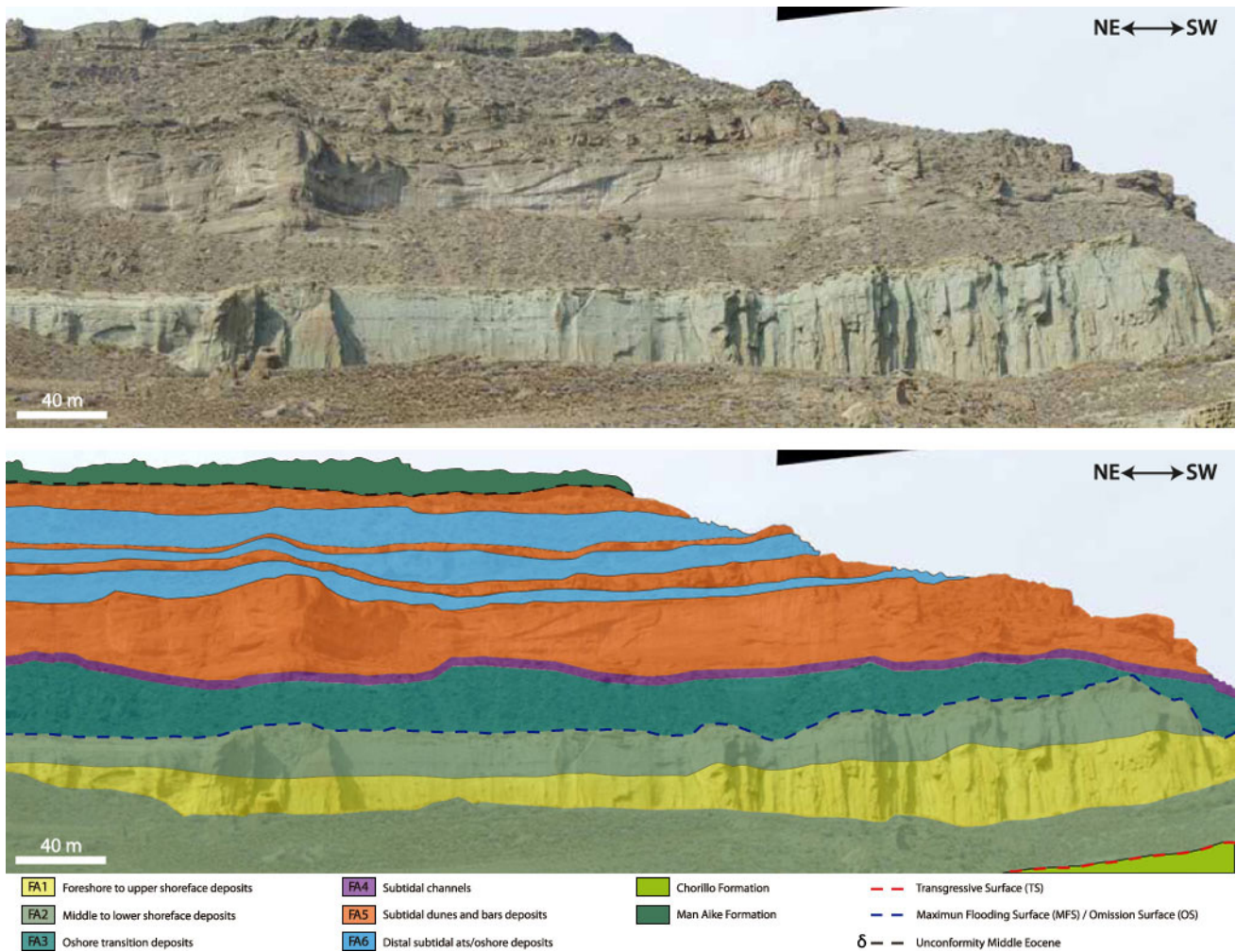


Figure 9. Photo panel showing the distribution of facies associations of the Calafate Formation at the Cerro Calafate type locality. The relationship between the facies associations described and the CC02P vertical section measured (see Fig.1 for location) can be observed. Note the transgressive surface (TS) at the base of the studied unit, the overall deepening-upward trend from FA1 deposits (foreshore to upper shoreface) to FA3 deposits (offshore transition), over which FA4 deposits incised and erode (subtidal channels). Note the maximum flooding surface (MFS) and the omission surface (OS) separating FA2 (middle to lower shoreface) deposits from FA3 deposits (offshore transition). The upper part of the Calafate Formation is represented by FA5 deposits (subtidal dunes) and FA6 deposits (distal subtidal flats/offshore) showing an aggradational stacking pattern.

for the lower and upper environments described for the Calafate Formation.

Sequence stratigraphic architecture

According to previous authors (Arbe and Hechem, 1984b; Arbe, 1989), the Calafate Formation forms part of the fifth depositional cycle of the Austral-Magallanes Basin, named Lago Argentino cycle. This is formed by the transgressive Calafate sub-cycle (Maastrichtian) and the regressive Río Leona sub-cycle (Paleocene-lower Eocene). Taking this into consideration and based on the facies association

analyses as well as the identification of key surfaces, a sequence stratigraphic architecture focusing on the Calafate Formation is attempted.

The shallow marine Calafate Formation overlies directly the fluvial deposits of the Chorrillo Formation (Feruglio, 1938; Arbe and Hechem, 1984), which evidences a transgressive surface (TS) (Fig. 9, 10). The basal succession of the Calafate Formation is dominated by shoreface deposits, varying from foreshore to upper shoreface and middle to lower shoreface, and reaching up to 70 m in thickness. These sandstones passed abruptly upwards to heterolithic deposits and thin-bedded muddy

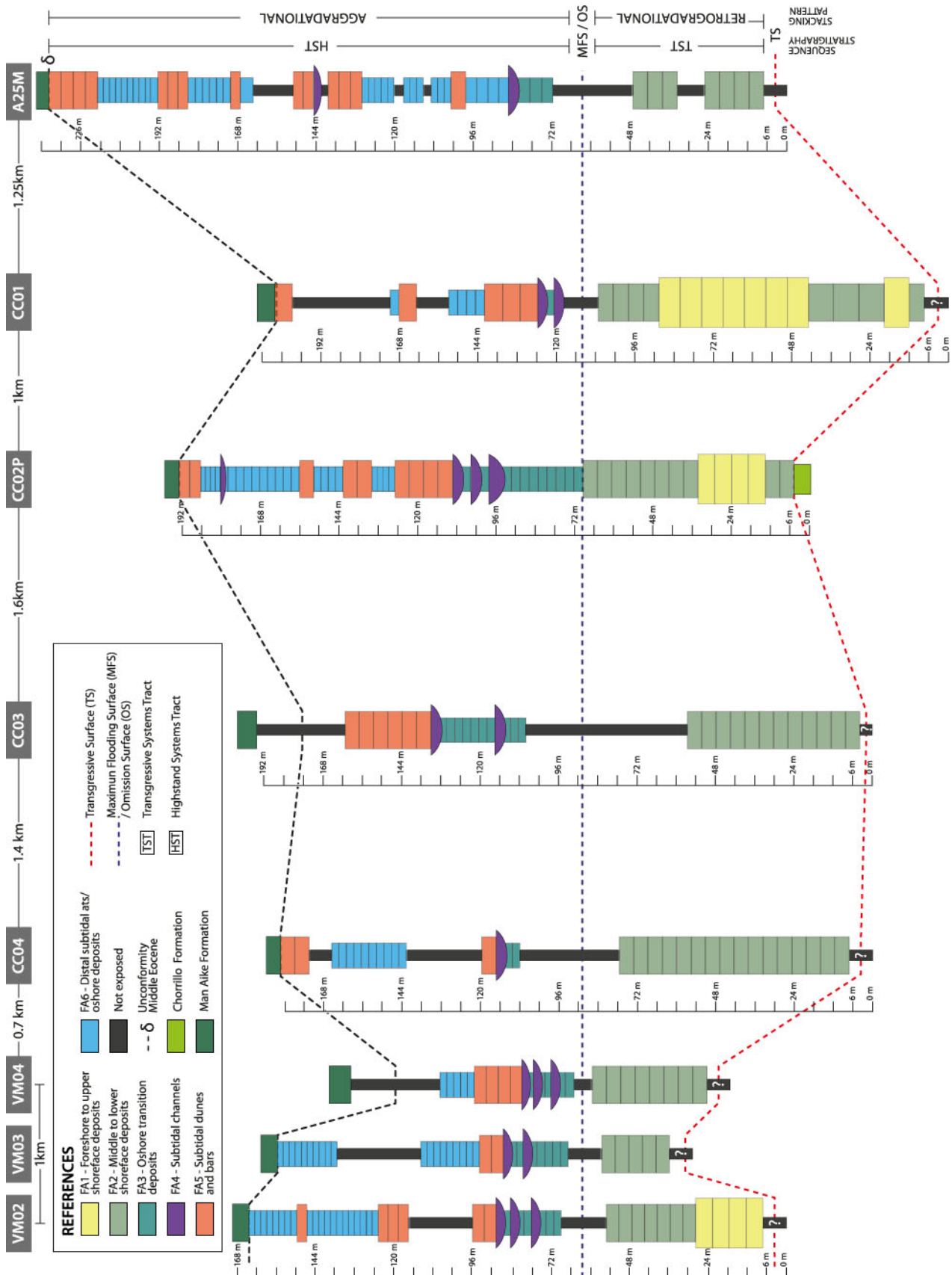


Figure 10. Correlation scheme across de Cerro Calafate type locality (from Vertedero Municipal to Arroyo 25 de Mayo) showing lateral distribution of facies associations, vertical stacking patterns, and sequence stratigraphic architecture of the Calafate Formation. The maximum flooding surface (MFS) has been used as correlation datum and its position assumed where it is not exposed.

sandstones deposited in the offshore transition that lie on an omission surface demarcated by the *Glossifungites* suite (Fig. 5d). This occurred during a depositional hiatus related to the sedimentation of the overlying unit, due to landward migration of the shoreline during transgression. Moreover, this omission surface indicates a deepening of the shallow-marine depositional system and therefore, it is interpreted to represent the maximum flooding surface (MFS) (*cf.* Cattaneo and Steel, 2003) (Fig. 9, 10). The vertical trend, observed from the base of the Calafate Formation up to the base of the offshore transition deposits corresponds to a retrogradational stacking pattern, and reflects a higher rate of creation of accommodation space than the rate of sediment supply. Consequently, this part of the sedimentary succession can be defined as a transgressive systems tract (TST) (Fig. 9, 10).

The upper deposits of the Calafate Formation that were accumulated over the maximum flooding surface (MFS), characterized by subtidal channels and a superposition of subtidal dunes and bars and distal subtidal flats/offshore deposits, constitute an aggradational succession (Fig. 9, 10). Here, the aggradational stacking pattern indicates short-term periods when the accommodation space rate was nearly equaled to the sediment supply rate. This scenery could have been reached in response to a temporary decrease in the rate of relative sea-level rise or by an increase of the rate of sediment supply. In agreement, it can be assumed that the upper sandstones represent the highstand systems tract (HST). Finally, due to the truncation of the Calafate Formation by the erosion surface that delimitate it from the overlying Man Aike Formation, the vertical extension of the HST could not be determined.

CONCLUSIONS

1. The detailed facies analysis of the Calafate Formation allowed the recognition of six facies associations, representing a shallow-marine depositional system. The basal FA1 represents the foreshore to upper shoreface deposits; FA2 represents the middle to lower shoreface deposits; FA3 depicts the offshore transition deposits; FA4 is interpreted as subtidal channels deposits; FA5 represents subtidal dunes and bars deposits, and FA6 depicts distal subtidal flats/offshore deposits.
2. The vertical trend observed for the lower half of the

unit is characterized by shallow to deeper conditions of sedimentation, represented by foreshore to upper shoreface (FA1, FA2) and culminating with offshore transition deposits (FA3). This trend continued with subtidal channels (FA4) over which three fining upward cycles, represented by subtidal dunes and bars (FA5) with vertical intercalation of distal subtidal flats/offshore deposits (FA6) are recognized.

3. The lower sandstones (FA1, FA2; 80-85 meters thick) of the Calafate Formation, separated of the Chorrillo Formation by a transgressive surface (TS), present a retrogradational stacking pattern, reflecting a higher rate of accommodation space than the rate of sediment supply. The stacking pattern for the lower sandstones represents the transgressive system tract (TST). In addition, an aggradational stacking pattern is defined for the upper sandstones (FA3, FA4, FA5, FA6; 90-140 m thick), which is interpreted as the response to a temporary decrease in the rate of relative sea-level rise or by an increase of the rate of sediment supply. The stacking pattern for the upper sandstones represents the highstand systems tract (HST) separated of the lower sandstones by the maximum flooding surface (MFS).

4. The shallow-marine depositional system is differentiated into a wave-dominated coast (FA1, FA2, FA3) and a tide-dominated coast (FA4, FA5, FA6). The tide-dominated coast could resemble an estuarine or an incised valley depositional model according to depositional models described by previous authors.

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