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2	Article Sub- Title		
3	Article Copyright - Year	**Springer-Verlag Berlin Heidelberg 2016 (This will be the copyright line in the final PDF)**	
4	Journal Name	Geo-Marine Letters	
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21	Schedule	Received	6 June 2016
22		Revised	
23		Accepted	31 October 2016
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25	Keywords separated by ' - '	
26	Foot note information	Responsible editor: B.W. Flemming

Geo-Mar Lett
DOI 10.1007/s00367-016-0481-3

ORIGINAL

Sequential development of tidal ravinement surfaces in macro- to hypertidal estuaries with high volcaniclastic input: the Miocene Puerto Madryn Formation (Patagonia, Argentina)

Roberto A. Scasso[1] · José I. Cuitiño[2]

Received: 6 June 2016 / Accepted: 31 October 2016

Abstract The late Miocene beds of the Puerto Madryn Formation (Provincia del Chubut, Argentina) are formed by shallow marine and estuarine sediments. The latter include several tidal-channel infills well exposed on the cliffy coast of the Peninsula Valdés. The Bahía Punta Fósil and Cerro Olazábal paleochannels are end members of these tidal channels and show a fining-upward infilling starting with intraformational channel lag conglomerates above deeply erosional surfaces interpreted as fluvial ravinement surfaces (the erosion surface formed in the purely fluvial or the fluvially dominated part of the estuary, where erosion is driven by fluvial processes). These are overlain and eventually truncated (and suppressed) by the tidal ravinement surface (TRS), in turn covered with high-energy, bioclastic conglomerates mostly formed in the "tidally dominated/fluvially influenced" part of an estuary. Above, large straight or arcuate point bars with alternatively sandy/muddy seasonal beds and varying trace and body fossil contents were deposited from the freshwater fluvially dominated to saline-water tidally dominated part of the estuary. The upper channel infill is formed by cross-bedded sands with mud drapes and seaward-directed paleocurrents, together with barren, volcaniclastic sandy to muddy heterolithic seasonal rhythmites, both deposited in the fluvially dominated part of the estuary. Volcanic ash driven by the rivers after large explosive volcanic eruptions on land resulted in sedimentation rates as high as 0.9 m per year, preserving (through burial) the morphology of tidal channels and TRSs. The channel deposits were formed in a tide-dominated, macrotidal to hypertidal open estuary with well-developed TRSs resulting from strong tidal currents deeply scouring into the transgressive filling of the channels and eventually cutting the fluvial ravinement surface. The TRSs extended upstream to the inner part of the estuary during long periods of low sedimentation rates, extended channel migration and sediment bypass, interrupted by transient, high volcaniclastic input. The tidal channels of the Puerto Madryn Formation constitute a unique example of estuary sedimentation with pulsed sediment supply in a macrotidal to hypertidal estuary.

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Introduction

The nature of discontinuity surfaces in estuaries and their relationships to sea-level changes have been studied since the advent of sequence stratigraphy, but their unambiguous identification in ancient deposits is still difficult. The study of Recent and Holocene infillings in tide-dominated estuaries (e.g., Tessier et al. 2012) is helpful because it involves short and well-constrained periods of time, and sea-level change is limited and well known. Identification of the tidal ravinement surface (TRS) is crucial to understand the evolution of tide-dominated (and some mixed energy) estuaries (Chaumillon et al. 2010). TRSs are formed at the erosional base of tidal channels (Allen and

Posamentier 1993) by upward and backward (retrogradational) migration of the estuarine system (Boyd et al. 1992; Dalrymple et al. 1992), and may extend throughout tide-dominated estuaries (Zaitlin et al. 1994; Tessier 2012). The depth of tidal ravinement is related to the tidal range and current energy in tidal channels within tidally dominated estuaries. The TRS may erode very deep in some macrotidal or hypertidal settings, eventually cutting the transgressive surface (e.g., Allen and Posamentier 1994) and becoming the main discontinuity within the infill of incised valleys. Furthermore, they may cut the subaerial incision surface in starved estuaries (Chaumillon et al. 2010; Tessier 2012). In these tracts, the TRS becomes itself (and is coplanar to) the sequence boundary.

In tide-dominated estuaries, autocyclic processes (e.g., channel migration) interact and overlap with allocyclic processes (e.g., sea-level changes) to produce complex sediment bodies bounded by erosion surfaces. Most of these sediment bodies are lensoidal and result from sedimentation in channels with extended or limited lateral migration. They typically range from hundreds of meters to a few kilometers wide and a few meters to several tens of meters thick. These laterally discontinuous sediment bodies are difficult to trace and correlate in outcrops. Conversely, they can be traced and correlated to discontinuities with high-resolution seismic techniques in the subsurface (e.g., Ashley and Sheridan 1994; Maynard et al. 2010) where direct observation of the sedimentary rocks is limited. The potential for preservation of estuarine sedimentary bodies is primarily controlled by tidal accommodation, defined by the depth of the main tidal channel belt (Tessier 2012).

On the other hand, high sedimentation rates and rapid aggradation in tidal channels within macro- to hypertidal areas promote the abundance of tidal rhythmites under transgressive conditions (Archer and Greb 2012; Archer 2013). Aggradational conditions are dominant during volcanic eruptive periods (Smith 1991), and may lead to the instantaneous preservation of channel geometry in transitional settings (Cuitiño and Scasso 2013).

Superb exposures of the tide-dominated estuarine deposits of the late Miocene Puerto Madryn Formation (Haller 1979; Scasso and del Río 1987) on coastal cliffs and gullies along the coasts of Golfo Nuevo and Golfo San José in the Peninsula Valdés (Provincia del Chubut, Argentina; see Fig. 1) have allowed detailed paleoenvironmental analyses and the reconstruction of the 3-D geometry of channel fills as well as tracing erosion surfaces along tens of kilometers (Scasso et al. 2012, 2014, 2015a, 2015b), but an integrated sedimentological, paleoenvironmental and sequence-stratigraphical analysis was still missing. In order to achieve this, two stratigraphic intervals, representative of different parts of ancient estuarine systems with channel deposits and prominent erosion surfaces, were selected. This allowed reconstruction of the geometric and temporal relations of the subaerial (fluvial ravinement) and TRS surfaces in incised valleys with high-energy tidal channels within macro- to hypertidal systems during times of sea-level rising. Neither the stratigraphic relation of both surfaces nor the aggradational volcaniclastic infilling has been documented in estuarine ancient deposits such as those of the Puerto Madryn Formation. Moreover, the influence of volcaniclastic input in the preservation of the irregular discontinuity surfaces is analyzed.

Geological setting

The Cenozoic succession of the Puerto Madryn–Península Valdés region comprises flat-lying strata on top of a Jurassic volcanic basement (Scasso et al. 2010). The Cenozoic succession wedges out to the west but its thickness greatly increases on the Atlantic shelf (Marinelli and Franzín 1996; Caramés et al. 2004). The integrated stratigraphic column derived from surface studies (Fig. 2) starts with the early Miocene Gaiman Formation, which is covered by yellowish-rusty brown late Miocene beds of the Puerto Madryn Formation (Haller 1979). The Puerto Madryn Formation is assigned to the late Miocene (10 ±0.3 Ma, Tortonian; Zinsmeister et al. 1981; Scasso et al. 2001). This age assignment is supported by information on malacofauna (Martínez and del Río 2002; del Río 2004), palynology (Palazzesi and Barreda 2004), foraminifers (Marengo 2015) and mammals (Dozo et al. 2010).

The Puerto Madryn Formation crops out extensively in the Península Valdés (Fig. 1), and it is nicely exposed at the coastal cliffs as well as inland in some gullies. It is formed by more than 150 m of shallow-marine heterolithic and cross-bedded volcaniclastic sandstones, muddy sandstones, and sandy shales interbedded with whitish tuffs and distinctive shell beds (coquinas). The Puerto Madryn Formation locally represents the late Miocene marine transgression that covered a large part of Argentina (and South America), forming a shallow sea connected to the Atlantic Ocean known in the literature as the "Entrerriense" sea (e.g., Scasso and del Río 1987). A southern branch of the "Entrerriense" sea formed a wide bay that penetrated westward in the Península Valdés region and was subjected to strong tidal currents. Facies distributions and paleocurrent patterns point to a provenance and sediment dispersion from the south and southwest to north and northeast (Scasso and del Río 1987).

Sequence stratigraphy and paleoenvironments: synthesis from previous work

The Puerto Madryn Formation lies on a regionally extensive ravinement surface cut on older marine strata of the

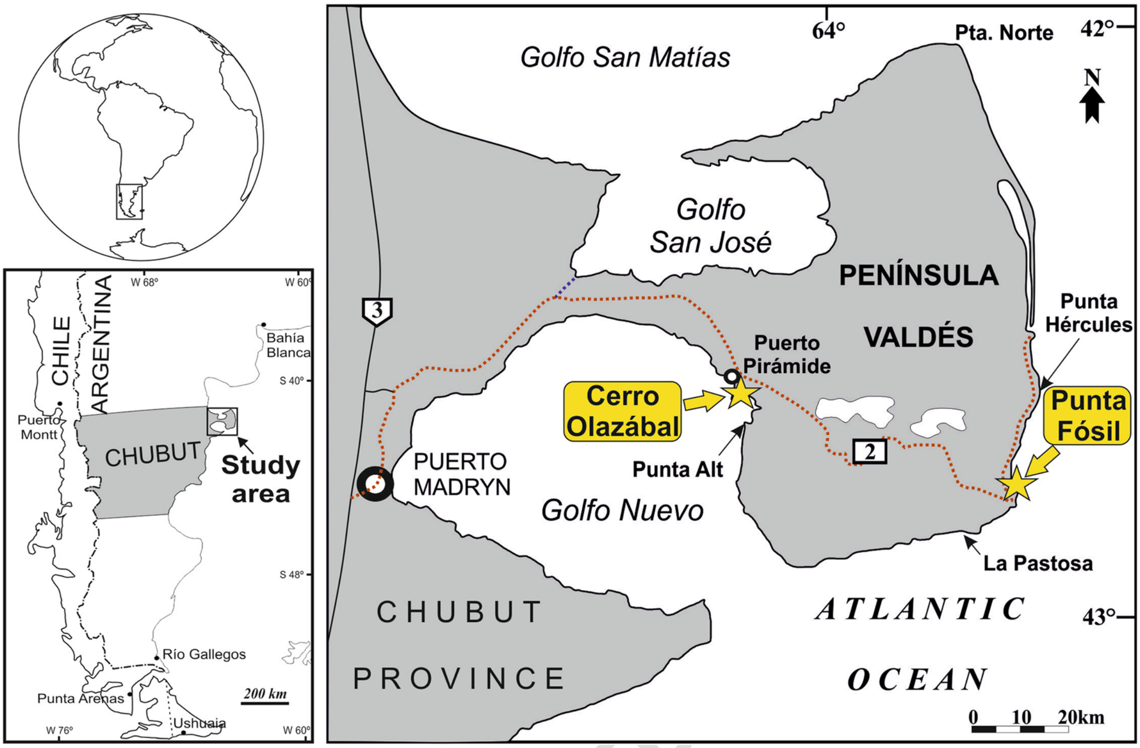

Fig. 1 Location sketch map of the Península Valdés in Patagonia, with location of the study sites and other nearby sites referred to in the text. National road 3 and provincial road 2 are also indicated

early Miocene Gaiman Formation (Scasso and del Río 1987). Previous work subdivided the Puerto Madryn Formation into three vertically stacked units called (from base to top) the transgressive phase, the maximum highstand phase, and the regressive phase (del Río et al. 2001). The maximum highstand phase refers to deposits that accumulated when the sea level was at its maximum, and is separated from the underlying transgressive phase by the maximum flooding surface (del Río et al. 2001). From a standard sequence stratigraphic point of view, the strata forming the unit can be organized as a third-order transgressive-regressive (T-R) sequence, in which the transgressive phase of del Río et al. (2001) corresponds to the transgressive systems tract (TST), and the maximum highstand phase and the lower part of the regressive phase correspond to the highstand systems tract (HST). The sequence-stratigraphic assignment for the upper part of the regressive phase is currently under study, because new sequences associated to large paleochannels are defined in this paper.

Taphonomic analysis of the mollusk fauna within the transgressive phase (TST), combined with sedimentary facies and sequence stratigraphic data, allowed identifying a range of paleoenvironments from the deepest mid-inner shelf to the shallow intertidal-foreshore (Scasso and del Río 1987; del Río et al. 2001). The lower part of the regressive phase (HST) is subdivided in low-hierarchy T-R cycles (probably fourth-order sequences) that start with transgressive surfaces displaying firm or hard-ground trace fossil suites, overlain by either reworked shell beds (coquinas) or strongly bioturbated bioclastic sandstones accumulated in sand bars in a storm-dominated shoreface to inner shelf environment (Scasso and del Río 1987; del Río et al. 2001). These deposits are often cut by deeply erosional surfaces in the middle and upper part of the regressive phase (Fig. 2), which are covered by channel deposits accumulated from the purely fluvial to the tidally dominated outer part of estuaries. These channel deposits are the subject of the present study.

Methods

Several channels were identified throughout the study area, and their deposits and discontinuity surfaces described by means of detailed logs and 3-D analysis, with special emphasis on tracing the discontinuities and the lateral changes in the deposits. The lithologic composition of the sediments was studied with a polarization microscope for the sand fractions and a scanning electron microscope for the mud fractions.

Two examples of paleotidal channels were selected for the present study, namely the Bahía Punta Fósil and Cerro Olazábal paleochannels, because they are nicely exposed on

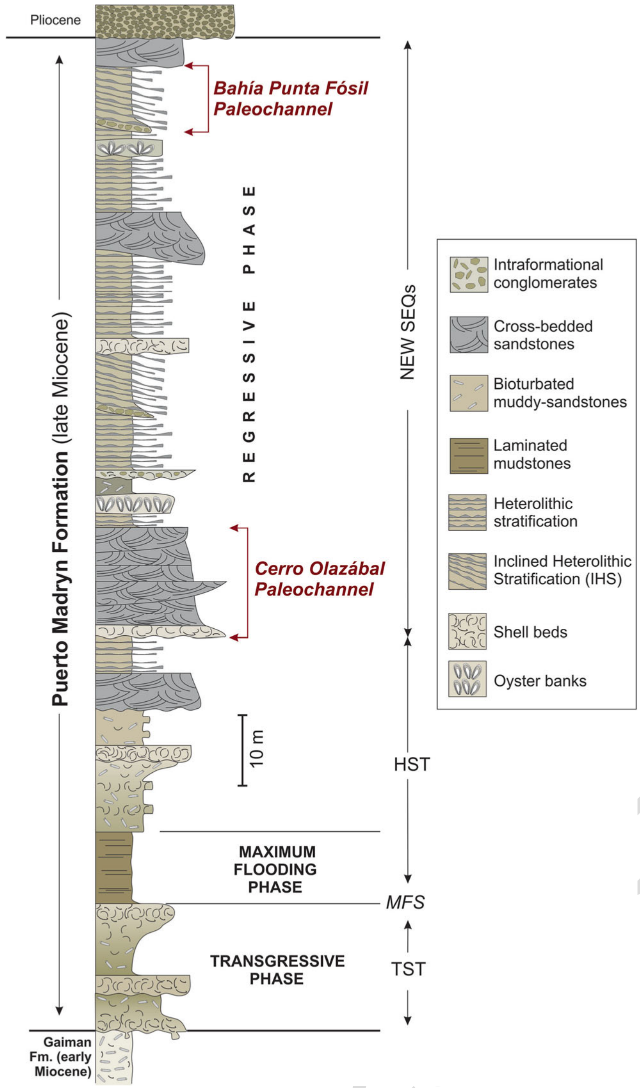

Fig. 2 Composite stratigraphic column from the Puerto Madryn Formation in the Península Valdés (modified after del Río et al. 2001). From a standard sequence stratigraphic point of view, the transgressive phase of del Río et al. (2001) corresponds to the transgressive systems tract (TST), and the maximum and the *lower part* of the regressive phases correspond to the highstand systems tract (HST). *MFS* Maximum flooding surface. The *upper part* of the regressive phase is currently under revision, and new sequences (*NEW SEQs*) associated to tidal channels are defined

3-D cliffs, the TRSs and sequence boundaries can be traced for long distances, and they represent different locations within the estuarine system. The preserved deposits are mostly channel bars and lag conglomerates of different scales, whereas inter-channel deposits are rare or absent (compare with Scasso et al. 2012). Erosion surfaces are frequently cut into older channel deposits. The present study follows the fivefold estuary subdivision by Jablonski and Dalrymple (2016) for paleoenvironmental assignment in the fluvial-marine transition from land to sea: purely fluvial, fluvially dominated/tidally influenced, tidally dominated/fluvially influenced, and tidally dominated.

Results

Bahía Punta Fósil paleochannel

The Bahía Punta Fósil paleochannel is a large tidal channel exposed on the cliff 300 m south of Punta Fósil (42°44′24.97″ S, 63°38′3.82″W; Fig. 1) where several discontinuity surfaces covered by channel deposits were described (Scasso et al. 2015a). The Bahía Punta Fósil paleochannel axis is oriented 30° (oblique to the N–S cliff of Fig. 3) and shows a complex infilling on top of two erosion surfaces. It constitutes the uppermost stratigraphic interval of the Puerto Madryn Formation (Fig. 2), on top of a 320-m-thick column of middle to late Miocene age lying mostly in the subsurface and recorded in an oil well 3 km inland from the cliff (Masiuk et al. 1976; Caramés et al. 2004). Several large channels with terrestrial vertebrate remains in their channel conglomerate lags were identified in the area (Dozo et al. 2010; Scasso et al. 2012; Scasso et al. 2015b), lying above marked erosion surfaces entrenched up to 50 m deep into the underlying sediments (this a minimum value since some erosion surfaces are tracked down to the sea level but might go deeper).

The infill of the Bahía Punta Fósil paleochannel is composed (from base to top) of intraclast conglomerate, cross-bedded sandstone and decimetric packages of rhythmites (Figs. 3 and 4). The intraclast conglomerate lies above an irregular erosion surface called here “surface 1” (Fig. 3), and it is exclusively composed of whitish mud clasts of gravel to block size (Fig. 4a). The top of the intraclast conglomerate bed is cut by another, less irregular erosion surface, called here “surface 2” (Fig. 3). A 20-m-thick, fining-upward succession is developed above surface 2, formed (from base to top) by thin conglomerate deposits with parallel stratification and gravel-sized bioclasts, intraclasts and bones, well developed in the channel thalweg (Fig. 4b). They are covered by large- to small-scale cross-bedded sandstones with thick mud drapes and mud intraclasts. This facies is thicker along the northern margin of the paleochannel and changes laterally to decimeter-scale heterolithic beds (Figs. 3 and 4c) that become muddier both to the center (to the left in Fig. 3) and upward in the channel fill. Both sandy and muddy beds contain fresh, abundant shards and pumice.

Twenty pairs of several dm- to 1-m-thick rhythmites, each formed by a couple of sand- and mud-dominated heterolithic beds, were counted in the 18-m-thick interval in the northern part of the Bahía Punta Fósil paleochannel infill (Fig. 4c). To the south, as the cliff becomes higher, the number of pairs increases to about 62, and two discontinuity surfaces in the channel fill, mantled with coarser, cross-bedded beds, suggest an incomplete record. Within the decimeter-scale beds, centimeter-scale sand and mud layers form heterolithic beds (Fig. 4d). The centimeter-scale sand layers that compose the heterolithic beds show current-ripple lamination with

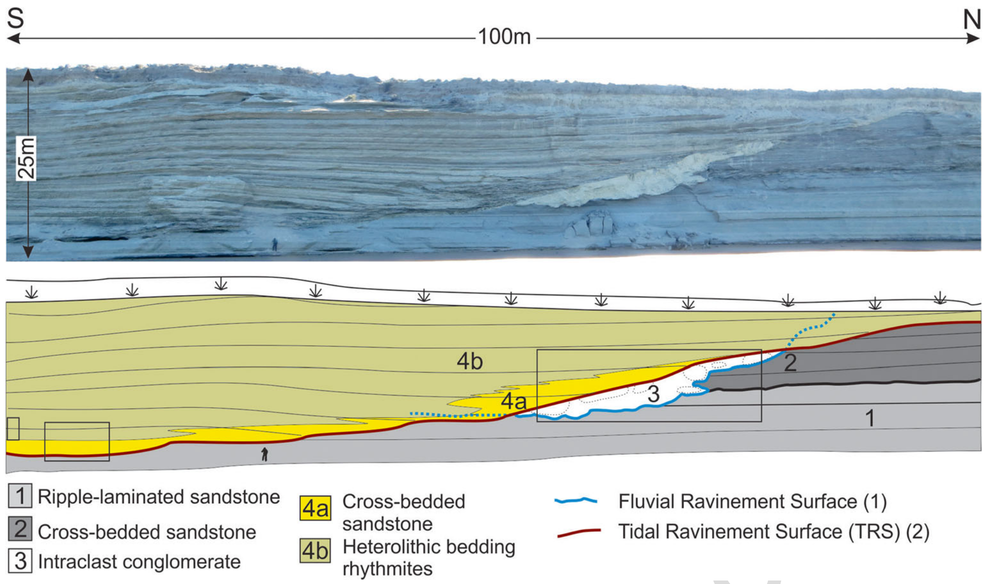

Fig. 3 Bahía Punta Fósil paleochannel deposits (*above*), and interpretation (*below*). The major erosion surfaces and sedimentary facies are highlighted. The subaerial fluvial ravinement surface (*1*) is cut by the TRS (*2*), pointing to a successive entrenchment of the base of the Bahía Punta Fósil paleochannel, which shows a complex infilling of bioclastic and intraclastic channel lags and decimetric packages of alternating muddy to sandy heterolithic rhythmites forming a fining-upward succession. *Rectangles* Locations of Fig. 4a (*right*), 4c (*center*), and 4d (*left*). Modified after Scasso et al. (2015a, their Fig. 34)

abundant alternating NE and SW paleocurrents (Fig. 4d). The NE paleocurrents dominate in the sandy beds and the SW paleocurrents dominate in the muddy beds.

Dynamics and evolution of Bahía Punta Fósil paleochannel

The 20-m-thick, fining-upward succession is thought to represent the infilling of a medium- to large-sized tidal channel. Surface 1 is interpreted as the bottom erosion surface of an incised valley related to a sea-level fall on the basis of its irregular erosional shape (Fig. 3) and the paleoenvironment of deposition inferred from the overlying deposits. The intraclast conglomerate above surface 1 represents erosion and block releasing from the channel-cut bank. As blocks and clasts show little transport, they must derive from the erosion of a bed stratigraphically higher in the succession aside the channel, which is not preserved in the cliff probably because of recent erosion (Fig. 3). The lack of marine fossils together with the steep relief of the channel margin and the consolidation of the mud needed for the formation of the eroded blocks (Fig. 4a) suggest the conglomerate formed in a subaerial environment after the mud beds underwent some dehydration in the purely fluvial part of the system.

Surface 2 cuts surface 1 and delineates the base of the channel in a later stage of its evolution (Fig. 3). The bioclastic conglomerate is interpreted as a channel lag deposit (cf. Flemming et al. 1992; Flemming and Davies 1994) reflecting marine influence. Upper-flow parallel bedding in bioclastic beds and small dunes of sand and bioclasts reflect strong tidal currents up to 1 m/s (Flemming and Davies 1994) in the tidally dominated part of the estuary. The lateral variation in the grain size of the rhythmites, from sand-dominated to mud-dominated, indicates higher current velocities in the northern, more active margin of the paleochannel, suggesting a sinuous shape with a meander-like bend. Rhythmic, vertical accretion dominates the channel infilling (Figs. 3 and 4a). The rhythmites mostly lack marine fossils and bioturbation is rare, suggesting deposition under stressing environmental conditions, which is consistent with brackish waters and high sedimentation rates with high suspended sediment concentrations and minimal bioturbation and wave reworking (e.g., Thomas et al. 1987; Tessier and Gigot 1989; Dalrymple and MakinoY Q1 1991). The rhythmites are regarded as typical of macrotidal to hypertidal settings (Archer 1995; Tessier 2012), and they are better developed with extreme tidal dynamics within transgressive systems (Archer and Greb 2012).

The decimeter-scale heterolithic beds forming rhythmites in the Bahía Punta Fósil paleochannel (Fig. 4c) are interpreted as seasonal rhythmites whereas the centimeter-scale beds are interpreted as neap/spring and semidiurnal/diurnal rhythmites. Alternating NE (ebb) and SW (flood) paleocurrents indicate numerous current reversals with flood dominance in the muddier beds and ebb dominance in the sandier beds (Fig. 4d). Similar decimeter-scale beds composed of predominantly sandy and muddy centimetric layers, with heterolithic and ripple bedding, were assigned to seasonal changes in river discharge (Van den Berg et al. 2007) in the fluvial-tidal transition zone of the estuarine system. During periods of high river discharge, sandy layers with ebb-directed paleocurrents

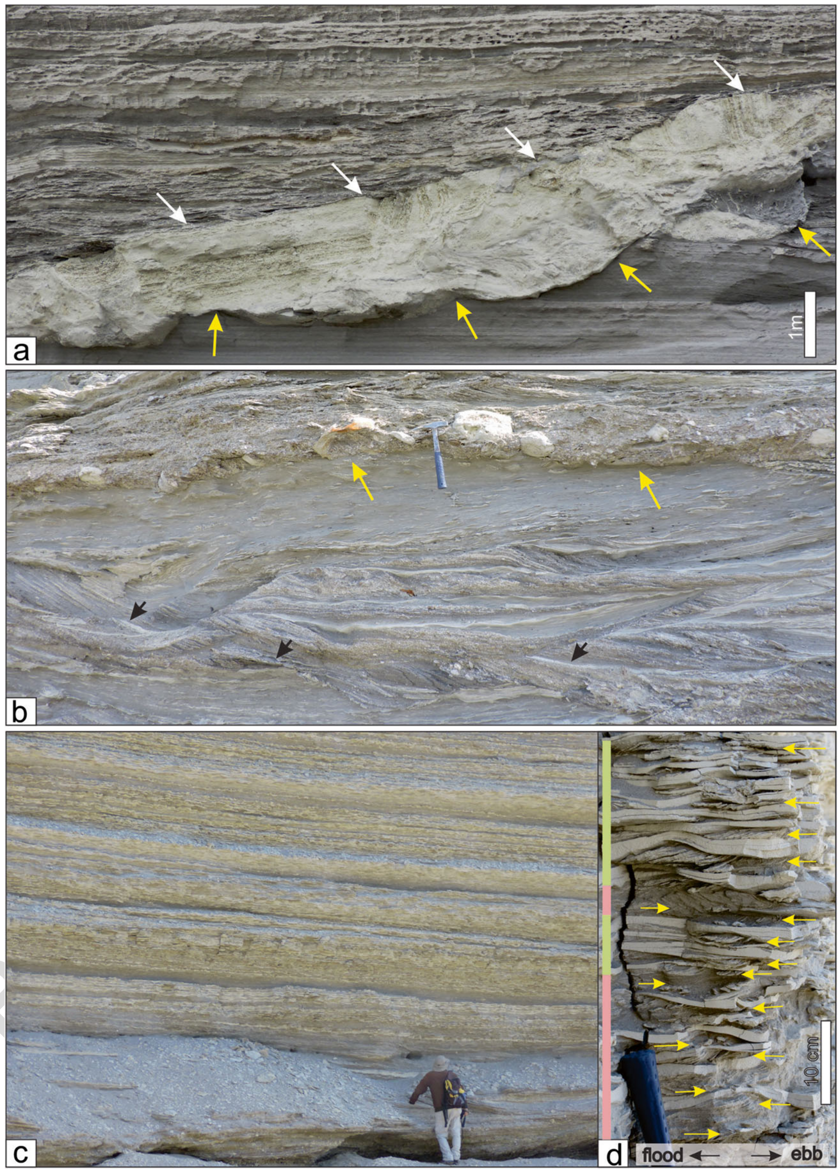

Fig. 4 Facies details of the Bahía Punta Fósil paleochannel. **a** *Yellow arrows* Subaerial fluvial ravinement surface covered by mud blocks; *white arrows* TRS. Above this surface, cross-bedded and ripple-laminated sandstones form the tidal channel infill. Modified after Scasso et al. (2015a, their Fig. 34). **b** Channel deposits dominated by cross-bedded sandstones with mud drapes (*black arrows*) and abundant mud intraclasts. Some layers concentrate bioclasts, rounded intraclasts and transported cetacean bones (*yellow arrows*); 25 cm long hammer for scale. **c** Seasonal rhythmites formed by muddy (*light color*) and sandy (*dark color*) heterolithic beds. Modified after Scasso et al. (2015a, their Fig. 38). **d** Detail of heterolithic rhythmites (*pink bars* sand-dominated intervals, *green bars* mud-dominated intervals). Alternating NE (ebb) and SW (flood) paleocurrents indicate numerous current reversals with flood dominance in the muddier intervals. Thick slack water mud drapes reflect high concentrations of suspended volcaniclastic particles. Modified after Scasso et al. (2015a, their Fig. 39)

predominate. During periods of low river discharge, the flood tide induces a flow directed upstream, which is active during a short period of the flood, because of the tidal wave asymmetry (e.g., Brenon and Le Hir 1999). Flood-directed ripples covered by thick slack water mud drapes reflect high suspended mud concentrations in the Bahía Punta Fósil paleochannel. The high amounts of fine, reworked ash may have aided in the development of a thick fluid mud layer around slack water, lacking intercalated sand laminae. Thick mud drapes (up to 2 cm thick) without intercalated sand laminae are interpreted as having been deposited during a single high-water slack period (e.g., Shanley et al. 1992). This style of sedimentation is typical of an estuary with a turbidity maximum zone and may be related to the intrusion of a salt wedge (Van den Berg et al. 2007), a process that takes place in the fluvially dominated/tidally influenced part of an estuary.

According to the seasonal interpretation for each pair of tidal rhythmites, a 20 year period of continuous sedimentation is involved in the 18-m-thick interval devoid of discontinuities (Scasso et al. 2015a). Sedimentation rates as high as 0.9 m/year are estimated. Channel-fill sedimentation rates calculated from rhythmites are highly variable and depend on the amount of space available to be filled during deposition (Greb and Archer 1998). In the Bahía Punta Fósil paleochannel, the accommodation space was at least 20 m and high volcaniclastic sediment supply led to rapid aggradation and subsequent channel filling and abandonment. Seasonal periodic changes in the energy of the system are evidenced by the alternating muddier or sandier nature of the beds, which preserved some daily/neap-spring tidal layers within them, but not complete sequences of tidal bundles.

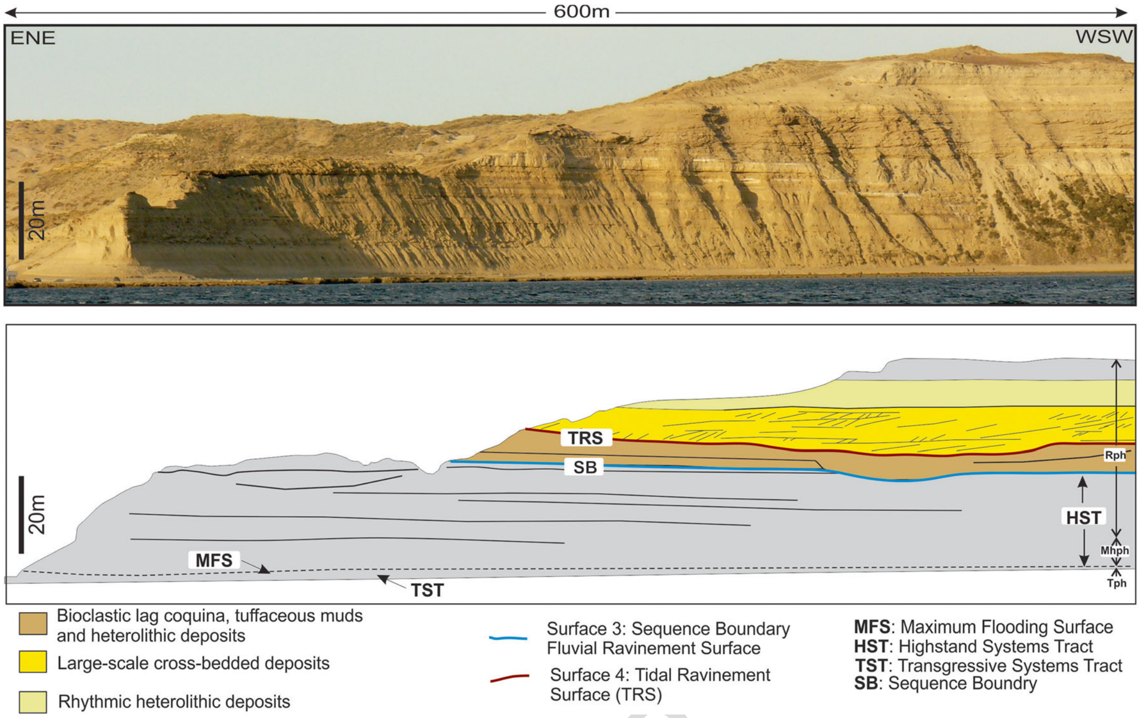

Fig. 5 Succession at the Cerro Olazábal cliff (*above*) and its interpretation (*below*). The paleochannel deposits and the discontinuity surfaces are highlighted. The regressive (*RPh*), maximum highstand (*Mhph*) and transgressive (*Tph*) phases of del Río et al. (2001) are also indicated

Cerro Olazábal paleochannel

The Cerro Olazábal paleochannel deposits constitute the upper part of the Cerro Olazábal section (42°34′40.63″S, 64°16′14.15″W; Fig. 1), a classical section studied since Florentino Ameghino times (e.g., Feruglio 1949). The paleochannel deposits are part of the regressive phase above the transgressive and maximum flooding phases, also represented in the section (Figs. 2 and 5).

The interval studied here starts with a coquina bed with broken and reworked shells above an irregular, high-relief erosion surface, called here "surface 3" (Figs. 2 and 5). The coquina bed is covered by a 2-m-thick, white bed composed of fine, reworked siliceous tuffs (Fig. 6, image A). Together with the underlying surface 3, both can be traced for many km to the south. They pass upward into thin heterolithic deposits and well-sorted, fine-grained sandstones with internal cross-stratification displaying thick mud partings. Large *Ophiomorpha* sp. galleries can be observed in these deposits. At the top of these beds, intense burrowing by a monospecific suite of *Skolithos* sp. penetrates from the overlying bed.

A ~0.3-m-thick whitish, massive mudstone bed overlies the cross-bedded, fine-grained sandstones, which are in turn covered by a ~7-m-thick cross-bedded bioclastic sandstone (Fig. 6, image B). The lower contact of these coarse deposits is a surface with erosional relief of several meters cut into the underlying beds, traced for several kilometers along the cliff and called here "surface 4" (Fig. 5). It is locally irregular and punctuated by traces of *Gastrochaenolites* sp. (Fig. 6, image B). The coarse-grained deposits are composed of shell hash in large-scale trough cross-stratified beds dipping to the west (Fig. 6, images A, B), separated by master bedding planes also dipping to the west. An internal fining-upward trend is observed within this body, which culminates in fine-grained sandstones with medium-scale trough cross-stratification and abundant mud drapes (Fig. 6, image C) or inclined heterolithic stratification (Fig. 6, image A). The uppermost beds in the cliff are packed in two, 10-m-thick intervals of alternating heterolithic and muddy heterolithic bedding (Fig. 5), a lower muddy one, with very thin, weakly bioturbated sandy partitions, and an upper one lying above an irregular surface bioturbated by *Thalassinoides* sp. These upper heterolithic deposits are sand dominated and show intervals of strong bioturbation. To the east of this site, an isolated lenticular oyster bed is intercalated within the heterolithic deposits. It contains large thick-valved oysters, articulated and stuck to each other.

Dynamics and evolution of Cerro Olazábal paleochannel

The basal erosional, high-relief surface 3 can be traced along the coast for 10 km to the south. It separates the underlying marine shelf sediments from the overlying estuarine sediments that represent the channel fill. It was caused by fluvial ravinement during a sea-level fall and it is therefore

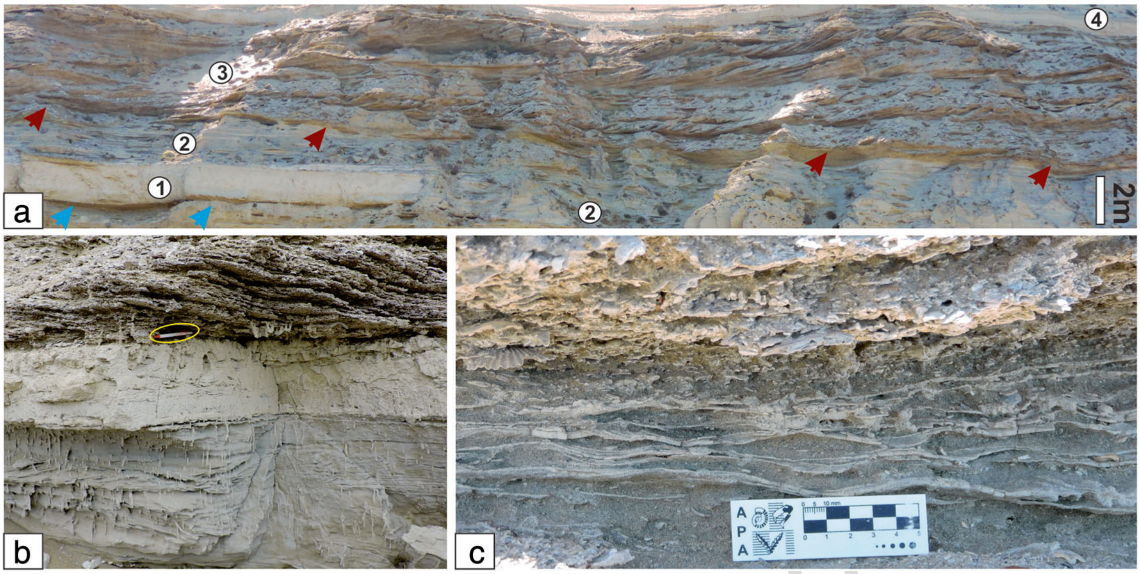

Fig. 6 Facies details for Cerro Olazábal paleochannel deposits. *Image A* General view of facies: massive volcaniclastic mud bed (1) on top of thin lag coquina overlying surface 3 (*blue arrows*), a fluvial ravinement surface that constitutes the sequence boundary. This bed is covered by heterolithic deposits (2), which in turn are covered by large-scale cross-bedded sets composed of coarse sandstones and shell hash (3). Paleocurrent directions to the left (W) indicate flood-dominated conditions. Between facies 2 and 3, surface 4, a TRS, is arrowed (*red*). Overlying the cross-bedded bioclastic sandstones, a muddy heterolithic bed (4) culminates the channel infill. *Image B* Detail of the base of the large-scale cross-bedded sets overlying surface 4, a TRS bioturbated with *Gastrochaenolites* sp. Pencil (15 cm long) for scale. *Image C* Detail of fine-grained sandstone bed with abundant mud drapes in the *upper part* of the tidal channel deposits

interpreted as a sequence boundary in an incised valley system. The coquina above is interpreted as a marine transgressive lag, associated with marginal marine conditions during initial stages of sea-level rise. The incised valley was later filled with volcaniclastic white muds (Fig. 6, image A), a guide layer that can be also traced for many km to the south. The volcaniclastic muds are interbedded with intertidal-flat and nearshore storm-influenced deposits in the outer tidally dominated part of an estuary.

The overlying coarse bioclastic deposits are related to a major tidal channel system lying above a TRS (Fig. 5). Large subaqueous dunes of abraded shells reflect strong tidal currents close to 1 m/s (cf. Flemming and Davies 1994). The channel was incised into the substrate after an increase in tidal current power caused by a relative sea-level rise. Westward (landward), paleocurrents as well as abundant and strongly abraded marine shell remains indicate a landward migration of bedforms in response to the flood tidal current. It is interpreted as a large channel with a flood-dominated tidal point bar with partial "downstream" accretion at the meander ends, formed in the tidally dominated/fluvially influenced part of an estuary, similar to those illustrated by Cuevas Gonzalo and de Boer (1991) and Martinius (2012, their Fig. 18.23) for the Lower Eocene tidalites in the southern Pyrenees (Spain).

The muddy to fine-grained sandy heterolithic deposits above the bioclastic beds in the upper part of the channel infill (Figs. 5 and 6, image C) show varying bioturbation intensity resulting from the variation in salinity and sediment input into the channel. High rates of river discharge lowered the salinity and supplied large amounts of sediment, precluding colonization by organisms. On the other hand, lower river discharge favored colonization by marine organisms in the channel, resulting in highly bioturbated beds and oyster biostromes. The10 m packages of muddy or sandy heterolithics are interpreted as tidal rhythmites within a tidal channel (Greb and Archer 1998), formed in the fluvially dominated/tidally influenced part of an estuary. The lenticular oyster beds intercalated within the heterolithic deposits are mostly preserved in life position and represent an oyster biostrome developed in the shallower parts of the channel under low sedimentation rates. Oyster biostromes were described by Pufahl and James (2006) in similar paleoenvironments.

Discussion

Deposits and discontinuities in tidal channels of the Puerto Madryn Formation

The Cerro Olazábal and Bahía Punta Fósil paleochannels were selected for the present study because they present most of the typical characteristics of tidal channels in the Puerto Madryn Formation, in addition to well-exposed discontinuities interpreted as fluvial and tidal ravinement surfaces (Figs. 3 and 5). According to the above analysis, the Cerro Olazábal

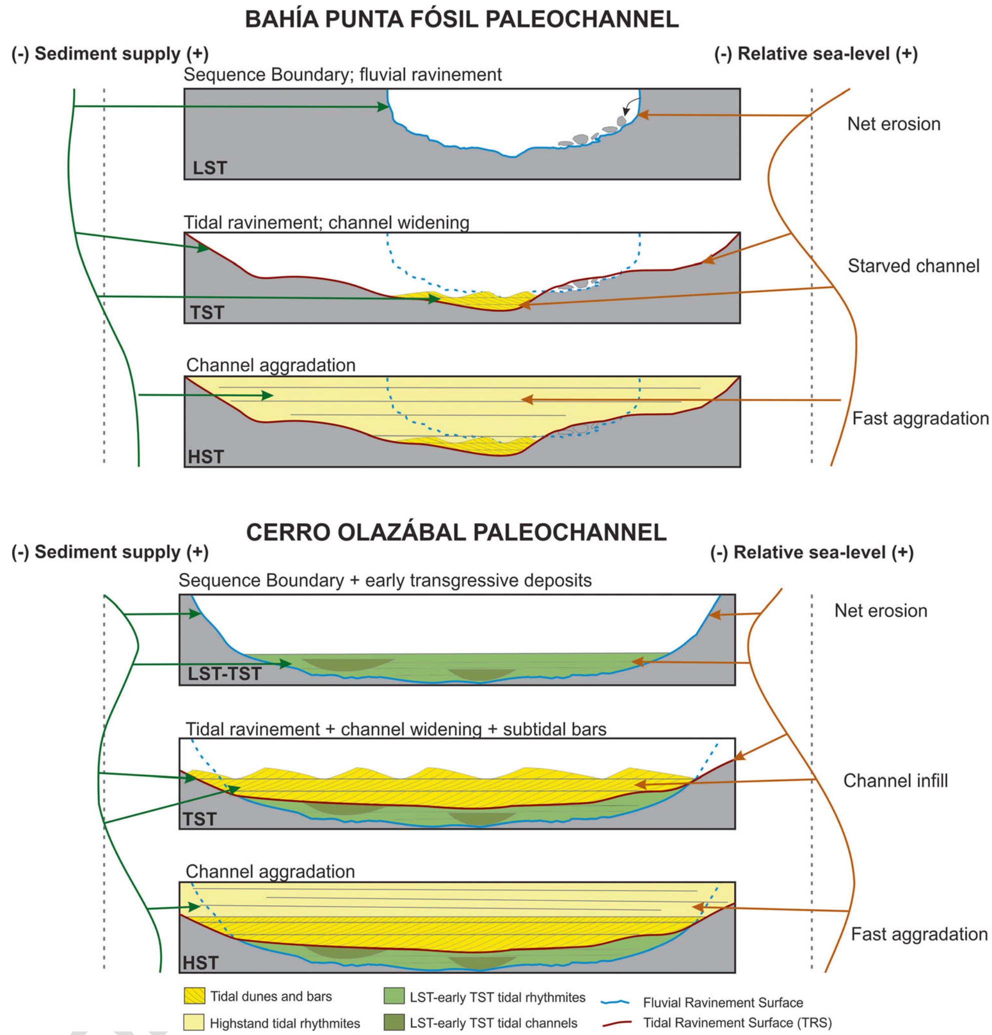

Fig. 7 Schematic evolution of the Bahía Punta Fósil and Cerro Olazábal paleochannels (*LST, TST and HST* lowstand, transgressive and highstand systems tract, respectively)

paleochannel deposits accumulated between the lowstand and highstand shorelines, mostly in the tidally dominated/fluvially influenced part of estuarine tidal channels, as revealed by the bioclastic lags rich in marine mollusks, abundant body and trace fossils, and flood-dominated paleocurrents (Fig. 7). Episodic marine influence evidenced by the trace fossils and body fossils may have been associated with seasonal, upstream shifts of the salt wedge in the estuary during dry periods (Jablonski and Dalrymple 2016). On the other hand, the Bahía Punta Fósil paleochannel deposits indicate sedimentation mostly in the fluvially dominated/tidally influenced part of the estuary, as revealed by the intraformational conglomerate lag at the base, ebb-dominated paleocurrents in cross-bedded sandstones, and mostly barren seasonal rhythmites.

The Bahía Punta Fósil paleochannel deposits accumulated landward of the Cerro Olazábal paleochannel, although minor and major paleoenvironmental variations are recorded in both columns. The former may represent seasonal variations that resulted in minor shifts of the estuary zones. The latter are associated with sea-level fluctuations that resulted in large paleoenvironmental shifts from purely fluvial to tidally dominated parts of the estuary (Fig. 7).

In addition to the Cerro Olazábal and Bahía Punta Fósil paleochannels, other paleochannels have been described for the Puerto Madryn Formation (Scasso et al. 2012, 2014, 2015a). Together, they allow reconstruction of a general pattern for the tidal-channel infilling in this unit. They display a general fining-upward trend similar to the model proposed by Choi et al. (2004) for modern Korean tidal flats, with variable facies and discontinuities depending on the environmental setting. Some paleochannel lags, as those from La Pastosa (Fig. 1), are formed by intraformational clasts and blocks, and contain terrestrial and freshwater vertebrate remains (Scasso et al. 2012). They lie on irregular surfaces deeply eroded into the underlying deposits, being interpreted as fluvial ravinement surfaces/subaerial unconformities formed by fluvial channel erosion during relative sea-level falls in the purely fluvial part of the estuary. The conglomerate lags then accumulated in the inner segment of incised valleys in the "purely fluvial" or "fluvially dominated/tidally influenced" part of the estuary. In other cases (e.g., Scasso et al. 2015a), the channel-fill succession starts with upper-flow regime parallel-stratified bioclastic lag deposits or large-scale cross-bedding. Reworked shells can be completely broken down into minute fragments or be preserved in articulated form. In some cases, firm to hard-ground fossil traces are found at the channel bed and margins. These deposits are assigned to the outer segment of incised valleys (sensu Zaitlin et al. 1994) and were formed in the tidally dominated/fluvially influenced or in the tidally dominated part of the estuary. Under conditions of low sediment supply, extensive tidal channel migration produced thick bioclastic lag conglomerates and cross-bedded bioclastic in-channel bars with dominantly landward-oriented paleocurrent bedding formed by flood currents. These channel sediments overlie erosion surfaces interpreted as TRSs.

On top of the lag conglomerates, large arcuate point bars with inclined heterolithic stratification (IHS) show rhythmic alternation of sandy and muddy beds, which are assigned to seasonal changes in river discharge following Jablonski and Dalrymple (2016). They were formed in the brackish to freshwater fluvially dominated/tidally influenced part of the estuary. Varying trace and body fossil contents in the IHS suggest varying salinity, river discharge and sediment supply. Closer to the channel mouth, in the tidally dominated/fluvially influenced part of the estuary, IHS bedsets form straight bars, show extensive bioturbation and bear mollusk body fossils as described by Scasso et al. (2015a, 2015b) in the Punta Alt (lower paleochannel) or Punta Hércules paleochannel (see location in Fig. 1).

Cross-bedded sandstones with mud drapes are commonly found above the IHS deposits, although they can directly overlie the lag conglomerates. They are barren or show little bioturbation, with paleocurrents being mostly directed seaward due to dominant ebb currents transporting land-derived sediments. These are typical of the fluvially dominated/tidally influenced part of the estuary.

The upper part of the channel fill is usually composed of heterolithic beds with rippled sands and muds of tuffaceous composition, and which are interpreted as seasonal rhythmites (Scasso et al. 2015a). They lie above any of the underlying facies. Their volcaniclastic composition is revealed by abundant silt- to sand-sized shards present both in the muddy and sandy layers of the heterolithic beds. Ash supplied by the rivers after large explosive volcanic eruptions on land resulted in high inputs of sediment into the system and rapid accumulation of the rhythmites, with temporary sedimentation rates as high as 0.9 m per year. The system was suddenly overloaded with volcaniclastic sediments, the tidal channels providing the accommodation space for swift deposition and "freezing" of the paleorelief through burial. Rapid burial of the overloaded channels precluded lateral migration, favored channel avulsion and, for instance, preserved steep channel walls. The fine-grained facies that form the channel infill may show well-defined tidal rhythmites that indicate that the channels were filled up in a few hundred years. The finest-grained muddy heterolithic deposits correspond to the bedload convergence zone that is located in the tidal freshwater to brackish-water zone (or the fluvially dominated/tidally influenced part of the estuary; Jablonski and Dalrymple 2016), probably reflecting mud flocculation and deposition at the turbidity maximum (La Croix and Dashtgard 2014). Oyster biostromes grew on channel bars and form part of the channel system during pauses in sediment supply or minor rises in relative sea level (e.g., Scasso et al. 2012). Channel migration and associated erosion of bars produced large, monospecific oyster accumulations (Fig. 2).

Fluvial vs. tidal ravinement in sequence boundaries

Fluvial ravinement refers here to the process of fluvial erosion in a purely fluvial or fluvially dominated part of macro- to hypertidal estuaries. Erosion is driven by fluvial currents, mostly in meandering channels, in contrast to the tidal ravinement that is driven by tidal currents. It differs from the fluvial erosion surface or subaerial unconformity because it is always linked to an estuary with a large tidal range, and because it may occur even during sea-level rise, much like tidal ravinements. By analogy with the TRS, the fluvial ravinement surface is defined as "the erosion surface formed in the purely fluvial or fluvially dominated part of the estuary, where the erosion is driven by fluvial processes".

Repeated lateral migration and vertical incision of estuarine channels in the Puerto Madryn Formation produced a complex pattern of channel fills bounded by erosion surfaces that suggest a complex evolution (Fig. 7). These discontinuities may theoretically be assigned to autocyclic processes such as seasonal channel reactivations or centennial/millennial channel migration (Scasso et al. 2012), or allocyclic processes such as climatic changes, uplift or secular sea-level variations that affected sedimentation within the estuary. In the Puerto Madryn Formation, as in many ancient deposits, it is difficult to disentangle the origin of the discontinuity surfaces because the erosional processes tend to erase them together with the older deposits. In addition, the lack of accurate dating methods for discriminating short-term processes and limited outcrop observation, even in excellent exposures, such as the cliffs of the Península Valdés region, preclude a complete 4-D reconstruction of the geometry and history of the deposits. However, detailed observations give some clues about the origin and preservation of the sedimentary bodies and discontinuities between them.

The lowermost discontinuities at the base of the main channels are regarded as the fluvial ravinement surface that forms the lower sequence boundary in incised valleys during lowstands, following the ideas of Maynard et al. (2010). On the basis of architectural subsurface reconstructions, these authors suggest three criteria for the recognition of incised valleys between highstand and lowstand shorelines: (1) an elongate, channel-shaped incision that can be correlated over a long distance, (2) the base of the incision is a sequence boundary, and (3) the sequence boundary can be correlated regionally on the interfluve flooding surface/sequence boundary. Their study illustrates incised valleys ranging from tens of meters to a few kilometers in width and from 5 to 60 m in depth that may contain one or multiple channel fills about 5–30 m thick and a few hundred meters wide, similar in size to the channels of the Puerto Madryn Formation. The channel-shaped incision, bounded at its base by an erosion surface, which is the sequence boundary in the case study of Maynard et al. (2010), is also found in the paleochannels of the Puerto Madryn Formation. In fact, these authors suggest that even minor incision within channel deposits may represent sequence boundaries because scouring is related to falls in sea level.

The studied intervals of the Puerto Madryn Formation succession meet the criteria listed above for incised valleys. Therefore, the deep regional incision below multiple channeling and channel migration may be indicative of a marked, relative sea-level fall that promoted the main valley incision. The recurrent channeling in the deposits above the regional incision can be related to high-order sea-level oscillations. However, the characteristics of some erosion surfaces and their overlying deposits relate better to TRSs resulting from deep tidal ravinement in macro- or hypertidal environments. Notably, Zaitlin et al. (1994) stated that the TRS is typically confined to an incised valley and can be mistaken for a second sequence boundary because it is typically overlain by coarse-grained channel deposits.

TRSs were traditionally assumed to form at the erosional base of a tidal (inlet) channel (Allen and Posamentier 1993) by upward and backward (retrogradational) migration of the estuarine barrier/inlet system (Boyd et al. 1992; Dalrymple et al. 1992). They cut into the filling of incised valleys in the outer incised valley system (Fig. 1a of Zaitlin et al. 1994) and are part of the transgressive systems tract. As they overlie the erosional surface of incised valleys formed in response to a relative sea-level fall, they constitute the lower sequence boundary (Van Wagoner et al. 1990; Maynard et al. 2010) above the transgressive surface separating the lowstand systems tract from the transgressive systems tract.

The depth of tidal ravinement is related to the tidal range and current energy in tidal channels within tidally dominated estuaries. Strong currents in some macrotidal or hypertidal settings can erode very deep, eventually cutting the transgressive surface (e.g., Allen and Posamentier 1994). Moreover, they may become the main discontinuities within the valley fill (Menier et al. 2006; Chaumillon et al. 2010; Tessier et al. 2012; Ahokas et al. 2014). Estuary models for the regressive part of the Puerto Madryn Formation (Scasso and del Río 1987; del Río et al. 2001; Scasso et al. 2012) fit into the tide-dominated, open-estuary depositional-coast type of Chaumillon et al. (2010) that is typically macrotidal to hypertidal. Strong tidal currents and tidal dominance for the Puerto Madryn Formation is clearly expressed in the coarse-grained lag deposits flooring the channels, the abundant scour surfaces, the presence of large subaqueous dunes and upper-flow regime sedimentary structures (Scasso et al. 2015a, their Figs. 28 to 32; compare with Flemming and Davies 1994, and with the axial deposits of Dalrymple et al. 2012) as well as in widespread tidal rhythmites, which are typical of macro- to hypertidal systems (Archer 1995, 2013; Tessier 2012; Archer and Greb 2012). On the other hand, a macrotidal regime is still present in the Península Valdés region and it must have been similar in the late Miocene because only negligible changes in latitude or shelf width took place. Therefore, well-developed TRSs resulting from energetic tidal currents should be expected in the Puerto Madryn Formation. In modern sediment-starved estuaries of France, the TRS expands upstream, allowing reworking processes by the TRS to occur all along the estuary, and leading in some places to a complete erosion of underlying units (Menier et al. 2006; Chaumillon et al. 2010; Tessier et al. 2012). In the case of the Bahía Punta Fósil and Cerro Olazábal paleochannels, the TRSs deeply scour into the transgressive filling of the channels. They get close to (Cerro Olazábal paleochannel) and eventually cut (Bahía Punta Fósil paleochannel) the fluvial ravinement surface (Fig. 7). According to the identified paleoenviroments, these tidal channel deposits occur from the outer part of the estuary up to the inner, fluvially dominated/tidally influenced part.

On the other hand, the Puerto Madryn Formation shows a transient high sediment input, in response to episodic volcanic eruptions, interspaced with long periods of low sedimentation rates and sediment bypass to the offshore Valdés Basin (Scasso et al. 2015a). The rivers were eventually overloaded with volcaniclastic sediments, swiftly burying the incised valleys and thereby precluding extensive lateral migration of fluvial and tidal channels. Consequently, some morphological features of the channels, like the steep channel walls or the TRSs, are well preserved through rapid burial and channel avulsion in a system with pulsed sediment input. Relatively large accommodation space in the deep channels was provided by the large tidal range in the Miocene estuaries of the Puerto Madryn Formation (compare with Tessier 2012).

Conclusions

The Puerto Madryn Formation tidal channel infill shows a general fining-upward succession that starts with intraformational lag conglomerates formed by intraformational clasts and blocks with terrestrial and freshwater vertebrate remains lying on irregular, deeply eroded surfaces interpreted as subaerial unconformities or fluvial ravinement surfaces. The latter are regarded as the "erosion surface formed in the purely fluvial or fluvially dominated part of the estuary, where the erosion is driven by the fluvial processes". The lag conglomerates are overlain and eventually cut (and suppressed) by a TRS covered by high-energy bioclastic lag conglomerates composed of marine fossils that formed in the "tidally dominated/fluvially influenced" part of an estuary under transgressive conditions during times of sea-level rise, as shown in the Bahía Punta Fósil and Cerro Olazábal examples, but also in several other examples elsewhere in the Península Valdés region. On top of the channel lags, large point bars with IHS show rhythmic alternations of sandy and muddy beds that are products of seasonal changes in river discharge, with varying trace and body fossil content. Their arcuate or straight shape, and their fossil contents suggest deposition in the freshwater, fluvially dominated to the saline, tidally dominated part of the estuary. Cross-bedded sands with mud drapes and seaward-directed paleocurrents, together with dominantly barren sandy to muddy heterolithic seasonal rhythmites, accumulated in the channels of the fluvially dominated part of the estuary. They make up the upper part of the channel infillings, their volcaniclastic composition indicating that ash supplied by rivers after large explosive volcanic eruptions on land resulted in high inputs of sediment into the system that produced temporary sedimentation rates as high as 0.9 m per year. The channel system was overloaded and the accommodation space provided by the large channels was swiftly filled up by volcaniclastic sediments, preserving the morphology of the tidal channels and TRSs through burial.

The channel deposits of the Puerto Madryn Formation fit into the tide-dominated, open-estuary depositional-coast type of Chaumillon et al. (2010), which is typically macrotidal to hypertidal. A large tidal range is also suggested by the presence of abundant tidal rhythmites and coarse sediments deposited under upper-flow regime conditions within the tidal channels. Therefore, well-developed TRSs resulting from energetic tidal currents deeply scoured into the transgressive channel fills, eventually cutting the fluvial ravinement surface and becoming the sequence boundary. This occurred during long periods of low sedimentation rates, extended channel migration and sediment bypassing, whereas transient, high volcaniclastic input interrupted that process through sediment overloading and rapid burial under transgressive conditions during times of sea-level rise, as shown in the Bahía Punta Fósiland Cerro Olazábal examples, but also in several other examples elsewhere in the Península Valdés region.

The TRS extended upstream to the inner part of the estuary, cutting deeply into the channel fill and eventually into the fluvial ravinement surface or the subaerial erosion surface. The tidal channels of the Puerto Madryn Formation constitute a unique example of estuarine sedimentation under pulsed high and low sediment supply in a macrotidal to hypertidal estuary.

Acknowledgments Thanks go to the owners and workers of many Estancias and touristic settlements of the Península Valdés. Special thanks are extended to Claudia Villegas from the Punta Delgada Hotel, Teresa Dozo and Julio César (Bocha) Rúa (CENPAT-CONICET) for field support, and the Administración del Área Natural Protegida Península Valdés for permission to work in the area. Funding by CONICET, ANPCYT and UBACYT is greatly acknowledged. Two anonymous reviewers substantially contributed to the improvement of this paper.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest with third parties.

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Q1. Dalrymple et al. 1991 has been changed to Dalrymple and MakinoY 1991 as per the reference list. Please check if okay.