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Sediment input from fluvial sources and cliff erosion to the continental shelf of Argentina *

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ABSTRACT

The coasts of southern Buenos Aires, Patagonia and Tierra del Fuego are dominated by cliff erosion. Mean rates of cliff retreat are estimated to be about 0.5-0.6 m/year by comparing old photographs with modern satellite images. Considering the height of the Patagonian and Fueguian cliffs (70 to 120 m), the volume of sediment eroded from these cliffs exceeded the volumes provided by the erosion of the cliffs of Buenos Aires (10 to 20 m height). These erosion rates support an estimated delivery of 217 million tons of sediment per year to the continental shelf, exceeding significantly the 22 millions of tons/year transported by the larger Patagonian rivers Negro and Colorado. However, the contribution of these rivers has decreased since the Late Pleistocene changes in the direction of transport of some watersheds. The Chubut and Chico de Santa Cruz rivers suffered reductions of 21-24% in their watershed areas, resulting in reductions of about 33-34% in the volume of water transported to the Atlantic Ocean per year. As the amount of sediment delivered to the Argentine continental shelf by cliff erosion is higher than the fluvial transport, it should be also considered in the balance of beaches fed by longshore transport.

Keywords: cliff erosion, sediment supply, drainage reversal, Patagonia, Buenos Aires

RESUMO

Fornecimento sedimentar de origem fluvial e da erosão costeira à plataforma continental Argentina

O litoral de Buenos Aires, Patagónia e Terra del Fuego é dominado pela erosão de falésias marinhas. As taxas de medias de recuo foram estimados em 0,5-0,6 m/ano, com base na comparação de fotografias aéreas antigas com imagens satelitárias modernas. Considerando a altura das falésias patagónicas e fueguinas (70 a 120 m), o volume de sedimento erodido supera os volumes que provêm das falésias de Buenos Aires (10 a 20 m). Estas taxas de erosão permitiram estimar um aporte de 217 milhões de toneladas por ano de sedimento à plataforma continental, superando os 22 milhões de toneladas/ano transportados pelos rios da Patagónia, Negro e Colorado. Além disso, a contribuição fluvial diminuiu devido às alterações na drenagem que afetaram algumas bacias desde o Pleistoceno Superior. Os rios Chubut e Chico de Santa Cruz sofreram reduções de 21-24% nas áreas de drenagem, o que significou diminuições de 33-44% nas contribuições de água para o Oceano Atlântico. Como o volume de sedimentos proveniente da erosão de falésias e fornecido à plataforma continental argentina supera o do fornecimento fluvial, tal deve ser também considerado na análise do balanço sedimentar das praias alimentadas pela deriva litorânea.

Palavras-chave: *erosão de falésias, aporte sedimentar, inversão da drenagem, Patagonia, Buenos Aires*

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1. Introduction

During the 20th century, the study of cliff-erosion rates required use of detailed topographic maps or aerial photographs. These methods were expensive and needed much care to handle projections, scales, resolutions, relationships between vertical and horizontal datums, and the precision to represent intertidal areas (Barrier & Sloan, 2007). The use of aerial photographs applied to coastal areas was initiated during World War II with the objective of forecasting landing conditions at the Pacific Islands (Lundahl, 1948). These techniques evolved later to monitor cliff erosion rates (Hapke 2004, Maiti & Bhattacharya, 2009). The first satellite planned for land resources (Landsat 1) had no spatial resolution useful for measuring cliff recession rates (79 m). To the end of the 20th century, improvements in spatial resolution (Ikonos, Quickbird and OrbView satellites) permitted monitoring programs with a minimum resolution. The GPS (Global Position System) constellation was another improvement to reference fixed points for the change analysis.

Some empirical models have been proposed to forecast cliff-recession rates:

$$dX = Cs * f * dt \qquad (1)$$

where dX is the rate of erosion, t is time, f the erosive force, and Cs is considered as the rock erodability (Horikawa & Sunamura, 1967); f is considered a function of a constant and the wave altitude. Significant differences in Cs were explained by the different behavior of igneous and sedimentary rocks (Emery & Kuhn, 1982; French 2001). Specifically, the lithology, structure and slope of the cliffs should be considered (Del Río & Gracia, 2004). Modern studies incorporated the effects of variations of the water table (Leatherman, 1986), heavy rainfalls (Duperret *et al.,* 2004) and the episodic effects of earthquakes or El Niño effects (Hapke & Richmond, 2002; Hampton *et al*., 2004). Groundwater and rainfall effects are particularly important to forecast the retreat rates of the cliffs of Buenos Aires. In recent years, anthropogenic effects are considered to be of increasing concern (Wilkinson & McElroy, 2007). In urbanized areas south of Mar del Plata, the seasonal variations of the water table depend on the touristic demand for water and the local recharge induced by the operation of multiple cesspools. Rock revetments recently constructed along the coastline of Mar del Plata have caused significant effects on the coastal sediment budget due to a decrease in the sand availability. In Patagonia, monthly variations in the tidal ranges can have significant effects on the erodability of clayey cliffs. In order to discern anomalous places or episodic recession rates (storm effects), it is useful to consider statistical approximations averaged either along distance or time (Galgano *et al.,* 1998; Zuzek *et al.,* 2003). Combinations of techniques are recommended, taking advantage of photographs from old satellites (as the Corona program) compared to new images of better spatial resolution (Bayram *et al.,* 2004).

The first evaluation of the sediment input to the Argentine Basin was estimated assuming that the main sources were provided by the continent, and neglecting the quantity of sediment provided from Antarctica (Siegel, 1973). Considering only the inputs of the Colorado (6.9-7.7 x 10^6 metric tons) and Negro rivers (15.2-13.6 x 10^6 metric tons, Depetris, 1968; Depetris & Griffin, 1968), Siegel summed a fluvial input of 22 x 10^6 tons transported by these two major Patagonian rivers; the input supply by coastal erosion was disregarded. It should be stressed that the watershed of the Colorado River can increase its discharge during ENSO events, when the Curacó-Desaguadero system can become operable (Spalletti & Isla, 2003).

Dealing with coastal erosion, cliff recession rates between 1 and 4 m/yr were estimated for the coastal cliffs north and south of Mar del Plata (Cionchi *et al.,* 1998). The processes that were controlling coastal erosion at the cliffs of the provinces of Rio Negro and Chubut were assumed to be different (Schillizzi *et al.,* 2003). At the northern coast of Rio Negro, cliff recession rates varied between 0.2 and 2 m/year (Del Río *et al.,* 2007).

In the present study, cliff erosion rates of the whole coast of Argentina, comprising Buenos Aires, Patagonia and Tierra del Fuego, were estimated for the first time, combining information extracted from aerial and satellite photographs, and the modern referenced satellite images. Taking advantage of some GIS procedures to enhance definition, this cliff contribution of sediment to the continental shelf was compared in relation to the sediment transport provided by the more important rivers. In this sense, the Holocene decay in the contribution of these rivers was also evaluated.

2. Regional Setting

The coast of Argentina extends from 33º S to 50º S. Climate varies from temperate and humid in Buenos Aires, to very cold and dry in northern Tierra del Fuego (Schäbitz, 1994). There are significant variations in the precipitation in Patagonia, spanning from 200 mm/yr at the north to 2500 mm/year at the southwestern extreme (Coronato *et al.,* 2008). In Tierra del Fuego, differences of 2000 mm/ year occur to both flanks (north and south) of the Darwin Cordillera (Tuhkanen, 1992; Coronato *et al*., 2008).

The Buenos Aires coast is dominated by storm effects in a microtidal regime with diurnal inequalities (spring tidal range is lower than 1 m). On the other hand, semi-diurnal tides over a 4 m tidal range are dominant in Patagonia (Figure 1). Tidal ranges increase within gulfs: in the Bahía Blanca embayment it increases from micro to a mesotidal regime (Isla & Bértola, 2003); in the San Jorge Gulf it increases from meso to a macrotidal regime (Isla *et al.,* 2002).

Along the Tierra del Fuego coastline, mean tidal range diminishes from 6.6 m in San Sebastián Bay (Isla *et al.,* 1991) to 5.7 m in Caleta La Misión, 4.16 m in Río Grande and 4.63 m in Caleta San Pablo. Due to the westerly winds, in San Sebastián Bay, maximum tidal currents are over 2 knots at the inlet and of 5 knots within the bay. Spring tides can increase to 10.4 m (Figure 1).

In regard to wave climate at high latitudes of the South Atlantic coast, it can be stated that:

(a) the frequency of wave heights higher than 3.5 m is very low; 20% of the waves were less than 1 m in height throughout the year;

(b) long-period waves are relatively uncommon; wave periods greater than 10 s come from the E and NE,

(c) gales of 41–47 knots from any direction between N and ESE (with a return period of 50 years) are estimated to generate extreme wave heights of 12 m (period of 11.5 sec) in a depth of 50 m (Isla & Bujalesky, 2004).

A regional longshore drift has been reported from north to south in regard to coastal features and sediment transport experiments (Codignotto & Malumián, 1981; Codignotto & Kokot, 1988; Isla *et al.,* 1991). However, beach heavy minerals suggest longshore transport from south to north (Gomez Peral & Martínez, 1997). The recurving spit of Río Grande inlet also evolves in response to a local drift from south to north (Isla & Bujalesky, 2004).

The Buenos Aires coastal plain is composed of sandy silts, with caliche levels that fortunately resist the persistent erosion induced by waves. Waves dominate from SE and NE in Mar del Plata, and from the S in

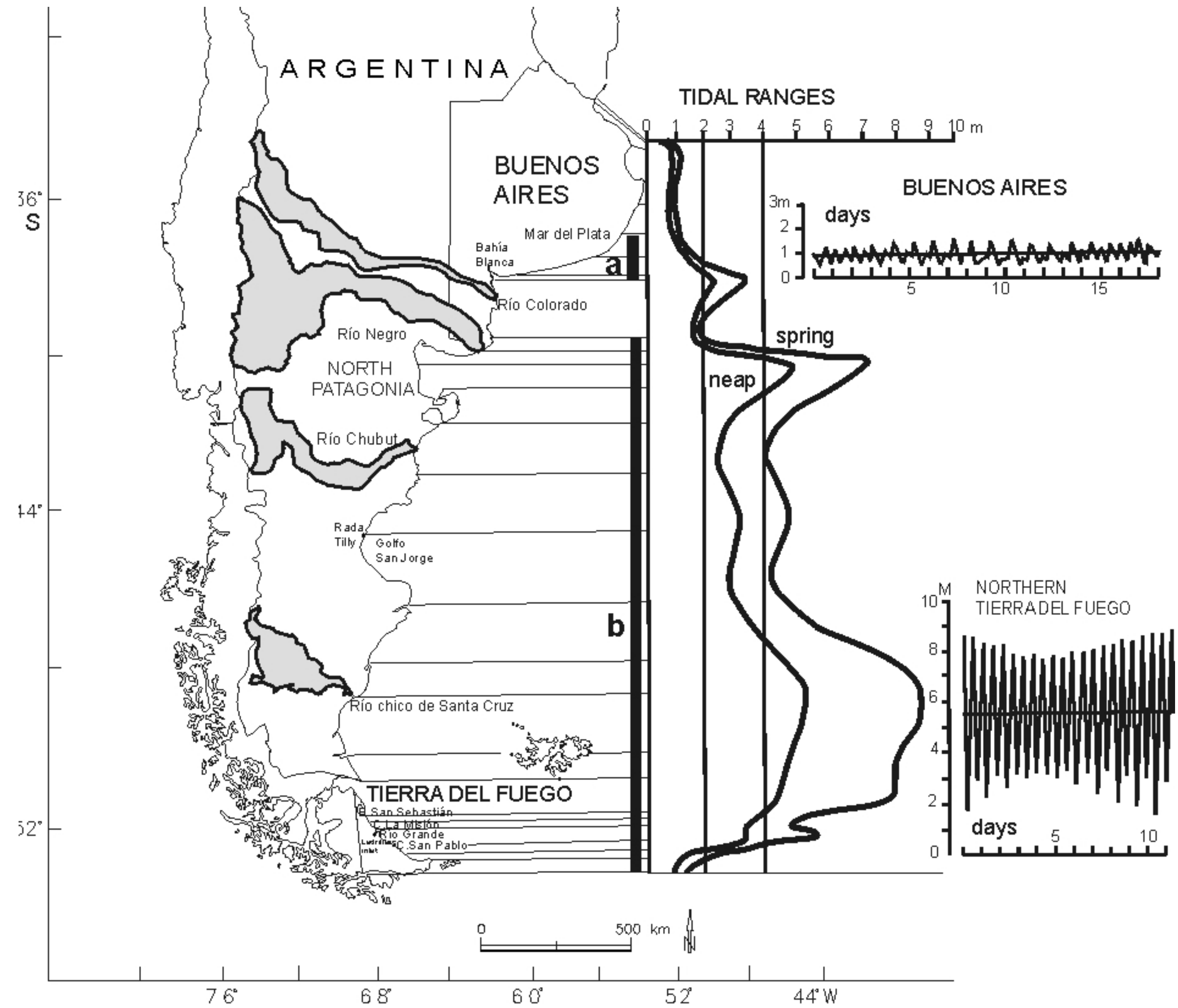

Figure 1 - Location of studied cliffs and the watersheds analysed. Bar "a" comprises the cliffs reported from Buenos Aires Province; bar "b", the cliffs studied from Patagonia.

Figura 1 - Localização das falésias estudadas e das bacias hidrográficas analisadas. "a" compreende as falésias da Província de Buenos Aires; "b", as falésias estudadas da Patagónia.

Necochea; higher waves are more frequent (seasonal) in Mar del Plata than in Necochea. The Patagonian coast consists of different systems of plateaus of tectonic origin and marine terraces originated by Quaternary sea-level fluctuations (Rutter *et al.,* 1989; Schellmann, 1998; Isla & Bujalesky, 2008). The cliffs are of 40-50 m height at the Rio Negro Province, and increase to more than 120 m towards the Magellan Strait. An uplift of the southern extreme of the South American Plate was estimated at about 8 cm/1000 years (Guilderson *et al.,* 2000). At the coast of Tierra del Fuego, glacial moraines and marine terraces are reminders of the climatic fluctuations that occurred during the last 120,000 years (Isla & Bujalesky, 2008).

3. Materials and methods

Old aerial photographs, from 1964 and 1971, were compared to modern Landsat ETM images (spatial resolution 15 m) registered into the Gauss-Krugger coordinate system (National reference system of Argentina). Edge-enhancement techniques were applied to distinguish coastal cliffs (Figure 2).

For the Buenos Aires cliffs, Landsat 5 images were applied (from 1998 and 1999), while in Patagonia, Landsat 7 images (from 2003) were also used. In all cases fixed points, mostly lighthouses of known geographic position, and altitudes (at their bases) referred to mean sea level, were recognized and measured in their distances to the top of the cliffs, with the help of charts and publications of the National Hydrographical Survey (Servicio de Hidrografía Naval, 1978, scales 1/50,000 or 1/100,000). These comparisons generated variations in the precision of the distance measurements (Hapke & Richmond, 2002; Zuzek *et al.,* 2003; Hapke, 2004). It is assumed that shoreline variations are subjects to errors of ± 50-150 m using aerial photographs,

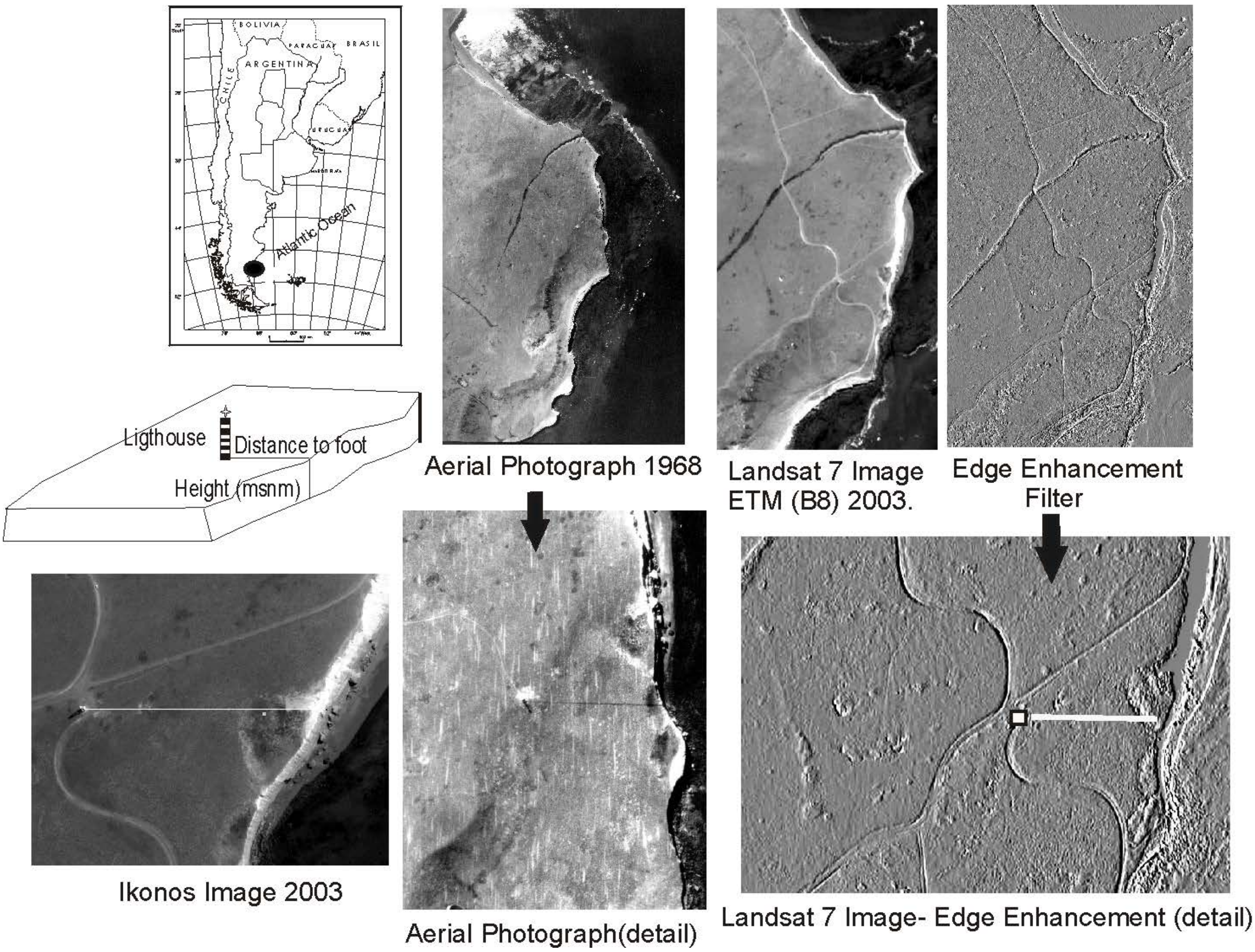

Figure 2 - Remote sensing methods applied to Curioso cape (Santa Cruz Province). Aerial photographs of 1968 are compared to a Landsat TM images of 2003. The position of the lighthouse is related to the cliff foot applying edge enhacement procedures.

Figura 2 - Métodos de sensoriamento remoto aplicados ao Cabo Curioso (Província de Santa Cruz). Fotografias aéreas de 1968 são comparados com imagens Landsat TM de 2003. A posição do farol está relacionado com a base da falésia através da aplicação de procedimentos de realce.

reduced to ± 15 m dealing with topographic surveys (Ruggiero *et al.,* 2003). Different statistical methods to analyze the cliff retreat can be useful for different purposes (Fletcher *et al.,* 2003). For the identification of the coastal retreat, the foot of the cliffs (or foredunes) was considered as the most sensitive feature. However, where the shadows of the tall cliffs prevented the recognition of their feet, the top of the cliffs were selected for monitoring. The sources of error increased for the TM images where the spectral reflectance of the cliffs is similar to the spectral reflectance of the beach (sand or gravel beaches). In macrotidal coasts, the area washed by the last high tide helped to distinguish the foot of the foredune.

Annual erosion rates (m/year) were multiplied by the height of the cliffs in order to obtain the volume eroded per meter of coastline (French 2001). Considering the distances assigned for each lighthouse, the annual volume of sediment eroded was calculated (m^3/year). The volumes eroded from the retreat of abrasion platforms were disregarded because their sediment contribution is negligible if there is not a significant change in sea level. As sea level is thought to be dropping during the Holocene (Isla, 1989), no long-term sea-level rise factor was considered in these estimates.

In order to evaluate the changes in the watersheds that reversed during the Last Deglaciation, two watersheds, Chubut and Chico of Santa Cruz, were compared in their areas and volumes of discharge during Late Pleistocene (“ice divide”) and Holocene (“water divide”).

A Digital Elevation Model (DEM) was downloaded from the SRTM web site (Shuttle Radar Terrain Model; http://srtm.csi.cgiar.org). This model has a ground spatial resolution of 90 m. The information was handled with the Global Mapper v.7.04 (http://www.globalmapper.com). Modern watersheds were drawn in a Geographic Information System (GIS) and compared to drainage areas provided by the web (http://www.hidricosargentina.gov.ar). As the differences between both watersheds showed significant decrease in the water discharge, this evaluation not only considered variations in the basin area but also in the amount of water discharge per year (assuming that the distribution of rain within the basins has not changed significantly).

Both watersheds were digitized into an Arc View 3.0 environment (Environmental Systems Research Institute 1996). Isohyets were also plotted into this GIS environment in order to calculate the annual recharge in each watershed (km^3/yr).

4. Results

4.1. Buenos Aires cliff retreat

Comparing photographs of 1970 and images of 2004, a recession cliff retreat of 0.4 to 0.7 m/year is common. To the north of Mar del Plata, from Camet Norte to Mar Chiquita, the coast is composed of foredunes under erosion, where the retreat increases from 1.5 to 3.9 m/year (Figure 3a). Volumes eroded increase to the south as the cliffs have higher altitudes (Figure 3b).

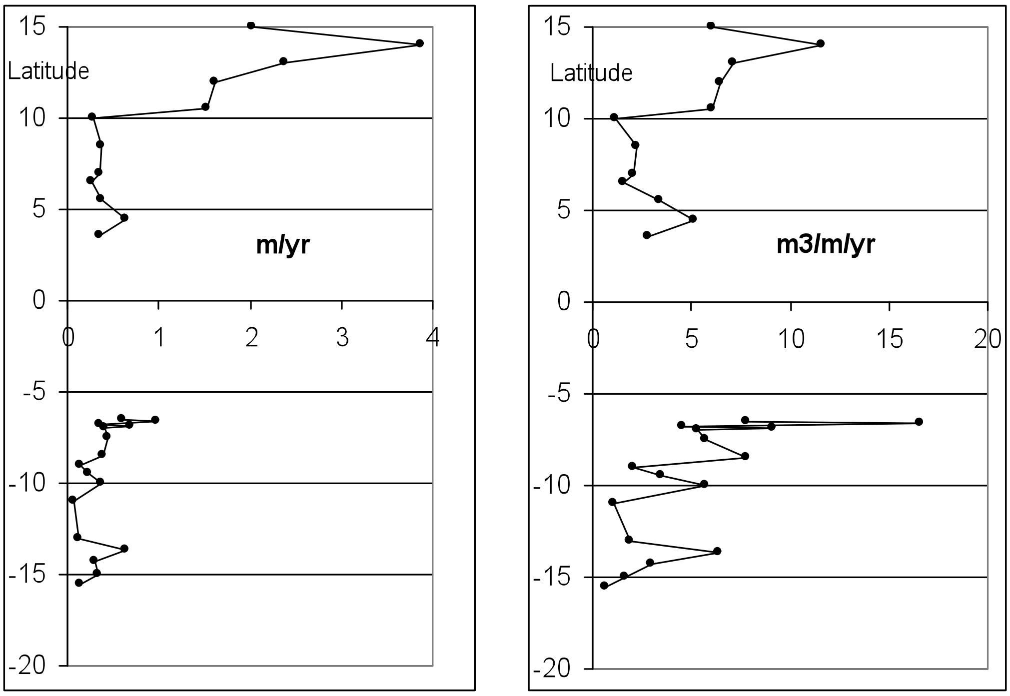

Figure 3 - a) Coastal erosion rates (X=m/yr) close to Mar del Plata city (y axes in minutes to the north and south of the parallel 38º S). b) Volumes eroded (m^3/m/year) to the north and south of Mar del Plata.

Figure 3 - Taxas de erosão costeira nas proximidades da cidade de Mar del Plata (eixos x em m/ano; eixos y em minutos ao norte e ao sul do paralelo 38º S). b) Volumes erodidos (m^3/m/ano) ao norte e ao sul de Mar del Plata.

Similar results from these cliffs of Mar del Plata were estimated between 1970 and 1992 conducting periodic topographic surveys (Cionchi *et al.,* 1998). It was confirmed that erosion rates can have significant variations during different periods, without any regional trend. In a simple interpretation of cliff erosion rates, the anthropogenic activity has been stated as the main cause, considering storms as a secondary cause, and neglecting any significant effect of sea-level rise (Cionchi *et al.,* 1998). However, in discriminating between the northern and southern coast, it can be concluded:

1. The coast north of Mar del Plata is more affected by man-made constructions blocking beach drift. Although groyne fields have diminished cliff erosion, they increased it where the drift is more severely blocked. Some groin fields have caused significant changes in the grain-size composition of some beaches (Isla *et al.,* 2001).
2. The coast south of Mardel Platais less affected by groin fields, but more subject to the direct attack of storms coming from the south. The coast has increased its erosion rate due to these episodic effects (Table 1).

Considering the volume of sediment eroded annually, and due to the higher altitude of the cliffs, the critical area is located south of Mar del Plata where the average volume eroded is greater than 5 m^3/m/year (Figure 3b).

Buenos Aires is a populated province where cliff erosion is a critical problem at touristic areas. Percolation of water causes fracture cracks, and groundwater fluctuations also impacts cliff stability (Figure 4a). Joints or plant roots also increase this instability (Bird, 1994). Touristic facilities are difficult to maintain due to the recurrence of episodic storms from the South (Figure 4b). Riprap walls and revetments are assumed to be the most economic solution to maintain the stability of these cliffs (Figures 4c and d).

4.2. Patagonia cliff retreat

From the measurements calculated, the cliffs from Patagonia to Tierra del Fuego (Río Negro inlet to Beagle-Channel) are receding at a mean rate of 0.47 m/year, and delivering 25 m^3/m/year average (Figure 5). Considering the altitude of the retreating cliffs and the distance assigned between lighthouses, maximum inputs of sediment caused by this mechanism are located at Rio Negro (Río Negro), Punta Lobos (Chubut), Punta Campana (Santa Cruz) and Cabo San Pablo (Tierra del Fuego) lighthouses (Figure 5a). In terms of volumes eroded per year, Punta Lobos is delivering a maximum of 140 m^3/m/year (Figure 5b). These estimates imply that cliff retreat yields an annual input of sediment to the continental shelf of 82 x 10^6 m^3/year. Considering the density of the sediments similar to quartz (2.65 g/cm^3), the total annual sediment input amounts to 217 million tons per year.

The Patagonian cliffs are composed of Pliocene sands at the north (Figure 6a), and bioclastic sediments corresponding to the Miocene transgression (Scasso *et al.* 2012) from 42 to 50º S (Figure 6b). The retreat of some cliffs is reduced by the natural setting of armored bedforms at their feet (Figure 6c). In the Atlantic Tierra del Fuego, soft cliffs are composed of silt at the north (Tudisca *et al.,* 2012), and very hard siltstones at the southern

Table 1 - Erosion rates estimated for the 1970-88 and 1988/92 intervals, to the north and south of Mar del Plata city (from Cionchi et al. 1998). Erosion rates estimated in this paper spanned between 1970 and 2004. Values are given in meters/year.

Tabela 1 - Taxas de erosão estimadas para os intervalos de 1970-1988 e 1988-1992, para as partes norte e sul da cidade de Mar del Plata (de Cionchi et al., 1998). As taxas de erosão estimadas neste trabalho referem-se ao período entre 1970 e 2004. Os valores são dados em metros / ano.

Location	70/88 Cionchi *et al* 1998	88/92 Cionchi *et al* 1998	cause	70/04 This study
GADA-FUCamet	1.10	1.33	Anthropic increase	0.31
Parque Camet Norte	2.83	1.75	Anthropic decrease	0.64
Parque Camet Sur	0.69	-		0.64
Arroyo La Tapera	0.55	0.80	Anthropic increase	0.35
MAR DEL PLATA				
Playa San Jacinto	4.44	2.50	Natural decrease	2.3
Playa San Carlos	3.56	-		1.6
Estafeta Chapadmalal	0.16	1.87	Natural increase	0.10
Colonia Chapadmalal	0.20	0.55	Natural increase	0.13
Arroyo Las Brusquitas	0.61	1.00	Natural increase	0.30

Figure 4 - Cliffs from Mar del Plata (38º S, see figure 1 for location). a) Fracture cracks on the top of the cliffs. b) Sea-side constructions are usually located attached to the cliffs composed of indurated siltstones. c) Rock revetments under construction. d) Armored structures are today protecting some cliffs.

Figura 4 - Falésias de Mar del Plata (38º S, ver figura 1 para localização). a) Fissuras de fratura no topo das falésias. b) As construções à beira-mar estão geralmente localizadas junto às falésias constituídas por siltitos endurecidos. c) Enrocamento em construção. d) Estruturas enrocadas protegem atualmente algumas falésias.

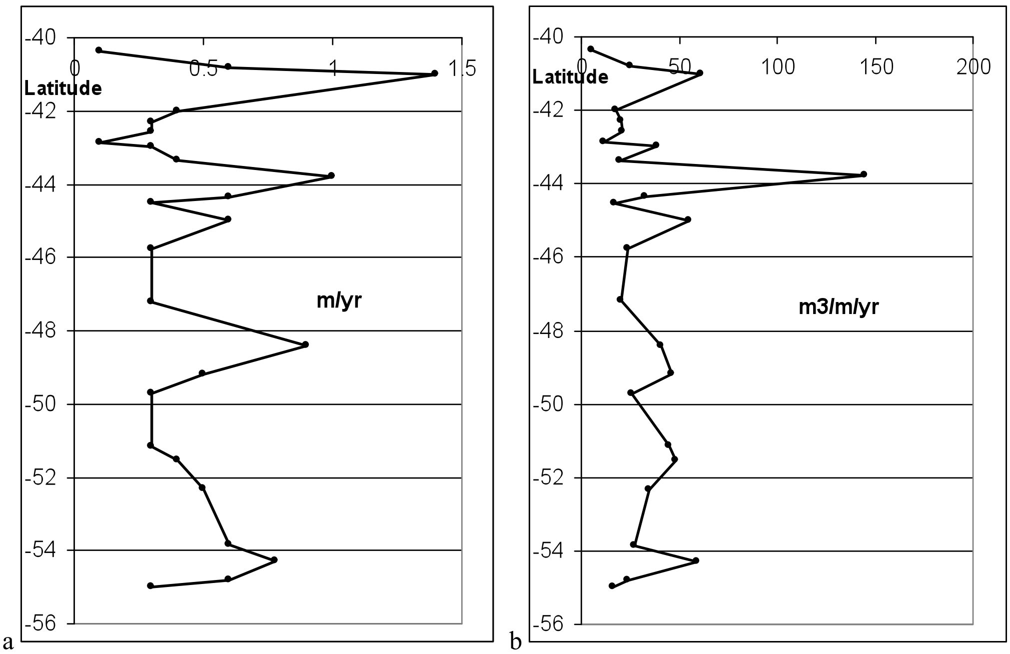

Figure 5 - a) Coastal erosion rates (in m/yr) vs. Latitude South (y=degrees South) from Northern Patagonia to Tierra del Fuego. b) Volumes eroded (in m^3/m/yr) from the cliffs of Patagonia and Tierra del Fuego.

Figura 5 - a) Taxas de erosão costeira (em m/ano) vs Latitude Sul (y = graus sul) do Norte da Patagônia à Tierra del Fuego. b) Volumes erodidos (em m^3/m/ano) das falésias da Patagônia e Tierra del Fuego.

Figure 6 - a) The very tall cliffs close to the Rio Negro estuary are composed of Pliocene aeolian sandstones. . b) Rada Tilly (Chubut Province) is a pocket beach composed of sand and gravel between very tall cliffs. c) Along the northern coast of Santa Cruz Province, some cliffs remain stable due to the natural armor of resistant blocks. d). Gravel-dominated spits are protecting the cliffs at the inlet of the Ladrillero River (Northern Tierra del Fuego Province). See Figure 1 for locations.

Figura 6 - a) As falésias de grande altura próximo do estuário do Rio Negro são compostas por arenitos eólicos pliocénico. b) Rada Tilly (província de Chubut) é uma praia de bolso composto por areia e cascalho entre falésias muito altas. c) Ao longo da costa norte da Província de Santa Cruz, algumas falésias permanecem estáveis devido à proteção natural constituída por blocos resistentes. d) As falésias à entrada do rio Ladrillero (norte da província de Tierra del Fuego) estão protegidas por restingas cascalhentas. Ver localização na Figura 1.

extreme of the island. During the last mid- Holocene fluctuation spits and barriers formed, blocking estuaries, and protecting cliffs from wave attack (Isla & Bujalesky, 2008) (Figure 6d).

4.3. The quiz about Patagonian fluvial loads

Patagonian rivers are misfit in the sense of Thornbury (1954). They transported more water and sediment during the Pleistocene than they do today. The moraines left by the Last Glaciation (Oxygen Isotopic Stage 2, or Wisconsin in North America) dammed the original pathways to the Atlantic Ocean, reversing their drainage direction towards the Pacific Ocean (Quensel, 1910). Some of the piedmont lakes reversed in their direction of flow during Late Pleistocene; others 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 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, *sensu* McCulloch *et al*., 2000). Some watersheds, as the Chubut and Chico de Santa Cruz rivers, diminished significantly during that Pleistocene-Holocene transition. Moraines left during the last Glaciation enclosed piedmont lakes. Their snow recharge areas at the Andes are today flowing towards the Pacific Ocean (Martínez & Coronato, 2008). These reductions in the drainage areas were about 21-24 % in relation to the Late Pleistocene watersheds (Figure 7), and signified reductions between 32 and 34 % in terms of volume discharged per year (Table 2).

5. Discussion

No relationship was found between tidal range and cliff erosion. At the microtidal coast of Buenos Aires, storms were the significant factor controlling cliff retreat (Fiore *et al.,* 2009). On the other hand, the indurated abrasion platforms of Buenos Aires are more resistant to erosion than the bases of the Patagonian cliffs, where wave action distributes its impact on different levels of the cliffs. Geology is largely known as a significant factor to explain long-term spatial differences in cliff recession rates (Honeycutt & Krantz, 2003).

Present scenarios of sea level rise lead to modeling the response of different rocky cliffs using Bruun's Rule (French, 2001). However, the modeling of the soft cliffs of Southern England induced errors that can fluctuate

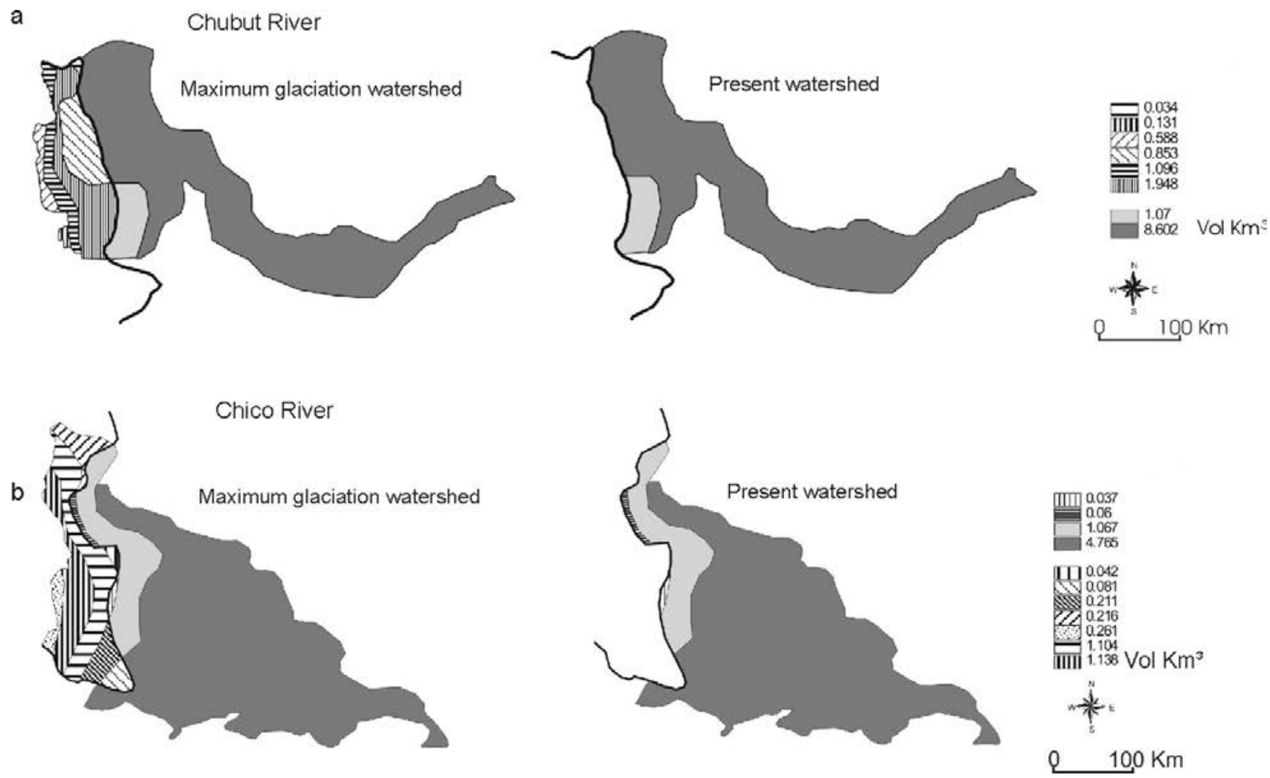

Figure 7. Reductions of Patagonian watersheds from Maximum Glaciation to Present considering similar amounts of precipitations. a) Comparison of the area of the Chubut watershed since Maximum Glaciation to Present. b) Comparison of the area of recharge of the Chico de Santa Cruz river watershed since Maximum Glaciation to Present. Significant changes were estimated (See Table 2).

Figura 7 - Reduções das bacias hidrográficas da Patagônia desde o Máximo Glaciário até ao Presente, considerando quantidades semelhantes de precipitação. a) Comparação da área da bacia hidrográfica de Chubut desde o Máximo Glaciário até ao Presente. b) Comparação entre as áreas de recarga da bacia do rio Chico de Santa Cruz desde o Máximo Glaciário até ao Presente. Foram estimadas as alterações significativas (ver Tabela 2)

Table 2 - Differences in the areas of the watersheds of the Chubut and Chico de Santa Cruz rivers (km^2), and their volumes precipitated per year (assuming similar P rates) in km^3/yr.

Tabela 2 - Diferenças nas áreas das bacias hidrográficas dos rios Chubut e Chico de Santa Cruz (km^2), e volumes de precipitação por ano (assumindo taxas semelhantes de P) em km^3/ano.

watershed	Upper Pleistocene Only Atlantic	Present Atlantic	Present Pacific	% of change Atlantic
Chubut (km^2)	61,640	46,577	15,063	-24.40
Chubut (km^3/yr)	14.3	9.67	4.62	-32.30
Chico (km^2)	35,144	27,700	7,444	-21.18
Chico (km^3/yr)	9.05	6	3.05	-33.70

between 22 and 133 % (Bray & Hooke, 2007). Cliff recession from the coast of Oregon, USA, is related to major storms that become more frequent during El Niño years (Allan *et al.,* 2003). For Patagonian cliffs, this sea-level-rise effect was not considered as sea level has been dropping in the last 6,000 years (Isla, 1989; Schellmann, 1998).

When comparing the erosion rates between Patagonia and Buenos Aires (disregarding the effects of different tidal ranges), the armoring accumulations of shingle at the base of the Patagonian cliffs are considered to be of significant importance, reducing the potential effect of waves and storms.

On the other hand, it should be also considered that some depressions on the Argentine continental shelf (San Matías, Nuevo and San Jorge gulfs) are perfect traps for sediment delivered by cliff erosion (Isla, 2013). Experiments performed along the coast of the

English Channel demonstrated that the main effect of shingle is to reduce the water depth at the toe of the cliff (Bossard & Duperret, 2004). In Oahu (Hawaii), rigid armored structures have induced an increase in beach erosion in sectors without coastal protection (Fletcher *et al.,* 1997). The excessive armoring of cliffs can induce erosion problems at areas downdrift from the protected coast, mainly where the sand supply depends on cliff retreat (Runyan & Griggs, 2003).

Dramatic geomorphological variations occurred in Patagonia in the past, reducing the frequency of floods, but also changing the cliff-recession rates. It is assumed that coastal erosion rates were at their maxima during the early millennia of the Holocene when the sea level was rising at maximum rates (Guilderson *et al.,* 2000; Isla, 2013), and diminished when the sea level stabilized 6000 years ago (Isla, 1989; 2013). In a more extended perspective, Kokot (2004) proposed a climatic explanation for the diminution of sediment input to the Patagonian coast during the Pleistocene. He paid attention to the gravel deposits composing the glaciofluvial terraces (Schellmann, 1998), and estimated the maximum discharges necessary to transport those gravels. He concluded that Patagonian rivers reduced their discharges during Late Quaternary, and that the maximum discharge of present Santa Cruz river (2520 m^3/s) is one tenth of the discharge estimated for the Pleistocene fluvial terraces. In this sense, he concluded that these maximum discharges would have been similar to those occurring today at the Paraná River (Kokot, 2004). In the same line of reasoning, climatic reconstructions derived from pollen and glacier studies indicate more humid conditions during the Holocene than today (Rabassa & Clapperton, 1990; Schäbitz, 1994; Mancini *et al*., 2008).

Similar drainage reversals have been repeatedly recorded in association with Quaternary morphological changes induced by glaciations and deglaciations. In the cases described for Patagonia the amount of water delivered can be estimated. At the upper Tuttle Creek reservoir, Kansas, USA, there is evidence that the creek reversed its flow direction due to the deposition of an ice lobe during the Upper Pleistocene (Chelikowsky, 1976). Tectonics may also cause significant changes in the watersheds. During Upper Tertiary, Lake Russell changed in its flow direction within the Mono Basin, central Sierra Nevada (Reheis *et al*., 2002).

6. Conclusions

1. Present cliff erosion is annually contributing about 82×10^6 m^3 of sediment to the Patagonian continental shelf, i.e., about 217×10^6 tons/yr. This amount of sediment is exceeding the present contribution of major Patagonian Rivers.
2. Although an increase in precipitation probably occurred in the transition from the Maximum Glaciation to Present Interglacial, there were dramatic geomorphological changes that explain a discharge reduction of some Patagonian watersheds.
3. These reversals in the direction of the flow of some Patagonian rivers, as the Chubut, and Chico de Santa Cruz rivers, caused a reduction of about 21-24% in the extension of the Holocene watersheds, and a reduction of about 32-34% in their annual water discharges.
4. Defense structures have decreased the erosion rates in some intervals of Buenos Aires coastline, although they have also increased the erosion and beach loss where they block beach drift.

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