Journal of Hydrology 529 (2015) 632–639

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Avulsion at a drift-dominated mesotidal estuary: The Chubut River outlet, Patagonia, Argentina

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ARTICLE INFO

Article history:
Available online 24 December 2014

Keywords:
Avulsion
Lower floodplain
Diatoms
Pollutants
Chubut River
Patagonia

SUMMARY

The Chubut River flows from the Andes to the Atlantic Ocean, and is interrupted by a single dam built at the middle valley. The lower valley is dominated by the aggradation of an alluvial plain induced by a complex of spits that enclosed the inlet in the last 5000 years. The river has reduced its flow because the blocking of the upper basin by terminal moraines during the Upper Pleistocene. At least the last two marine transgressions have flooded this estuary, and contributed to the aggradation during regressions. The area is of particular interest in regard to irrigation channels practiced since the XIX century. Today, the mean monthly flow is less than 10 m^3/s although peaks of 95 m^3/s have been recorded in Gaiman in July 2001. The dynamics of the estuary is dominated by waves (wave-dominated estuary) as tidal effects attenuate in less than 5 km. Three vibracores were collected within this floodplain: (a) at Gaiman, an area without any effect of the sea (35 km from the coast); (b) at Trelew, at the former avulsion plain of the river (18 km from the coast); and (c) at Playa Magagna, a saltmarsh located 0.4 km from the beach.

(a) At the Gaiman core (1.54 m long) fresh-water epiphytic diatoms dominate (*Epithemia sorex*, *Cocconeis placentula*, *Ulnaria ulna*) suggesting the aggradation of an alluvial plain.
(b) The Trelew core (2.19 m long) was collected from a deltaic plain. It was composed by fine sand with organic matter at the base that evolved into silty layers to the top. Several unconformities and laminae with heavy minerals were detected by their geochemical composition analysed by micro X-ray fluorescence (Itrax XRF core scanner). Fine-sand laminated layers were perfectly detected by their high content in S and Cl. On the other hand, mud layers presented lower content in Mg and Al with increments in Ca and V.
(c) The core from the marsh area (1.67 m long) was analysed in terms of the diatom evolution in order to detect Holocene sea-level and salinity effects. The sand flats from the bottom of the core were dominated by *Nitzchia navicularis* (mesohalobous and benthic taxa) and evolved into mixed flats, mudflats and marshes to the top. Sharp contacts have been detected between these facies, with wavy and lenticular bedding characterising the mixed flat deposits. The middle of the sequence is dominated by a coastal marine diatom (*Paralia sulcata*) while the top was dominated by *Pinnularia borealis*, an aerophilous and brackish/freshwater taxa.

1. Introduction

Estuaries evolve under changing sea level conditions. Estuaries of the Southern Hemisphere content the record of the sea-level fluctuation that occurred during the late Holocene.

Patagonian rivers are misfit in the sense of Thornbury (1954): they have transported more water and sediment during the Pleistocene than they do today. The moraines left by the Last Glaciation (Oxygen Isotopic Stage 2, Wisconsin in North America) dammed the original pathways to the Atlantic Ocean, reversing their drainage direction towards the Pacific Ocean (Quensel, 1910; Isla and Cortizo, 2014). Some watersheds, as the Chubut River, diminished significantly during the Pleistocene–Holocene transition (Fig. 1). Moraines left during Last Glaciation enclosed into piedmont lakes.

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http://dx.doi.org/10.1016/j.jhydrol.2014.12.019
0022-1694/

Their snow recharge areas at the Andes are today flowing towards the Pacific Ocean (Martínez and Coronato, 2008). These reductions in the drainage areas of the Chubut River were about 24% in relation to the Upper Pleistocene watersheds, and signified reductions between 32% in terms of volume discharged per year (Isla and Cortizo, 2014). In terms of the transport of heavy metals, the Chubut River is one of the rivers which transport lesser loads of Fe, Cu, Pb, Co, Mn and Ni to the South Atlantic Ocean (Gaiero et al., 2003). Significant changes occurred at the lower valley when the growing of littoral spits restricted the outlet increasing the avulsion effects.

The present paper is an analysis of the changes that affected the lower valley of the Chubut River in terms of sedimentation processes, sea-level effects, salinity changes and pollutants transport. Several proxies (grain-size changes, ^{14}C datings, diatoms, XRF) were handled to understand the autogenic and allogenic processes that controlled water and sediment transport, and compared to the evolution to other estuaries.

1.1. Setting

The Chubut River originates at the Andes Cordillera and runs across Northern Patagonia to its outlet at the Atlantic Ocean. It crosses a watershed with significant variations in temperature and precipitation. Esquel at the headlands has a mean temperature of 8 °C and rains about 500 mm/year; Trelew at the lower valley has 13 °C averaged and precipitations of less than 200 mm/year (Coronato et al., 2008). At the inlet, water temperature varies between 8 and 20 °C; dissolved oxygen between 4.5 and 8.3 mg/l (Helbling, 1989).

The river was subject to several studies regarding the sediment and water composition (Gaiero et al., 2002; Pasquini et al., 2005; Depetris et al., 2005). Patagonia is dominated by volcanic rocks (basalts, andesites, rhyolites) and continental deposits (Gaiero et al., 2002). Marine formations are restricted to the tertiary transgressions, today outcropping as coastal cliffs. The lower valley is cut between several fluvial terraces; the uppermost terrace is crowned by the Tehuelche Gravels (Feruglio, 1950; Beltramone and Meister, 1992; Martínez and Coronato, 2008). The watershed suffered significant changes during Late Quaternary (Césari et al., 1986; González Díaz and Di Tommaso, 2010). The end of the Last Glaciation caused the blocking of the Pleistocene drainage direction. Much of its former recharge area is today flowing to the Pacific Ocean via the Puelo River (Isla and Cortizo, 2014; Fig. 1). According to drills performed at the lower valley it was flooded by the sea at least during the Upper Pleistocene and Holocene interglacials (Auer, 1959, 1974). The growing of complex spits composed of gravel and sand caused the progressive restriction of the outlet (Monti, 2000) that increased the avulsion rates, increasingly towards the inlet.

2. Materials and methods

Vibracores were collected along the lower valley of the Chubut River, spanning from the outlet of the Florentino Ameghino Dam (130 km from the inlet) to the Atlantic Ocean (Fig. 1). Some of these cores were analysed in terms of grain-size and diatom variations. One cm diameter U-channel was extracted from the core of Trelew

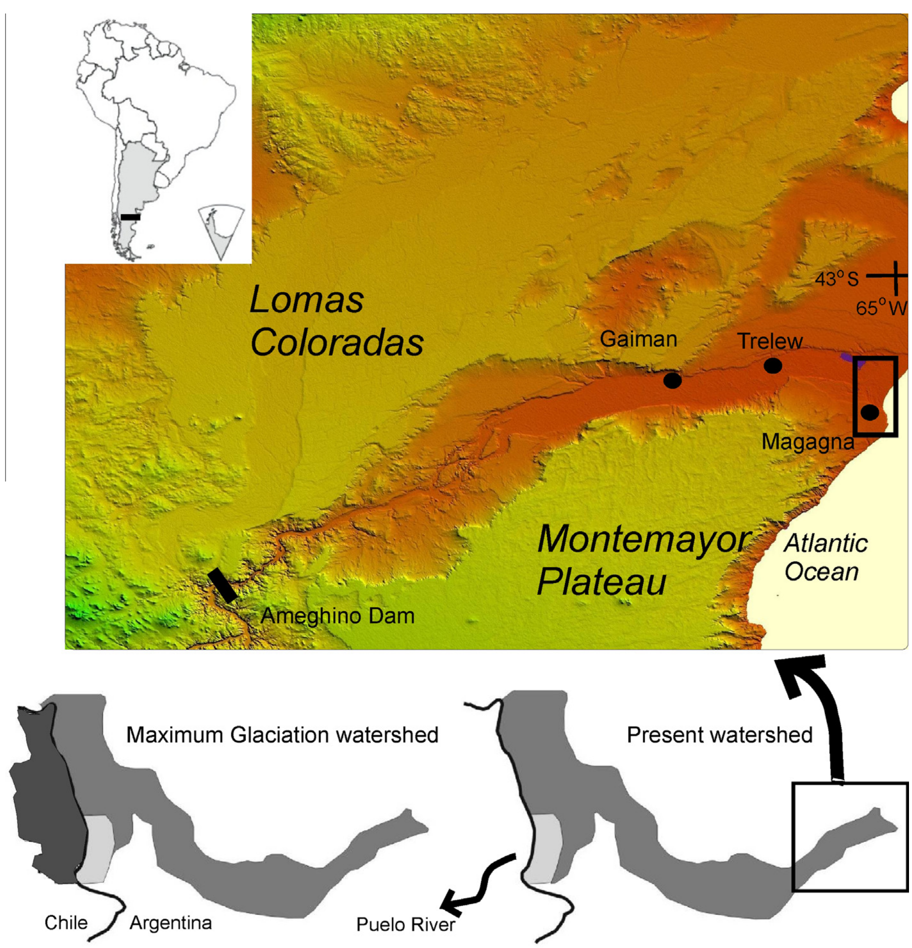

Fig. 1. Location of the Chubut River basin, and digital terrain model of the lower valley. The area of the watershed diminished since the Puelo River captured a significant portion (grey dark area) towards the Pacific Ocean (modified after Isla and Cortizo, 2014). Inset at the river inlet is in detail in Fig. 2.

(La Escondida), and was analysed with an ITRAX core scanner at the University of Vigo using a Cr-tube, with a voltage of 30 kv and 50 mA. The step size was 300 μm and the exposure time was 10 s. All results were re-evaluated using the Cox proprietary software Q-Spec 8.6.0. Data expressed as peak areas were smoothed by using 20 data in a moving-average routine, as suggested in modern investigations (Löwemark et al., 2011). Accelerator Mass Spectrometry (AMS) radiocarbon dates were performed from the La Escondida profile (Trelew) at the Arizona University Lab. Bulk-sample radiocarbon dates were performed at the Laboratorio de Tritio y Radiocarbono (LATYR, University of La Plata, Argentina). Corrections regarding the relationships between radiocarbon years and sideral years were performed. LATYR suggested corrections from marine samples of Southern Hemisphere (Mac Cormac et al., 2004) were also considered.

Water-quality measurements were performed using a multi-parameter Horiba U-10 water-quality checker: pH (0–14), conductivity (0–100 mS/cm), dissolved oxygen (0–19.9 mg/l), turbidity (0–800 nephelometric turbidity units, NTU), salinity (0–40 practical salinity units, PSU) and temperature (0–50 °C). The discharge data from the Chubut River was provided by EVARSA (2004).

Sediment samples for total persistent organic components (POCs), including polychlorinated biphenyls (PCBs), were collected in metallic cores of a diameter of 6 cm and preserved at −20 °C. At the laboratory, sediments were dried and analysed in relation to its grain-size composition expressed in weight (Carver, 1971). Sand was sieved while mud (silt and clay) was tested in relation to the settling velocity of the particles (pipette method). Sand (>0.063 mm) is assumed to be transported in the bed-load fraction while mud (clay < 0.004 mm, and silt 0.004–0.063 mm) moves in the suspended fraction. Oxidable organic matter was measured according to the Walkey and Black (1965) method. In order to estimate the level of organochlorine pollutants, sediment samples were homogenized using a blender. Water content was determined after drying the sediment in an oven at 110 °C. Subsamples of 5 g were ground in a mortar with anhydrous sodium sulphate and extracted with a 50:50 mixture of hexane and methylene chloride in a Soxhlet apparatus for 8 h. A clean up procedure was carried out using silica gel chromatography (Metcalfe and Metcalfe, 1997; Miglioranza et al., 2004). Total POCs were analysed by a Shimadzu GC-17A gas chromatographer with electron capture detector (ECD), equipped with a fused-silica capillary column of 30 m, SPB-5 (0.25 mm internal diameter, 0.25 μm film thickness). The organochlorine compounds analysed included: the HCHs group (α-, β-, γ- and δ-HCH), the DDTs group (p,p′-DDT and its degradation products, p,p′-DDE and p,p′-DDD) and the endosulfan group (α- and β-, isomers and endosulfan sulphate). Among PCBs, tri, tetra, penta, hexa and hepta chlorobiphenyls were considered. The pesticides are expressed including the sum of all groups as total POCs. In the case of PCBs they are expressed as the sum of all homologous groups as total PCBs. The quantification of the POCs was performed using an external standard purchased from Ultra Scientific and PCB#103 as internal standard. The detection limits for POCs analyses ranged from 0.06 to 1.4 ng/g dry weight. For PCBs, the detection limits were about 0.1–1.2 ng/g. Duplicate analyses of samples gave results that varied by less than 10%.

Heavy metal contents in sediments were evaluated by spectrophotometry of atomic absorption, air/acetylene mode. Four ml of nitric acid (HNO_3, Merck 65%) and 1 ml perchloric acid ($HClO_4$, Merck 65%) is added to each gram of sediment. Afterwards, the sample is digested in a glycerin bath to 1 ml. Results are expressed in dry weight, with detection limits of 0.06 mg/kg for Cu, 0.04 mg/kg for zinc, and 5 ng/kg for Cd. Mercury was also detectable in one sample close to a discharge of a channel discharging waste water.

Subsamples (one each 10–20 cm) were prepared for diatom analysis by oxidation in hot 30% H_2O_2 and 35% HCl to remove organic matter and carbonates – and then rinsed with distilled water. Diluted aliquots of cleaned slurries were evaporated onto coverslips, and mounted onto slides with Naphrax®. From each diatom-bearing interval in the cores, a minimum of 300 diatom valves was counted in transects including coverslip edges. All counts were performed under oil immersion (1000×), using a Zeiss microscope equipped with phase contrast optics. The identification of species was based on the local and standard diatom taxonomic literature. Diatom species were grouped in relation to salinity tolerances and life form, following the ecological classification of Vos and de Wolf (1988, 1993), and Denys (1992). Cluster analyses (CONISS) were performed to the diatom abundance matrices using TILIA and TILIAGRAPH software (Grimm, 2004) in order to define diatom assemblages based on a stratigraphically constrained classification (minimum variance, euclidean distance). For diatom analyses, all taxa were included in the similarity matrixes. Differences in diatom assemblages are clear enough for defining zones, rendering cluster analysis unnecessary.

3. Results

Surface sediments and vibracoring was collected in order to analyse the present situation and historical evolution during the Holocene.

3.1. Lower floodplain sedimentation

Three vibracorings were collected:

(a) The Gaiman core (43°17′17.6″S; 65°28′12.4″W; 1.54 m) was collected from a floodplain 35 km from the coast (Fig. 1). The base of the core gave a radiocarbon age of 8020 ± 88 years BP (8592–9144 calendar years BP; Table 1). The lowermost 1.30 m was composed of sand with rests of plants and roots (Fig. 2). Overlying, and beginning with a breccia layer, 0.24 m of silts with rests of plants with layers of organic matter crowned the sequence. The description of the core did not suggest any evidence of marine influence along the sediments.

(b) The Trelew core (La Escondida; 43°16′25.6″S; 65°15′17.5″W; 2.19 m) was obtained from the avulsion plain of the river, about 18 km from the coast of the sea. The sequence is a fining-upwards succession. As a fluvial deposit, it is graded from coarse sand and thicker layers at the base to fine sand – alternating with mud layers – to the top (Fig. 2). The two grey clay layers detected by Auer (1959, 1974) were confirmed. Several unconformities and laminae with heavy minerals were also described and detected by their geochemical composition under X-ray fluorescence (Itrax XRF core scanner). 122 mm from the top, a layer rich in organic matter was dated on 290 ± 31 years BP (1491–1602 AD).

(c) Playa Magagna core (43°19′54″S; 65°04′04″W; 1.70 m) was drilled on a saltmarsh located 0.4 km from the beach (Fig. 2). This core was composed by fine sand with organic matter at the base that evolved into silty layers to the top. The base of the core was dated on 4376 ± 69 years BP (4836–5079) while the top was deposited 672 ± 39 years BP (624–682; Table 1).

3.2. Salinity changes

The core from Gaiman (1.54 m long) was dominated by freshwater epiphytes diatoms (*Epithemia sorex*, *Cocconeis placentula*,

Table 1
Radiocarbon datings of the lower floodplain of the Chubut River.

CORE/sample	LAB#	Height (cm) Depth (cm)	Conventional ^{14}C Years BP	Calibrated age (cal years BP ± 2Δ)	Material	Reference
Paleospit 4	Ac-3892	+900	4987 ± 106	5579–5939	Mollusc shell	Monti (2000)
Paleospit I	Ac-3891	+800	3929 ± 97	4085–4629	Mollusc shell	Monti (2000)
Terrace 3	Ac-3819	+650	2770 ± 81	2745–3078	Mollusc shell	Monti (2000)
Terrace 3	Ac-3818	+550	1009 ± 97	731–1090	Mollusc shell	Monti (2000)
Gaiman	AA90822	141	8020 ± 88	8592–9144	Bulk organic matter	This paper
Gaiman	AA92985	57	Post-bomb	1955–2002 AD	Bulk organic matter	This paper
La Escondida	AA103360	122	290 ± 31	1491–1602 AD	Bulk organic matter	This paper
Magagna	AA90823	165	4376 ± 69	4836–5079	Bulk organic matter	This paper
Magagna	AA92986	33	672 ± 39	624–682	Bulk organic matter	This paper

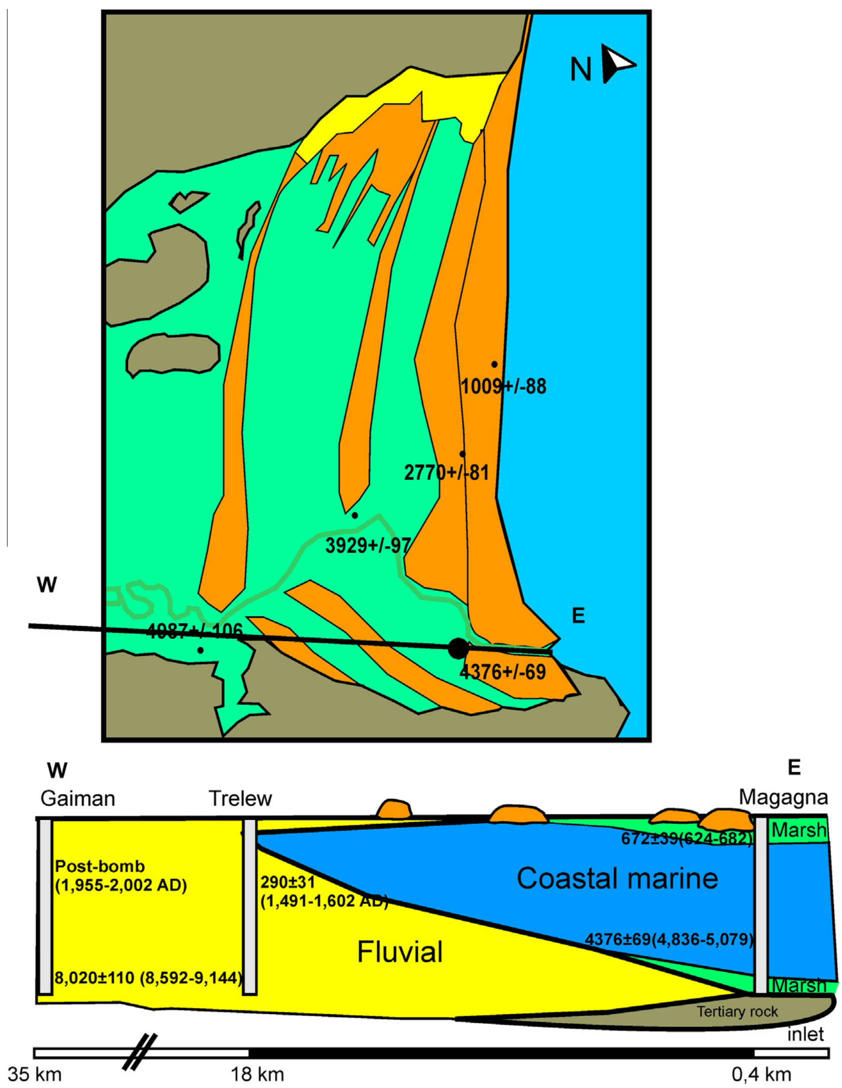

Fig. 2. Vibracores and sketch of the architecture of the Chubut River lower floodplain (modified from Monti, 2000, and Escandell, 2012). Vibracores were located according to Fig. 1.

Ulnaria ulna), suggesting the aggradation of an alluvial plain with freshwater species at the bottom and the appearance of brackish–freshwater epiphytes assemblages to the top (*Rhopalodia* spp., *Cocconeis pediculus* and *Gomphonema olivaceum*) (Fig. 3).

The Trelew (La Escondida) core is dominated by freshwater diatoms. From the base of the core to the last 0.4 m, freshwater plankton dominates. The assemblages are composed by *Stephanodiscus hantzschii* and *Aulacoseira granulata*, also accompanied with the epiphytes *C. placentula*, *Epithemia adnata* and *Rhopalodia gibberula* that are suggesting low depths. Brackish–freshwater assemblages succeeded: *Diatoma moniliforme*, *C. pediculus*, *U. ulna* and *Surirella ovalis*. To the top of the sequence, the same brackish–freshwater occur but less abundant and badly preserved and at 0.1 m broken frustules of marine–brackish taxa as *Thalassiosira oestrupii* and *Cyclotella striata* appear. Surface deposits are dominated by the same species of the bottom, suggesting fluvial processes.

The core from Magagna site (1.67 m long) was analysed in terms of the diatom evolution in order to detect Holocene sea-level variations and salinity effects. The sand flats from the bottom of the core were dominated by *Nitzschia navicularis* (brackish and

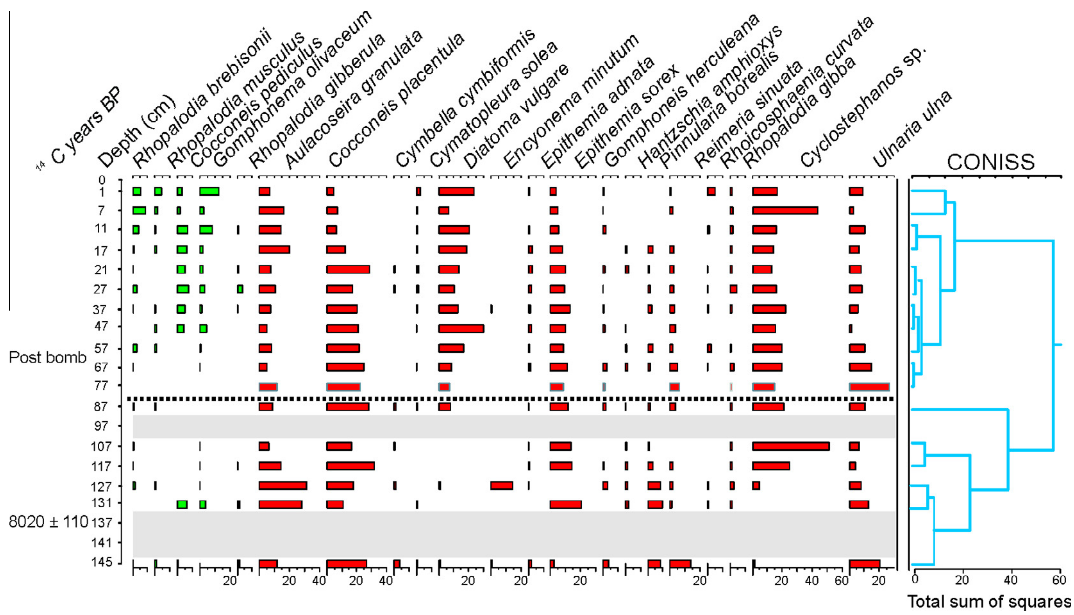

Fig. 3. Diatom diagram from the Gaiman core (modified after Escandell, 2012). Brackish–freshwater taxa are in green while freshwater taxa are in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

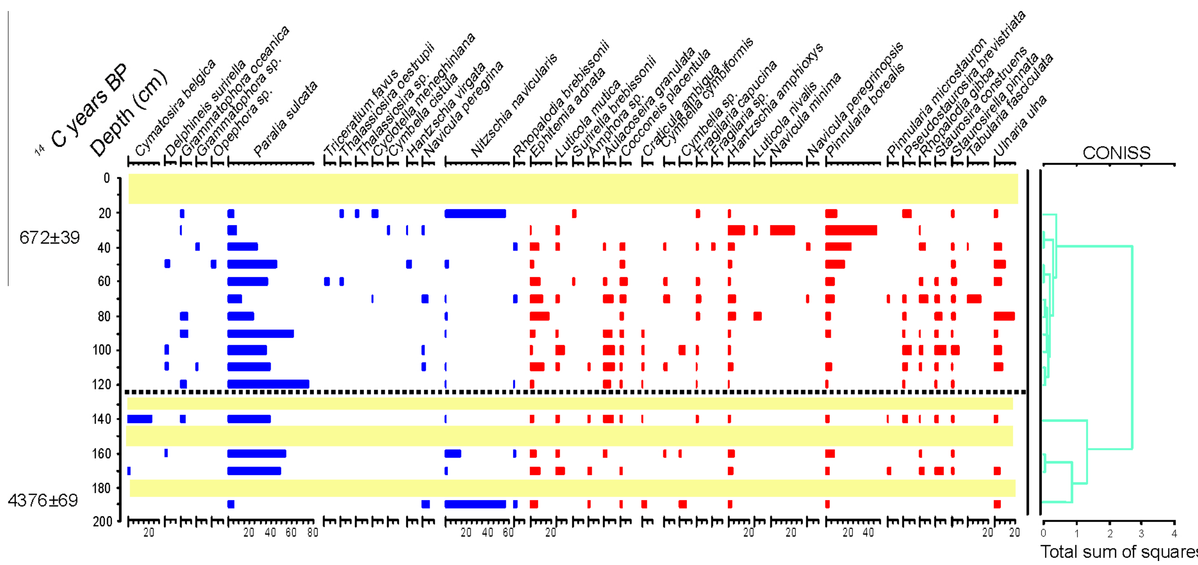

Fig. 4. Diatom diagram from Magagna core (modified after Escandell, 2012). Marine–brackish taxa are in blue while freshwater taxa are in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

aerophilous) and evolved into mixed flats, mudflats and marshes to the top (Fig. 4). Sharp contacts have been detected between these facies, with wavy and lenticular bedding characterising the mixed flat deposits. The middle of the sequence is dominated by the coastal marine diatom *Paralia sulcata* while the top was dominated by the aerophilous and brackish/freshwater *Pinnularia borealis* and *Nitzschia navicularis.*

3.3. Pollutant distribution and modern transport

Surface sediments from the river indicate an increase in pollutants after the Florentino Ameghino Dam (Fig. 1), where there is an increase in agriculture activities. The concentrations of heavy metals (Zn > Cu > Cd), total POCs and PCBs diminish approaching to the inlet (Fig. 5). However, the discharge of the channel collecting waste water indicates an increase in Cd approaching to 1 mg/kg. This peak is also coincident with high values in Zn and Cu suggesting a polluted site in the sense of Wedepohl (1995).

The core close to Trelew city (Fig. 1) was analysed by the ITRAX scanner of Vigo University. Fine-sand laminated layers were perfectly detected by their high content in S and Cl (Fig. 6). On the other hand, these mud layers had a lower content in Mg and Al with increments in Ca and V. The higher contents in Al, Si, K, Ti and Rb are suggesting terrigenous sources. The contents in heavy metals (Ni, Cu, Zn) and V are surely related to the supply from the basaltic plateaus that characterise Patagonia (Gaiero et al., 2002), and the attrition of the Tehuelche Gravels of volcanic composition. Arsenic in Patagonia was repeatedly related to the abundance of acid volcanic rocks and thick deposits of tuffs.

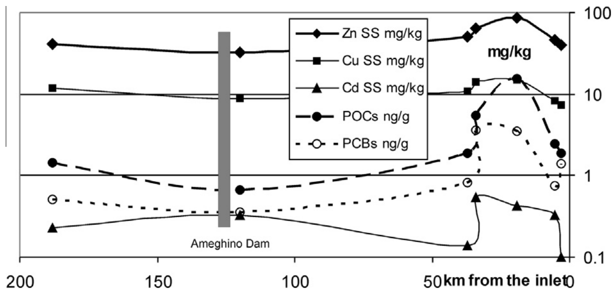

Fig. 5. Heavy metals (Zn, Cu and Cd), total POCs and PCBs concentrations along surface sediments of the Chubut River.

4. Discussion

Avulsion, the abandonment of all or part of a channel belt in favour of a new course, is controlled by both intrabasinal (autogenic) and extrabasinal (allogenic) processes (Stouthammer and Berendsen, 2007). Although the magnitude of avulsions can be assigned mainly to basin and river characteristics, the interavulsion intervals are known to vary in response to sea-level changes, climate or tectonics. Humans may have played a significant role in the sediment supply to certain deltas; however, this is not the case for Patagonian rivers. Avulsion is therefore a common phenomenon in lower valleys favoured by a diminution of the Holocene sea-level rise. In general terms, while sea level is still rising in Northern Hemisphere, it has been dropping in Southern Hemisphere since the Middle Holocene (Isla, 1989). This caused significant differences in the deltas evolution of both hemispheres. At the Rhine–Meuse delta, decreasing gradients – as a result of sea-level rise-, may have caused an increase in sedimentation within channels, their widening and an increase in the meanders wavelengths (Stouthammer and Berendsen, 2000). The Chubut River has increased significantly its sedimentation rate when the most modern spit composed of gravel and sand obstructed the inlet in the last 1000 years (see Fig. 2).

The Holocene changes of the Rhine–Meuse delta were caused by sea-level rising rates, tectonics and the human influence during the last five centuries (Stouthammer and Berendsen, 2000). Subsidence at the Nobi coastal plain (Japan) progressively increased the accommodation space and the aggradation of the natural levees (Hori et al., 2011). The avulsion of the lower valley of the Chubut River was favored by the fluctuation of the sea level and the longshore growing of gravel spits. Tidal flats progressively grew within this plan and afterwards they were colonised by salt-tolerant plants (Fig. 7). The building of the northern coastal barriers of The Netherlands surely affected avulsion processes.

Human influence was not important at the Chubut River until the Welsh colony initiated the construction of drainage channels during the middle of the XIX century (150 years ago). The extensions of the Patagonian and Fueguian marshes are related to annual precipitation and temperature in a similar way to the input of water and/or the tidal ranges (Isla et al., 2010).

The direction of flow of some of the piedmont lakes reversed during Upper Pleistocene when moraines blocked their drainage to the Atlantic Ocean; other watersheds reversed during the Early Holocene (Del Valle et al., 2007). Today, most of the rivers discharging to the Atlantic Ocean are not transporting much sediment. The

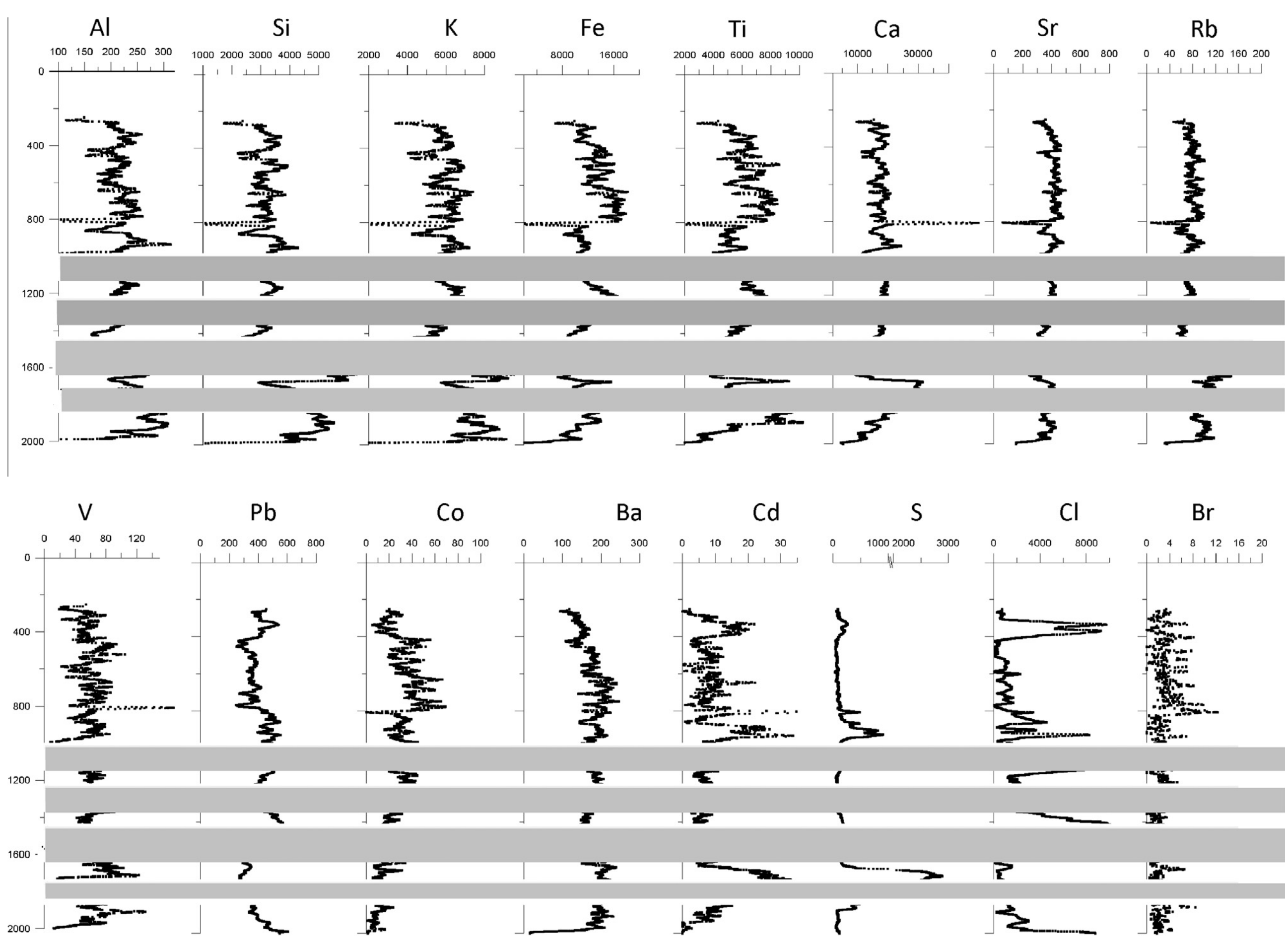

Fig. 6. ITRAX results from the Trelew core (La Escondida profile draw in Fig. 2). Grey bands correspond to intervals not analysed.

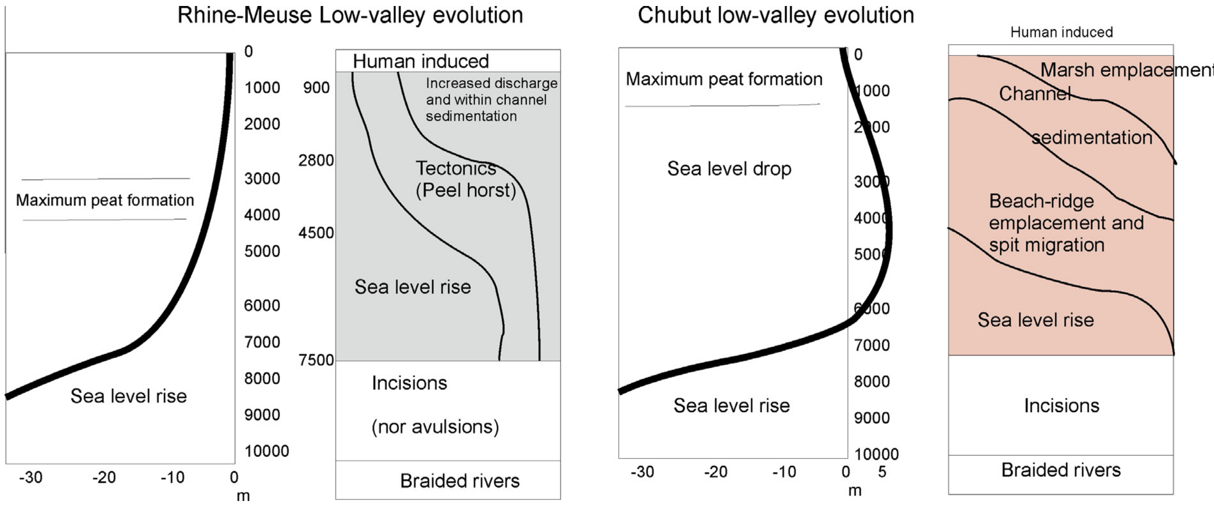

Fig. 7. Evolution of the lower valleys of the Rhine–Meuse and Chubut Rivers (modified from Stouthammer and Berendsen, 2000 and Isla, 2013).

Deseado River diminished significantly since the Last Glaciation and today it is not discharging a significant amount of water (Iantanos et al., 2002). The calving of the ice lobe of the Lago Buenos Aires valley occurred at the end of the Pleistocene. The division of the unique ice cover into two ice fields (North Patagonia and South Patagonia) was dated about 11,500 years BP (13,500 calibrated years BP *sensu* Mc Culloch et al., 2000).

Annual variations of the water quality at the inlet were significant in relation to the water temperature and the nutrients input from the watershed (Helbling, 1989; Helbling et al., 1992). In autumn–winter of 1987, two blooms were recorded. The bloom of May was dominated by *Aulacoseira granulata* and was related to low discharge of the river and high concentration of nitrates. The July bloom was dominated by *Odontella aurita* and occurred with a high river discharge in coincidence with stratification in the water column (Villafañe et al., 1991). Historical changes are therefore interpreted from the diatom content in the sedimentary record of different sectors of the lower floodplain.

It is not easy to explain X-ray fluorescence results where there is not much information about this Allochtonous river within a very large watershed. At the upper slope of Buenos Aires Province, Ca in contouritic deposits would explain biogenic supports while Fe the terrigenous inputs (Voigt et al., 2013). Dealing with modern estuaries (Aveiro coastal lagoon, Portugal), the lithogenic origin was related to the content of Al, Fe, Ti, Si, Rb, Ba, K, Cl, Br, S, Mn and Zr (Martins et al., 2013). As this coast of Portugal had mining activities, the contents of Pb, Cr, V, Ni, As, Cu and W was explained by human influence before 1920. The increase in the ratio between Si/Al was interpreted as a higher input in quartz (Martins et al., 2013).

Most of the deltas of the World began to grow when the sea-level stabilised or began to fall. Fluvial plains of Northern Hemisphere can have a lag between the maximum highstand and deltaic progradation. The Po and Tevere deltas have a similar eustatic history but they respond differently due to inherited morphology: the Po Delta progradated immediately after the maximum highstand (about 6–5 ka); at the Tevere fluvial plain a coastal lagoon infilled and afterwards the delta progradated to the open sea (Amoroso and Milli, 2001). In the last 2500 years the Tevere delta experienced alternating phases of progradation and stability while the Po had suffered changes in the avulsion conditions. At the coastal-lagoon complex of Southern Santa Catarina (Brazil), there were significant morphological changes associated to the enclosing of the former bay and the progradation of the Tiburão River delta (Do Nascimento, 2010). From 8000 to 2000 years BP, bay facies dominate until the Tubarão delta occupied the Mid-Holocene coastal lagoons. Three distributary arms were discriminated with different progradation rates: Da Guarda (8.8 m/year), Mirim (11.6 m/year) and (Sambaqui 30.9 m/year).

5. Conclusions

1. The floodplain of the lower valley of the Chubut River aggraded during the last 8000 years but this process increased since the last 2000 years BP when complex spits enclosed the outlet and avulsion effects increased.
2. Tidal flats and marshes therefore installed in the last 2000 years.
3. Fluvial sand contribution diminished since the channels dug by the Welsh colony, and the modern construction of the Ameghino Dam.
4. Some pollutants (organic pesticides and PCBs) are clearly increasing at the lower valley due to agricultural activities. The increment of heavy metals in sediments is suggesting other man-triggered activities.

Acknowledgements

Financial support was provided by the Minister of Environment by a UNDP Project, and the National Agency for Research Support (grant PICT 1856/12). A. Escandell was granted by a doctoral fellowship of the National Research Council of Argentina (CONICET). The paper was presented during the Sedimentological International Congress of IAS (Mendoza, Argentina, 2010). Juan A. Morales and an anonymous reviewer helped to improve the manuscript.

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