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Chapter 6 The Argentine continental shelf: morphology, sediments, processes and evolution since the Last Glacial Maximum

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Notes

Chapter 6

The Argentine continental shelf: morphology, sediments, processes and evolution since the Last Glacial Maximum

R. A. VIOLANTE[1]*, C. M. PATERLINI[1], S. I. MARCOLINI[1], I. P. COSTA[1], J. L. CAVALLOTTO[1], C. LAPRIDA[2,3], W. DRAGANI[4], N. GARCÍA CHAPORI[2], S. WATANABE[5], V. TOTAH[5], E. I. ROVERE[6] & M. L. OSTERRIETH[7]

[1]*Division of Marine Geology and Geophysics, Argentine Hydrographic Survey, Avenida Montes de Oca 2124, Buenos Aires C1270AVB, Argentina*

[2]*Department of Geology, University of Buenos Aires, IDEAN-SACMA, Ciudad Universitaria, Buenos Aires C1428EHA, Argentina*

[3]*CONICET, National Council of Science, Buenos Aires, Argentina*

[4]*Division of Coastal Oceanography, Argentine Hydrographic Survey, Avenida Montes de Oca 2124, Buenos Aires C1270AVB, Buenos Aires, Argentina*

[5]*Argentine Museum of Natural Sciences 'B. Rivadavia', CONICET (National Council of Science), Avenida Angel Gallardo 470, Buenos Aires C1405DJR, Argentina*

[6]*Division of Regional Geology, Argentine Geological Survey, Parque Tecnológico Miguelete, Avenida General Paz 5445, Edificio 25, San Martín, Buenos Aires B1650WAB, Argentina*

[7]*Institute of Coastal Geology and Quaternary, University of Mar del Plata, Funes 3350, Mar del Plata B7602AYL, Argentina*

**Corresponding author (e-mail: violante@hidro.gov.ar)*

Abstract: The Argentine continental shelf is one of the largest and smoothest siliciclastic shelves in the world. Although it is largely emplaced in a passive continental margin, the southernmost regions are related to transcurrent and active margins respectively associated with the Malvinas Plateau and Scotia Arc. Sea-level fluctuations, sediment dynamics and climatic/oceanographic processes were the most important conditioning factors in the modelling of the shelf, with a minor influence from isostatic and tectonic factors that are more relevant in the southernmost regions. The shelf is shaped by diverse geomorphic features, among which the most significant are four sets of terraces genetically associated to sea-level stillstands during the post-glacial transgression; the final one occurred at around 11 ka and is associated with the Younger Dryas event. The Last Glacial Maximum (LGM) sedimentary sequence is composed of, on average, 5–15 m-thick terrigenous, siliciclastic, relict–palimpsest sands mainly sourced from the Andean region, with minor amounts of bioclast and gravels, resulting from the reworking of pre-transgressive coastal environments.

The Argentine continental shelf (ACS) is one of the largest and smoothest siliciclastic shelves in the world. Its morphological and evolutionary characteristics are primarily the consequence of its geotectonic emplacement, associated with a passive margin on most of its surface. Processes involved in its final stages of evolution during glacial and post-glacial times comprise climatic and oceanographic changes, sea-level fluctuations, ocean dynamics and sedimentary processes. As a result of its large latitudinal extension and the proximity of its southernmost regions to the glaciated areas of Patagonia and Antarctica, most of the modelling processes that occurred during post-LGM times changed in magnitude from north to south, resulting in varied and complex morpho-sedimentary features.

Bathymetric and high-resolution seismic surveys, as well as coring and surface-sediment samplings, have been systematically carried out in the northern (Pampean) region of the ACS in the last 30 years by the Argentine Hydrographic Survey (see Parker & Violante 1982; Parker *et al.* 1982, 1996, 1997, 1999, 2008; Violante *et al.* 1992, 2007, 2012; Violante 2004, 2005; Violante & Parker 2004; Violante & Rovere 2005; Violante & Cavallotto 2011) in order to study Quaternary morpho-sedimentary, stratigraphic, dynamic and evolutionary aspects of the shelf. Those surveys complemented previous studies performed by the same institution (see Urien 1970; Urien & Ewing 1974; Urien *et al.* 1979). Other regions of the ACS, such as those adjacent to Patagonia, have not been studied in detail to date, at least not for the uppermost (Quaternary) sequences, although valuable regional information is available (see Urien 1970; Ewing & Lonardi 1971; Urien & Ewing 1974; Zambrano & Urien 1974; Urien *et al.* 1979; Ramos & Turic 1996).

Despite the presently uneven knowledge, with relatively well-known areas and others where studies are still lacking, an updated revision of the geological aspects of the ACS is necessary to obtain a framework for future studies. This contribution attempts to synthesize such a framework.

Geomorphological and geotectonic setting of the ACS

The ACS is part of the Argentine continental margin (ACM), which covers an area of around 2×10^6 km^2. Basic characteristics of the shelf are summarized in Table 6.1. The margin developed on different geotectonic settings, from the stable pericratonic areas of the Brazilian shield in the vicinity of the de la Plata River to the tectonically and isostatically active southern Patagonian regions. It comprises major physiographical features, such as the continental shelf, slope and rise, as well as the Malvinas Plateau and Scotia Arc (Fig. 6.1).

The ACM is located on the South American plate in a region of cortical extension associated with the break-up of Gondwana and constitutes, on most of its surfaces, a typical Atlantic passive continental margin. Only in the southern regions of the margin is it

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Table 6.1. *Summary of basic Argentine continental shelf characteristics*

Length of the shelf (km)	2400
Average width (km)	400
Tidal, wave, current ranges	Tides: between 1.5 and 12 m. Waves: 1–4 m. In both cases increasing to the south
Dominating process (wave/current/tide)	Waves dominate in northern sector (Pampas) Tides dominate in southern sector (Patagonia)
Average depth of the shelf break (m)	115
Siliciclastic/carbonate/authigenic/glacial sedimentation	100% siliciclastic
Modern/relict/palimpsest	98% modern sediments, *c.* 50/50% relict/palimpsest
Tectonic trend over the last glacial cycle (stable/uplifting/subsiding)	Stable, slight uplifting increasing to the south

transcurrent (around Malvinas Islands) and active (in the Southern Scotia ridge) (Ramos & Turic 1996). Despite these differences, the shelf does not change significantly according to its location on one type of margin or another, although distinct sectors can be recognized in relation to different deep tectonic and structural aspects (Table 6.2). Cavallotto *et al.* (2011) described the complex climatic, oceanographic and tectonic processes involved in the evolution of the ACM.

The base of the Quaternary deposits in the ACS was defined as a seismic discontinuity at a water depth of 140 m (seismic horizon ‘b’: Ewing & Lonardi 1971) that extends north of 43°S. Consequently, the substratum of the post-LGM deposits is represented there by almost complete Plio-Pleistocene marine sequences. However, south of 43°S, the substratum is represented mainly by late Tertiary pre-glacial continental and marine sequences with scattered and incomplete patches of Quaternary deposits. The discontinuous and reduced Quaternary deposits in the southern region can be attributed to a lack of space for deposition due to the post-glacial isostatic rebound, which was more significant there, closer to the glaciated areas of Patagonia.

The Argentine continental shelf

Morphology

The ACS covers an area of 9.6×10^5 km^2, trending north–south for 2400 km between the de la Plata River (35°30′S) and Cape Horn (57°S) (Fig. 6.1). The adjacent coastline is around 5300 km long if major irregularities are considered. Shelf width varies between 170 and 850 km. The inner (shorewards) shelf edge is represented by a 10–20 m-high shoreface. The outer (offshore) shelf edge (shelf break) follows a NE–SW direction between the de la Plata River and 44°S, from where it gradually changes to a north–south direction down to 50°S, then acquires an easterly direction towards Malvinas Island and, after surrounding them,

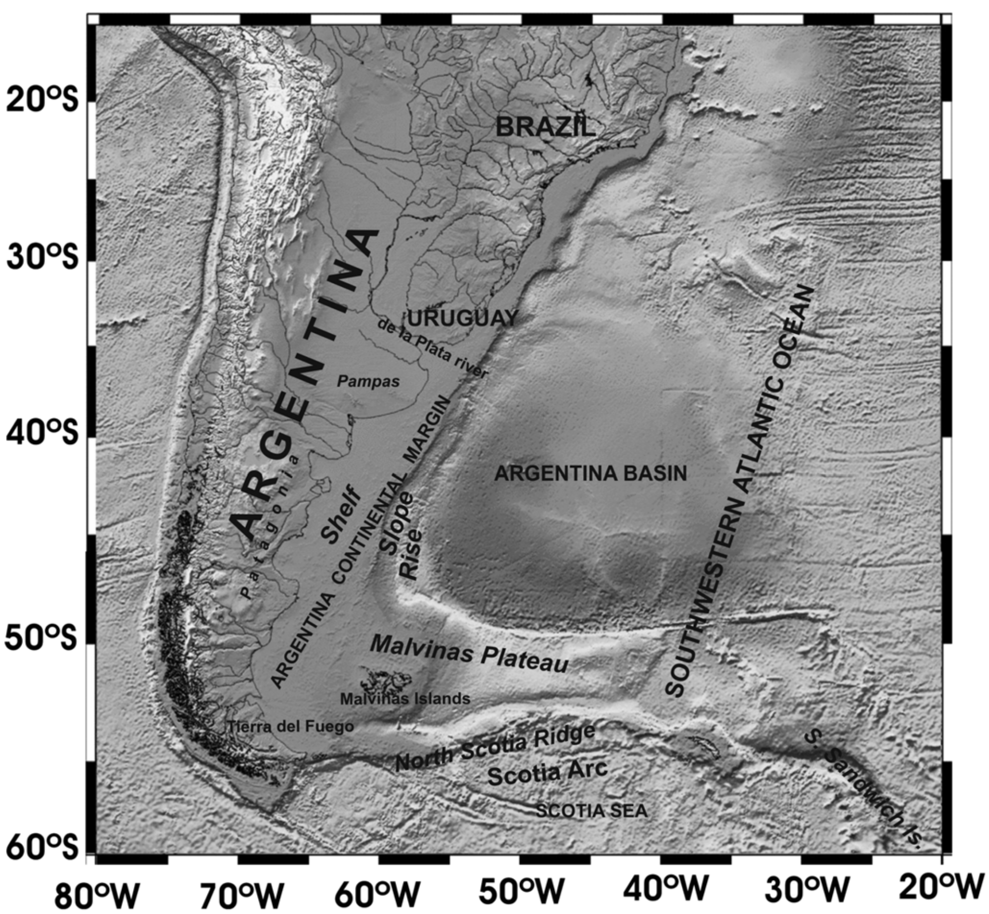

Fig. 6.1. Location map of the Argentine continental shelf.

Table 6.2. *Margin sectors on the basis of structure and stratigraphy*

Structure	North of 43°S		Typical lower-plate passive margin. An old basement and thick continental crust. Evolution controlled by cortical discontinuities and transverse extensional systems with little basaltic magmatism
	Between 43°S and 49°S		Same type of margin as above, although the crust is younger and thinner. Pre-rift associations and longitudinal rifts characterized by acid volcanism
	South of 49°S		Transcurrent and convergent margin as a result of interaction between the South American and Scotian plates
Tectonic processes	North of 55°S		Shelf affected by downwarping conditioned by isostatic equilibrium and sediment overloading. Thick sedimentary deposits as a result of increasing tilting of the continent towards the east occurred after the Andes cordillera rise in the Miocene
	South of 55°S		Complex tectonic processes conditioned a thin Cenozoic sedimentary cover that experienced intense marine erosion
Substratum	Below the shelf		Lies over continental crust
	Below the slope and rise. Malvinas Plateau and Scotia arc		Lies over oceanic crust
Stratigraphy (based on offshore oil drillings and reflection seismic data)	Pre-Cretaceous basement	North of 39°S	Precambrian metamorphic and intrusive rocks from the Brazilian shield, Silurian–Triassic sediments and Cretaceous basalts; seismic velocities of 5.5 km s^{-1}
		Between 39°S and 43°S	Igneous basement covered by metamorphosed Palaeozoic continental–marine sediments; seismic velocities between 5 and 5.5 km s^{-1}
		South of 44°S	Above a Precambrian metamorphic basement there are upper Palaeozoic–lower Mesozoic metamorphic and acid intrusive rocks with seismic velocities of up to 6 km s^{-1} segment, followed by Silurian–Jurassic pyroclastic and acid-mesosilicic extrusive rocks interbedded with continental sediments with seismic velocities of between 4.2 and 5.1 km s^{-1}
	Post-Cretaceous sedimentary filling of the basins		Post-Cretaceous sequence thickness of 6–8 km, composed of continental–marine shales, filites, lutites, limestones, sandstones and conglomerates

Compiled from Zambrano & Urien (1974), Ramos (1996, 1999), Turic *et al*. (1996) and Urien & Zambrano (1996).

goes back again to the west and reaches regions near the continent at 51°30′S. The depth of the shelf break is variable between 70 and 190 m (Parker *et al.* 1996; Violante & Cavallotto 2011), showing a broad north–south deepening (Fig. 6.2). Surface gradient is relatively smooth, with slopes ranging between 1:500 and 1:10 000. In the areas adjacent to the Pampean region, it has a convex profile (steeper gradient towards the outer shelf), whereas in the areas adjacent to Patagonia it is concave (steeper gradient towards the continent). North of 38°S, the slope gradient changes from 1:2000 above 90 m water depth to 1:500 below. Between 38°S and 48°S the shelf surface is more uniform and subhorizontal, with gradients of around 1:10 000. South of 51°S, the gradient is around 1:3000/1:4000. Relative relief does not exceed 20 m. Table 6.1 details most of the basic shelf characteristics.

The shelf is shaped in several terraced surfaces separated by high-gradient steps (Groeber 1948; Parker *et al.* 1997; Violante 2005; Ponce *et al.* 2011). Four terraces (named I, II, III and IV) are recognized, showing a predominant NNE–SSW direction subparallel to the coastline (Fig. 6.3, Table 6.3). Post-LGM transgressive deposits averaging 10 m thick constitute the subhorizontal surface of the terraces, particularly those closer to the coast and in the northern parts of the ACS, whereas the steps separating them are usually devoid of transgressive sediments; on most of these steps the relicts of Plio-Pleistocene marine transgressions and interbedded continental sediments crop out.

Exogenous conditioning factors involved in the morpho-sedimentary configuration

The morpho-sedimentary configuration of the ACS depends mainly on two major factors: (a) the heritage of the above-mentioned regional geotectonic framework (i.e. from the endogenous conditioning factors primarily associated with the margin structure and evolution); and (b) the external factors of climate, oceanography and associated processes (sea-level fluctuations and sediment dynamics), which become more significant (with respect to the endogenous) during the late Cenozoic.

Climate since LGM times. The climate in southern South America during glacial and post-glacial times was conditioned by global oceanographic and climatic factors, although it was also influenced by regional and local factors, such as: (a) atmospheric conditions imposed by the interaction between the South Pacific and South Atlantic anticyclonic centres that affected regional wind patterns; (b) the proximity to both the southern Andes and the Antarctic ice masses; and (c) the highly variable relationship between emerged and drowned lands throughout the glacial–interglacial cycle, which at Patagonian latitudes represented, respectively, a duplication and a reduction to half of the continental area with consequent ‘continentalization’ or ‘oceanization’ of climates as a result of the changing sea moderating effect. After the extreme cooling during the LGM, significant climatic changes and environmental instability characterized late glacial times with several glacial re-advances and recessions, including the Younger Dryas (Rabassa *et al.* 2011 and references therein). The major peak of the Hypsithermal occurred at 6 ka, with sharp climatic changes afterwards that evolved towards present climatic conditions.

Oceanography. The main sources of the ACS water masses are Subantarctic water flowing from the northern Drake Passage between the coast and the Malvinas Islands (Hart 1946), and the Malvinas Current in the outer continental slope (Bianchi *et al.* 2005). In the vicinity of the northernmost part of the shelf, the

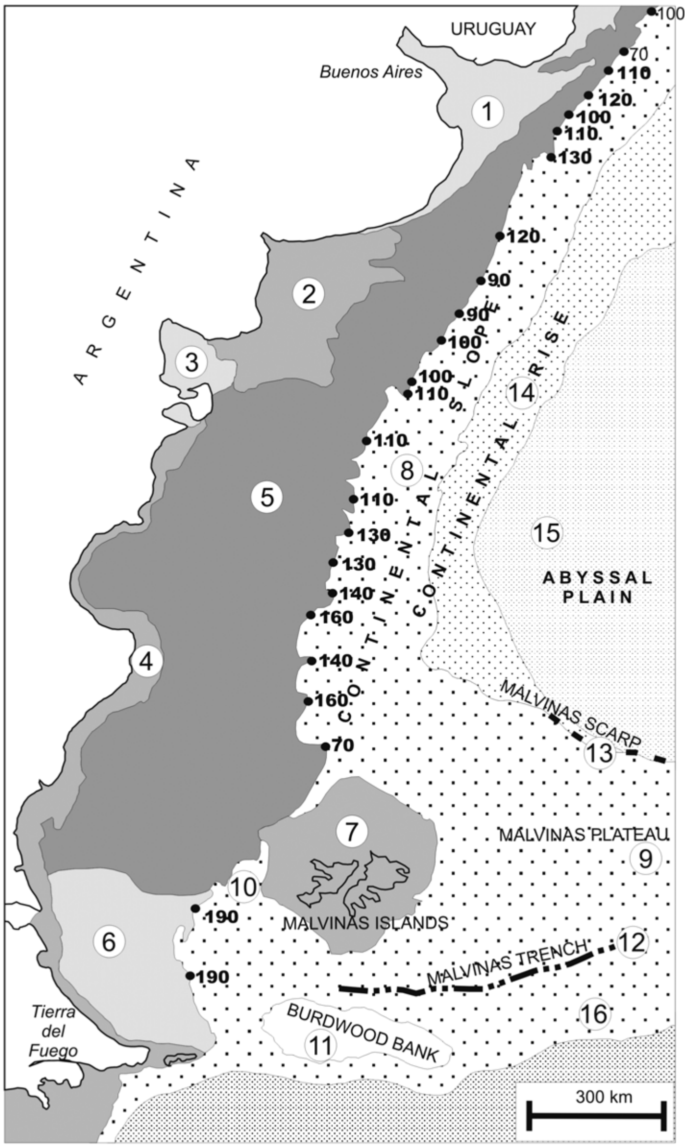

Fig. 6.2. Major physiographical features of the Argentine continental shelf (modified after Parker *et al.* 1996). Shelf is in grey shades. Numbers in bold at the shelf–slope boundary indicate the depth of the shelf break. 1, Rioplatense Terrace; 2, deltaic front of the Colorado and Negro rivers; 3, northern Patagonian gulfs; 4, Patagonian inner shelf; 5, Patagonian outer shelf; 6, Tierra del Fuego shelf; 7, Malvinas shelf; 8, continental slope; 9, Malvinas Plateau; 10, Malvinas depression; 11, Burdwood Bank; 12, Malvinas Trench; 13, Malvinas escarpment; 14, continental rise; 15, abyssal plain; 16, Scotia Arc.

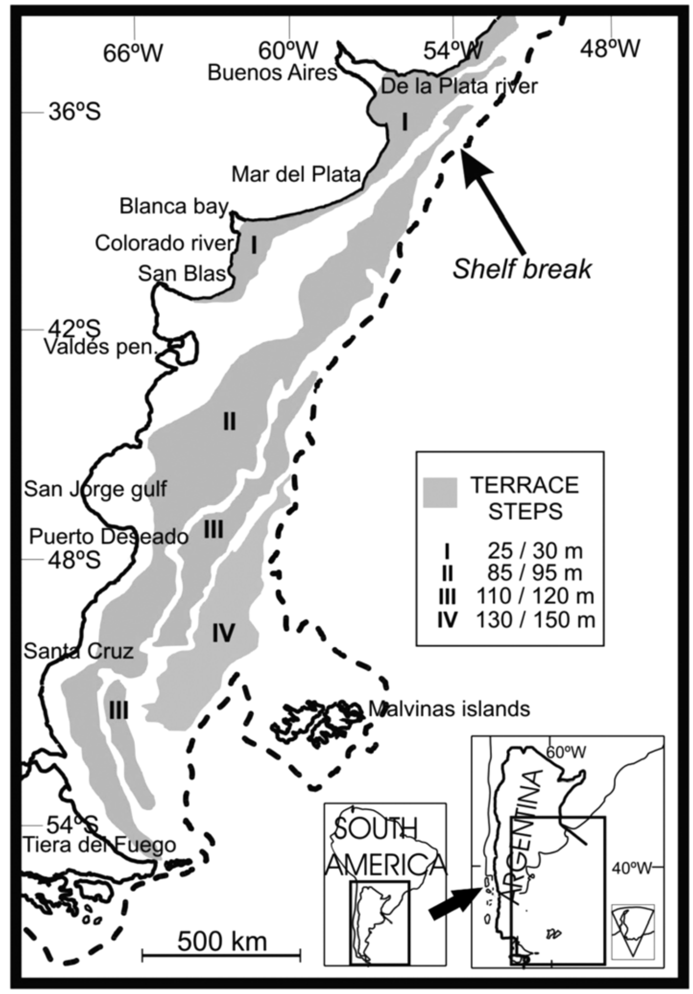

Fig. 6.3. Submarine terraces in the continental shelf (modified after Parker *et al.* 1997).

Confluence Zone between the Malvinas (flowing to the north) and Brazil (flowing to the south) currents occurs. The main freshwater source comes from the de la Plata River (around 25 000 $m^3 s^{-1}$: Simionato *et al.* 2007; Campos *et al.* 2008*a*), with much less influence (<2000 $m^3 s^{-1}$) from Patagonian rivers (Gaiero *et al.* 2003).

The mean shelf water circulation has a predominant NNE direction with a velocity of up to 0.30 $m s^{-1}$, slightly decreasing with depth. Forbes & Garrafo (1988) estimated an averaged depth intensity ranging from 0.01 to 0.07 $m s^{-1}$ in winter and from 0.02 to 0.04 $m s^{-1}$ in summer. Tidal amplitude varies between 1.5 m in the eastern Buenos Aires province and 12.3 m in southern Patagonia (Servicio de Hidrografía Naval 2011), with tidal waves propagating northwards. Persistent and strong wind blowing from the south and SE, coinciding with large or even moderately high tides, can induce surges that produce significant coastal erosion and offshore sand transport.

Wind waves in the Buenos Aires province coast show a wave height, period and direction of 0.87 m, 9.2 s and ESE to SE, respectively, indicating a predominant northward flow and sand transport maintained along that region. In the Tierra del Fuego inner continental shelf, the most frequent wave trains propagate from the sector comprising the southwesterly and northwesterly directions, coinciding with predominant winds. However, waves with the greatest heights are frequently propagated from the sector comprising the north and northeasterly directions, associated with the most severe storms. Owing to the fact that westerlies are dominant between 40°S and 55°S, these characteristics could be extended to the whole Patagonian shelf. Dragani *et al.* (2010) modelled an increase in wind wave heights between 32°S and 40°S. In general, for the entire continental shelf, wave heights vary between 1 and 4 m, increasing to the south.

According to the aforementioned aspects, the ACS is classified as wave-dominated in the northern region (adjacent to the Pampas) and tide-dominated in the south (Patagonian region).

Palaeoceanographic changes can by synthesized from the variability of oceanic temperatures, and water-mass displacement between the continents and the oceans during glacial–interglacial periods. According to CLIMAP Project Members (1981), sea-surface temperatures (SSTs) in glacial times were in the region of between 2 and 4 °C lower than present, undoubtedly affecting seawater evaporation and oceanic circulation. Berger & Wefer (1996) pointed out that, during the last glaciation, the North Atlantic Deep Water mass weakened in the SW Atlantic, at the same time that the Antarctic Bottom Water layer thickened. Foraminifera-based studies (Laprida *et al.* 2011; Groeneveld &

Table 6.3. *Terraces on the shelf*

Terrace	Level	Depth (m)	Location
I	A	30	Rioplatense Terrace associated with the de la Plata River deltaic body Bahía Blanca–San Blas area related to the deltaic bodies of the Colorado and Negro rivers Also in reduced sectors adjacent to the Patagonian coasts, as in Puerto Deseado
	B	50	Middle part of the outer step of Rioplatense Terrace
	C	70	Base of the step offshore the de la Plata River mouth, as well as offshore Blanca Bay where it is blurred by the deltaic deposits of the Colorado and Negro rivers Equivalent levels in some places in Patagonia (Valdés Peninsula, San Jorge Gulf and offshore Tierra del Fuego)
II	D	80	Very extensive, very low gradient and smooth, reaching its best expression between Mar del Plata and the Valdés península Covered by dark, fine and very fine silty–clayey sands
	E	90	Subhorizontal, smooth ramp-like feature extended south of the Valdés Peninsula that has its most extensive development south of the Santa Cruz River Covered by dark fine and very fine silty–clayey sands
	F	100	Very extensive and subhorizontal, covered by clean fine and medium sands with gravel concentrations offshore southern Patagonia Dissected by erosive channels and scours partially buried by Holocene deposits, representing an ancient fluvial network
III		110–120	Covered by bioclastic sands and gravels of probable glacio-fluvial origin Evidence of a relict fluvial network Small terraces without regional significance occur at the same levels in the upper edge of the slope offshore the de la Plata River
IV		130–150	Covered by bioclastic sands and gravels of probable glacio-fluvial origin Small terraces without regional significance occur at the same levels in the upper edge of the slope offshore the de la Plata River

Chiessi 2011; García Chapori 2013) document the increasing in intensity of the Malvinas Current during glacial times with the consequent northward displacement of the Confluence Zone, as well as offshore displacement due to reducing water depth. Most probably, mean wind–wave conditions on the whole ACS, and the magnitude and frequency of storm surges in the Buenos Aires coast, could have been a little different in glacial times due to stronger low-level winds resulting from a larger mean latitudinal atmospheric temperature gradient.

Sea-level fluctuations. The extension and geotectonic setting of the ACS introduced complex variables that influenced sea-level fluctuations. Rostami *et al.* (2000) considered that regional differences are evident in the fact that the predictions of sea-level fluctuations and models of deglaciation coincide for Northern Patagonia but not for Southern Patagonia. Several curves exist in different coastal regions of Argentina for the last part of the post-glacial transgressive event (Urien 1970; Farinati 1984; Peltier 1988; Isla 1989; Pirazzoli 1991; Aguirre & Whatley 1995; Gómez & Perillo 1995; Cavallotto *et al.* 2004 recently calibrated by Gyllencreutz *et al.* 2010). These curves match each other only in the general tendency of sea-level changes, not in the details. This is considered to be the consequence of ‘local’ factors characterizing each region. The only curve comprising the entire transgressive cycle since the LGM was published by Guilderson *et al.* (2000) (Fig. 6.4), which is considered by these authors as ‘eustatic’ after applying models for isostatic-tectonic compensation. This curve does not match the global eustatic sea-level curve established by Fleming *et al.* (1998) in what can be preliminary related to tectonic and hydro-isostatic influence. Neotectonism has been mentioned as being responsible for the recent reactivation of old faults in marine regions (Zambrano & Urien 1974). Codignotto *et al.* (1992) inferred a relative uplift along the Argentinean coast of 0.12–1.63 m ka^{-1} (higher in the interbasins than in the basins), with a general trend of 0.7 m ka^{-1} in the last 9.5 kyr decreasing from south to north. However, Rostami *et al.* (2000) and Schellmann & Radtke (2000) considered more uniform isostatic readjustment without significant differences between basins and interbasins. A model-based study performed by Rostami *et al.* (2000) obtained a relatively uniform regional uplift of 0.9 m ka^{-1} for the last 300 kyr, with progressively higher elevations to the south.

Based on this evidence, the sea-level curve by Guilderson *et al.* (2000) must be considered as ‘relative’. According to this curve, the LGM sea-level lowstand was approximately –105 m at around 18 ka (Fig. 6.4). The following relative sea-level rise occurred rapidly at the earlier stages of the transgression, at a rate of 11–12 mm a^{-1} (Cavallotto *et al.* 2004; Violante & Parker 2004; Schnack *et al.* 2005). No sea-level fluctuation is depicted around 11 ka in coincidence with the Younger Dryas event, although it could be the consequence of the scarcity of ^{14}C datings in that part of the curve. At 8.6 ka, the sea level was at −18 m below present, rising at a rate of 9.4 mm a^{-1}, and then decelerating before reaching its highest position (+6 m without subtracting tides and waves influence) at 6 ka (Cavallotto *et al.* 2004). The calibration of the Cavallotto *et al.* (2004) curve performed by Gyllencreutz *et al.* (2010) points to a sea-level maximum of 6.5 m above present at 7 cal ka BP, a conclusion that does not match the regional evidence, which indicates that at that time the sea level was still below its present position. Ponce *et al.* (2011) used digital models to depict palaeogeographical maps that show different positions of the coastline at different times during the post-glacial transgression, on the basis of the global sea-level curve proposed by Fleming *et al.* (1998). The authors state that at approximately 15.3 ka, the great emerged shelf plain was reduced to half of its original size.

The middle–late Holocene regressive event is not definitively well constrained. The differences in the tendencies of sea-level fall in different regions are the result of local tectonic–isostatic–subsidence characteristics. In general, it is considered that a constant but stepped decreasing in sea level occurred. Rapid drops in sea level at around 5–3 ka have been recorded by lithological and foraminiferal information by Laprida *et al.* (2007), and a possible drop below present sea-level position was mentioned at 2.6 ka offshore Blanca Bay (Gómez *et al.* 2006). Most of the authors that worked on relatively stable areas of Argentina concur with the age of the transgressive maximum occurring between 6 and 5 ka, although heights reached by the sea are not in agreement (they vary between 6 and 2.5 m). However, in Patagonian regions, the maximum Holocene beaches are documented

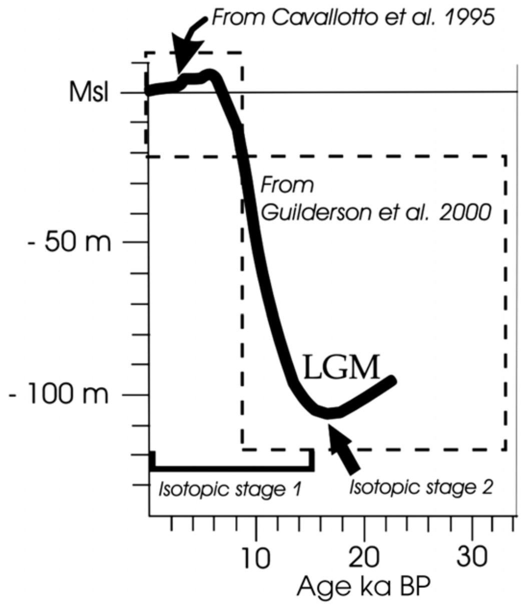

Fig. 6.4. Relative sea-level fluctuation curve for the Argentine continental shelf (from Cavallotto *et al.* 1995; Guilderson *et al.* (2000).

at >10 m (Codignotto *et al.* 1992; Rostami *et al.* 2000 and references therein), mostly dependent on isostatic influence.

Sedimentology and sediment dynamics

Sediment distribution on the shelf (Fig. 6.5) is the result of complex processes in which some of the 'external' forcing factors, particularly the way in which sea-level fluctuations affected the shelf surface as well as the oceanographic conditions, played a substantial role. Furthermore, in order to better understand the distribution patterns, the characteristics of the sediments themselves as well as their previous 'history' throughout the whole sedimentary cycle, including the source areas and sediment dynamics, must be taken into account.

Sediment provenance and source areas. The ACS sediments originated in two main source areas: the Andean region and the Brazilian Shield (Teruggi 1954; Etchichuri & Remiro 1963; Depetris & Griffin 1968; Berkowsky 1986; Campos *et al.* 2008*b*). The sedimentary and volcanic products originated in the Andean region were transported mainly to the east, conditioned by climate (dominant westerly winds) and morphology, and were partially trapped and/or reworked by fluvial and aeolian processes in the Pampean and Patagonian regions, and finally reached the coast and sea. The volcaniclastic composition of the shelf sediments, as well as the evidence of volcanic ash levels preserved in submarine cores, document the importance of these processes (Violante & Rovere 2005). However, the cratonic (igneous–metamorphic) regions of the Brazilian Shield provided sediments that were transported almost exclusively by streams through the de la Plata fluvial basin to the sea. The predominance of the volcanic Andean-sourced sediments with respect to the cratonic Brazilian-sourced sediments allowed Potter (1994) to classify the coastal regions of Argentina as 'Andean' in terms of the provenance of sand. In concordance with this, Mahiques *et al.* (2008) used neodymium and lead isotopes to interpret sediment transport and source rocks in the Argentine, Uruguayan and Brazilian shelves, concluding that the isotopic signature of most of the ACS sediments are typical of Andean rocks, whereas north of the de la Plata River it is concordant with the basaltic province from NE Argentina and southern Brazil. Campos *et al.* (2008*b*) discussed the types and spatial distribution of clay minerals according to the

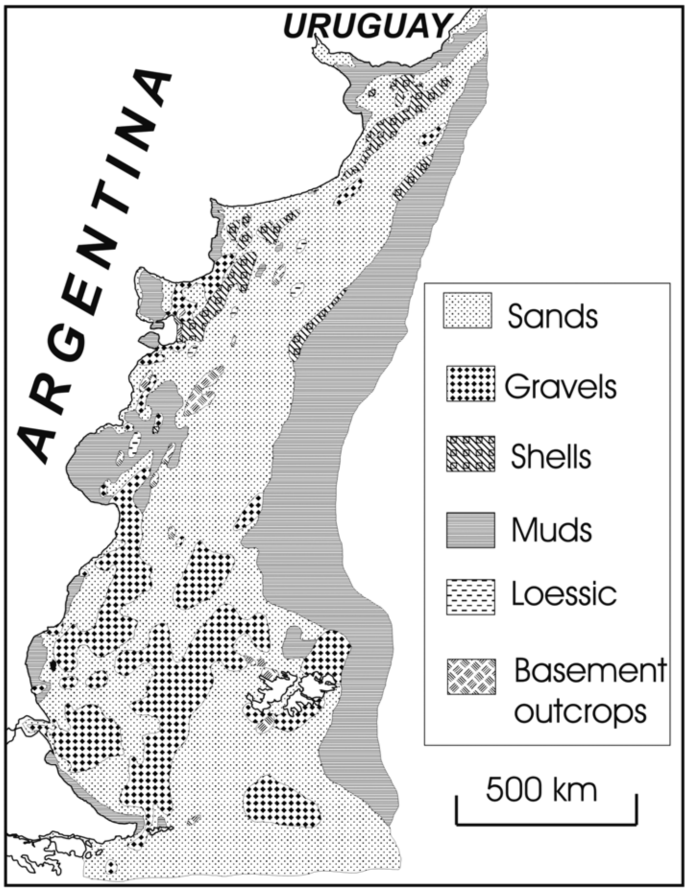

Fig. 6.5. Sediment distribution in the continental shelf and upper slope (modified after Parker *et al.* 1996).

source areas and the transport through the de la Plata River. Bozzano *et al.* (2011) revealed, after studying rock fragments contained in contourite deposits of the upper slope offshore Buenos Aires province, that both the basement of the Brazilian craton and the volcanic rocks from northern Patagonia supplied sediments that, after crossing the shelf, were transported towards the deeper-marine regions.

Sediment dynamics. Terrigenous sediments introduced into the coastal system by coastal erosion, as well as by fluvial and aeolian transport, were then delivered offshore, transported to the north as a result of the dominant northward littoral currents and, finally, deposited on the shelf where they became relict or palimpsest depending on how they had been reworked by marine processes. These processes occurred during the entire post-glacial cycle under the conditions imposed by sea-level fluctuations, climate, coastal water circulation and sediment supply. In the case of the post-LGM transgression, it provoked the sweep of the underlying pre-transgressive substratum through the ravinement process that resulted from the erosive coastal retreat and partial sediment transfer offshore (Urien & Ewing 1974; Parker & Violante 1982; Violante & Parker 2004; Parker *et al.* 2008). Isla & Cortizo (2005) estimated that 243.8 Mt a^{-1} of sediments are eroded from the Patagonian cliffs and introduced into the sea. Sediment supply by fluvial input is relatively low, as the low-flow Patagonian and Pampean rivers carry small amounts of sediments, whereas the larger rivers usually have estuarine environments that retain most of the sedimentary load. However, the de la Plata River seems to discharge large amounts of sediment to the shelf, mainly silts, ranging between 57 and 130 Mt a^{-1} (Depetris & Griffin 1968; Giberto *et al.* 2004; Campos *et al.* 2008*a*). Streams were more significant in pre-Holocene times as demonstrated by the existence of oversized fluvial valleys with respect to the present fluvial dynamic, as well as by the large amount of gravels on the southern shelf surface that cannot be transported by present streams. Kokot (2004) estimated that the Santa Cruz River in Patagonia presently has a discharge equal to one-tenth of the discharge in the Pleistocene. Aeolian activity has a greater significance as a provider of sediment to the shelf than streams do. The total amount of terrigenous sediments transferred to the sea bypassing the Patagonian coasts was estimated to be 70 Mt a^{-1} (Pierce & Siegel 1979; Gaiero *et al.* 2003), from which 56% (39 Mt a^{-1}) corresponds to coastal erosion, 41% (29 Mt a^{-1}) to atmospheric processes (dust transport) and 3% (2 Mt a^{-1}) to fluvial activity. Based on these data, the ACS can be classified as passive and 'autochthonous' in terms of the sedimentary regime (although sediments are allochthonous) following the concepts described by Swift (1968). Violante (2004) has also previously stated this classification. Although the mechanisms of sediment transfer from the shelf edge and upper slope to the head of the submarine canyons are not yet well known, the general consensus is that most of the submarine canyons are disconnected from the shelf. Pierce & Siegel (1979) estimated a shelf sediment export to the slope of 17 Mt a^{-1}.

Sediment composition and facies. Surface sedimentary facies are represented in decreasing order of abundance by sands (65% of the shelf surface), shells (12.5%), gravels (12.5%), muds (8%), and consolidated sediments and rocks (2%) (Parker *et al.* 1997) (Fig. 6.5). Table 6.4 shows details of these sediment types. Sands dominate over the entire shelf, whereas shells are more abundant in the northern (offshore Pampas) regions, and gravels in the southern (Patagonian) areas. Shelf sands are composed of two main mineralogical associations according to the source areas already described: the volcanic–pyroclastic association that dominates south of the de la Plata River (and so distributed on most of the ACM); and the igneous–metamorphic association that dominates only to the north of the de la Plata River.

Benthic foraminifer assemblages preserved in sediments collected in cores are good palaeoenvironmental/palaeoceanographic indicators, as suggested for different shelf settings (Boltovskoy 1954*a*, *b*, 1973; Giussani & Watanabe 1980; Ferrero 2005; Gómez *et al.* 2006; Laprida *et al.* 2007; Bernasconi & Cusminsky 2009; García Chapori 2013). North of 41°S at water depths >100 m, faunas in the lowermost levels of the cores (>4–5 m depth in the cores) suggest pre-LGM inner-shelf environments; at approximately 3–4 m, they reveal littoral–upper sublittoral environments related to the LGM lowstand, and in the uppermost levels (near the shelf surface) they indicate inner-shelf environments related to the early Holocene transgression influenced by the Malvinas Current. At water depths of between 50 and 100 m, faunal assemblages indicate a littoral and inner-shelf environment associated with the beginning of the post-glacial transgression; at about water depths of 70–100 m, isolated species typical of the Malvinas Current suggest short-term variations in its western bottom boundary during the early Holocene; currently, this boundary lies between 80 and 100 m north of 42°30′S, and between 110 and 115 m from 43°S–47°30′S. At water depths shallower than 50 m, faunas are exclusively Holocene, indicating coastal settings related to successive positions of the coastline during the sea-level rise prior to 6 ka; typical inner-shelf deposits were recognized at water depths of 12 m close to the south of the de la Plata River mouth. Salt marsh deposits from approximately 6.35 ka finally evolved to tidal flats at about 2.3 ka, and therefore concluded in high-energy coastal environments related to an increasing sea level. In the northern Patagonian shelf (41°S–46°30′S, water depth *c.* 50–100 m), foraminiferal assemblages indicate late Pleistocene lowstand deposits below about 4 m depth in the cores, and early Holocene inner-shelf facies above 4 m. Isolated Malvinas Current specimens were found in cores at approximately 75–100 m water depth. In Nuevo Gulf, faunas suggest a transition from normal marine conditions at 8–7.7 ka to marginal marine conditions in the late Holocene, accompanied by a change in the circulation dynamics. In the southern Patagonian shelf (45°S–47°S, water depth *c.* 40–143 m) Holocene sediments dominated by inner-shelf species are reported, with no outstanding vertical variations in faunal composition.

The post-LGM sedimentary sequence

Processes involved in the evolution of the shelf during post-LGM times produced a complex sedimentary sequence (SS), which was defined as a 'depositional sequence' (or 'seismic-stratigraphic unit') based on high-resolution seismic surveys undertaken in the northern region of the shelf (Violante *et al.* 1992; Parker *et al.* 1999, 2008; Violante & Parker 2004). The SS is bounded at its base by the transgressive surface, whereas its top is represented by the present topographical surface. The thickness of the SS averages 5–10 m, although it is thicker (10–15 m) in the shelf adjacent to the Pampas, and thinner (<5 m) in the Patagonian shelf. In the regions where the SS was studied in detail, it has a distinctive and homogeneous seismic-reflection pattern mainly represented by a chaotic and non-transparent character, which indicates a high sand content. In places where muddy content is high, as in coastal estuarine environments, transparent, either parallel or reflections-free patterns, are common. Piston cores and bottom grab samples recovered sediments that allowed the sedimentary facies that compose the SS to be depicted, which is in general represented by terrigenous, siliciclastic, relict–palimpsest deposits presenting varied facies associated with the different environments developed during the regional evolution.

Three systems tracts can be recognized in the SS: lowstand, transgressive and highstand.

Lowstand. Some seaward-prograding seismic-stratigraphic units made up of soft muddy sediments found in different positions in the upper slope could correspond to these deposits, although this needs to be confirmed as the regions beyond the shelf break are still under study. A recent finding (Violante *et al.* 2014) in a core obtained at the shelf break at 100 m water depth offshore the southern Pampean region (around 40°S) provided a 2.75 m-long sequence composed of fine sands of possible nearshore-beach origin in the base, followed upwards by sandy clay sediments containing mixohaline–freshwater microfaunas with vegetal remains in a heterolithic structure, indicating marginal–inshore lacustrine environments, then a shelly deposit representing a beach ridge and, finally, on top of the sequence, the present shelf sands. The marginal–inshore environments have been dated at 15 ^{14}C ka, thus indicating that the sequence represents the first record of a coastal environment in the Argentinian outer shelf associated with the first stages of the post-LGM transgression.

Transgressive. This constitutes the upper layer that covers the entire continental shelf. Although the deposits are mainly sandy, ridge-like features made up of coarse sands, gravels and shells are also common, as well as depressed sectors filled with muds. The surface levels are represented in the nearshore areas of eastern Pampas by shoal-retreat massifs containing linear-shoal complexes associated with sediment reworking during the late Holocene regressive event (Urien & Ewing 1974; Parker *et al.* 1982), as well as by estuarine facies in the vicinity of the de la Plata River mouth (Violante *et al.* 1992; Cavallotto *et al.* 2004; Violante & Parker 2004; Cavallotto 2008).

Highstand. The highest sea-level positions reached approximately +4/6 m at 6 ka. Deposits are found along most of the Argentine coasts at altitudes always above present sea level, ranging from 3 m in eastern Buenos Aires to 10 m in Tierra del Fuego, these differences being associated with different tectonic and isostatic

Table 6.4. *Sedimentary facies characteristics*

Sediment main type	Areal distribution	Description	Texture	Colour	Regional distribution	Morphologies
Sand	65% of the shelf surface.	Fine–medium sand. Subordinated coarse and very fine sand. Bioclastics	Loose deposits. Texturally mature. Moderate–well sorted	Yellowish, brownish and greyish	North and central Patagonia: fine–medium fractions. Pampean and Tierra del Fuego littorals: coarser fractions. Semi-enclosed areas (de la Plata River, Blanca Bay, and San Matías and San Jorge gulfs): very fine, sometimes silty-sands	San Antonio cape (NE Buenos Aires province, eastern Pampas): submerged dune systems and linear shoals related to tidal current action. Between Blanca Bay and the San Matías Gulf: giant submerged dunes. Buenos Aires province (Pampean coasts): relicts of barriers and beach-ridges. Offshore de la Plata and Colorado river mouths: submerged deltaic systems
Shells	12.5%	Entire shells and fragments up to several cm in diameter. Constituted by diverse species of pelecipods, brachiopods and arthropods (barnacles), fish bones and rest made up of echinoids	Loose, slightly consolidated or cemented coquinas. Sometimes as a subordinated fraction of sands	White, yellowish, pale grey	North of 43°S constitutes ridges that indicate the position of ancient coastlines	Ridge-like morphologies
Gravels	12.5%	Generally rounded gravels up to several cm in diameter	Loose gravelly deposits	Depends on source rocks	Offshore the Patagonian rivers mouth: very large gravel concentrations as the source is the glacifluvial deposits that extend over most of Patagonia	None evident
Muds	8%	Silts and/or clays or different kinds of combinations. High content of organic matter	Predominantly cohesive	Dark brown and green	Mainly located in semi-enclosed coastal regions (estuaries, bays and gulfs)	None evident
Consoli dated sediments and rocks	2%	Outcrops of different pre-transgressive substrata	Depends on the rock and sediment types	Depends on the rock and sediment types	Pre-transgressive substratum	Depends on the pre-transgressive morphology

behaviours. Deposits are mainly represented by beach ridges, tidal flats, estuaries, coastal lagoons and beach-dune complexes. A compilation of the available literature on the subject was carried out by Cavallotto (2008).

Evolution

The evolution of the ACS during post-LGM times resulted from the interaction of diverse factors, such as relative sea-level changes, climate, oceanographic processes, sediment dynamics and isostatic/tectonic components. The evidence of the evolution is recorded not only in the post-glacial morpho-sedimentary features and sedimentary sequences but also in the characteristics of the transgressive surface above which the last transgression took place.

The transgressive surface

During glacial times the ACS was an extensive subaerial plain with particular morphological, hydrographical, pedological and climatic characteristics. The post-glacial transgression, although it substantially modified this, did not completely eliminate some pre-transgressive features, which remained preserved in many places. The transgressive surface was the consequence of the ravinement process that occurred as a result of coastal erosional retreat during post-LGM times and, hence, it is time-transgressive (Parker *et al.* 1999, 2008; Violante & Parker 2004). Its characteristics resulted from: (a) the relief and lithological constitution of the pre-transgressive substratum; (b) the subaerial processes (fluvial, aeolian and lacustrine action, as well as soil formation, desiccation and oxidation) during pre-transgressive times; (c) the rate and variability of the relative sea-level rise; (d) the balance between erosive–depositional processes at each stage of the transgression, which depended on the littoral dynamics, the accommodation of the transgressive sediments to the rising base level and the sediment supply. The resulting sequences preserved in the shelf substratum can, therefore, change from exclusively marine sequences to mixed marine–coastal–fluvial–aeolian–palaeosol sequences, depending on its location (Fig. 6.6). The identification of pre-and post-transgressive sequences is clear in seismic records and cores when different environments are recorded but, when similar environments are superposed, sedimentological and geotechnical characteristics can serve to aid differentiation (Table 6.5). Major features preserved on the transgressive surface are incised valleys, evidence of glacial activity, palaeosols and relicts of ancient coastlines.

Incised valleys. Relicts of a palaeo-fluvial network are evidenced on the shelf surface. As it has not been completely obliterated during the transgression, the palaeodrainage pattern can be recognized (Parker *et al.* 1996; Violante *et al.* 2007). Although, in a regional sense, the drainage pattern is dendritic, north of 42°S the ancient fluvial valleys are subparallel and regionally orientated to the SE. South of 42°S, the pattern is more chaotic with numerous distributaries; main valleys are orientated to the south and then change to the SE towards their lowermost sections. Between 42°S and 46°S, some valleys seem to be connected with submarine canyons. South of 46°S, the valleys tend to converge towards the Malvinas depression located south of the Malvinas Islands. In relation to relict fluvial networks in coastal semi-enclosed areas, they show particular patterns more similar to the irregular branching of tributary valleys associated with submerged deltas (like the Colorado–Negro deltaic system) or a semi-radial, centripetal drainage in semi-enclosed basins (San Matías, Nuevo and San Jorge gulfs). Ponce *et al.* (2011) stated that the larger extension of emerged regions during glacial times favoured a better distribution and integration of the drainage network.

Glacial features. The southern extreme of the Andes was covered by ice during glacial times. Owing to the narrowness of the continent there, ice masses and/or glacio-fluvial deposits extended on to the coastal and nearshore regions of Tierra del Fuego, where relicts of glacial features are present in the shelf (Isla & Schnack 1995; Mouzo 2005). However, gravels that extended on to the shelf surface south of 46°S are associated with ancient fluvial and glacio-fluvial deposits.

Palaeosols and related aspects. In the vicinity of the de la Plata River outlet, Osterrieth *et al.* (2005) and Violante *et al.* (2007) described probable palaeosols based on the finding of silicophytoliths in sediment cores at water depths exceeding 80 m. Two palaeosols were found initially, one developed on continental late Pleistocene sediments and the other one on pre-transgressive coastal Holocene deposits. Cione *et al.* (2005) described mammal remains at water depths of 45 m in continental late Pleistocene–early Holocene sediments outcropping in the inner shelf.

Ancient coastlines. Longitudinal and parallel-to-the-coastline deposits mainly composed of coarse sand, gravel and shells were recorded in the outer border of the terraces, particularly on terrace I (TI), which have been interpreted as relicts of ancient coastlines (Urien & Ewing 1974; Urien *et al.* 1979; Parker *et al.* 1996, 1997). As mentioned above, a record of an ancient coastline was found in a core containing coastal (beaches to inshore lacustrine) sediments sandwiched between nearshore and shelf deposits at a water depth of 100 m (Violante *et al.* 2014).

The post-glacial morpho-sedimentary features

Main features of the ACS are terraces stepped at different depths, increasing offshore, and with different regional extensions. Its

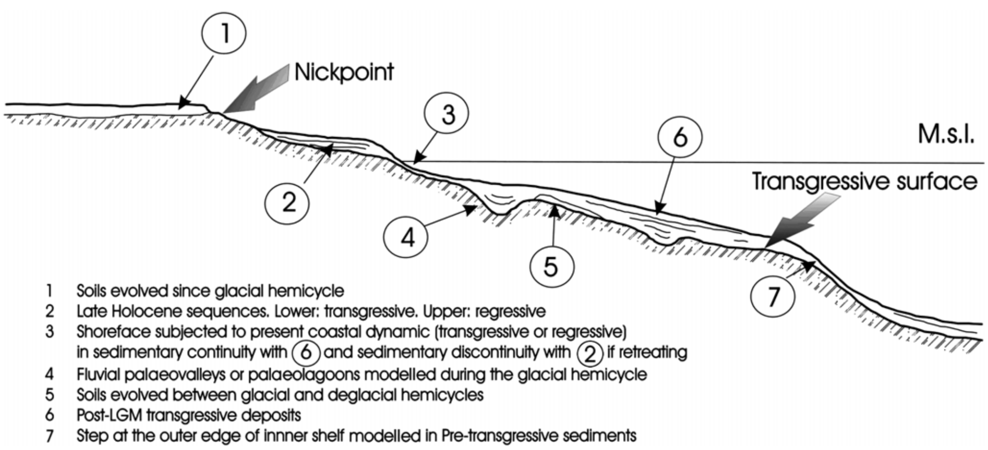

Fig. 6.6. Schematic cross-section showing the relative position of the different parts of the post-LGM sequence above the transgressive surface (from Violante & Parker 2004).

Table 6.5. *Sedimentological and geotechnical differences between pre- and post-LGM sequences*

	Lithology/environment	Shearing resistance (Parker *et al.* 1976)
Pre-LGM sequences	Continental (aeolian–lacustrine) semi-consolidated, reddy, browny and yellowish, silty to loessic sediments. Exceptionally littoral sands	2.40–4.60 g cm^{-2} increasing downcore
Post-LGM sequences	Littoral–shallow marine, not consolidated, yellowish, browny, greyey and greenish bioclastic fine sands to sandy muds.	Normally under 0.55 g cm^{-2} (exceptionally reaching 1.65 g cm^{-2})

origin and shaping was associated (Groeber 1948; Parker *et al.* 1997; Violante 2005; Perillo & Kostadinoff 2005; Ponce *et al.* 2011) with interruptions in the rate of sea-level rise during the post-glacial transgression. These interruptions were driven by climatic changes, with the consequent establishment of a stationary shoreline at that position for a relatively long time, so allowing the modelling of the outer edge of the terraces to occur by erosional coastal retreat.

The age of the terraces was estimated by Violante (2005) after comparing the depth of the base of the terraces and the local sea-level curve (Guilderson *et al.* 2000). TI coincides with the age of the Younger Dryas event, so enabling the possibility to be considered that this cold period could have induced a stillstand in sea level at a depth around 70–80 m, with consequent rapid coastal erosion and the modelling of the terrace front. After sea level began, once more, to rise, the diminishing coastal erosive processes were not able to substantially modify the terrace morphology. When sea level reached a position of around 20 m below present, in close agreement with a new decrease in the rate of relative sea-level rise observed at around 8.6 ka, the surface of TI was levelled by persistent wave action and covered by sediments that resulted from the reworking of the substratum. Based on the same comparisons, TII, TIII and TIV could have been modelled during sea-level stabilizations at around 12–13, 14–15 and 16–18 ka, respectively, the last one probably indicating the LGM. The modelling of TII at around 12–13 ka could possibly be related to some sea-level stabilization associated with the Antarctic Cold Reversal Event mentioned by McCullock *et al.* (2000).

Ponce *et al.* (2011) made similar comparisons based on the eustatic curve by Fleming *et al.* (1998) and the considerations by Hodgson *et al.* (2009). As a result, the ages of these terraces are different from those established by Violante (2005), the differences increasing as we go back in time. The extreme case is that when using the curve by Fleming *et al.* (1998), Ponce *et al.* (2011) considered that TIV could have an age of 1 Ma. These differences indicate that this statement needs more research. The modelling of terraces II, III and IV occurred during the first stages of the post-LGM transgression that corresponded with the unstable climatic oscillations which preceded the Younger Dryas. In addition, those terraces, unlike TI, could have been partially influenced by isostatic uplifting readjustment as they extend adjacent to Patagonia.

Apart from the sea-level fluctuations that modelled the terraces, the complex processes involved in the morpho-sedimentary evolution of the shelf resulted in the shaping of diverse features that have been defined as ‘geomorphological provinces’ (Parker *et al.* 1997) (Fig. 6.2):

- Rioplatense terrace – this is located in the northernmost part of the shelf corresponding to the northern sector of TI. It has been modelled during the post-LGM transgression in several erosional and agradational features represented by pre-transgressive relict reliefs and transgressive sand bodies.
- Deltaic front of the Colorado and Negro rivers – this is a feature formed by successive deltas evolved during the Pleistocene–Holocene, and shows a typical lobate shape and a gravelly–sandy–bioclastic composition. It is part of the southern sector of TI.
- North Patagonian gulfs – these are semi-enclosed coastal basins, with the peculiarity that the maximum depths of the gulfs are deeper than the shelf break. The gulfs are separated

Table 6.6. *Geomorphology of the shelf*

Sub-environments		
Inner shelf	From the coastline to around 30 m water depth	Sediments adjusted to the present nearshore hydrodynamic conditions (palimpsests). Active morphosedimentary features like shoal retreat massifs, linear shoals and giant subaqueous dunes are influenced by nearshore sedimentation, coastal currents, waves and tidal action. This sub-environment is more precisely defined in the Rioplatense terrace, above a water depth of 30 m
Middle shelf	From around 30–90 m depth	Represented by sedimentologically more stable areas with low sediment mobilization (relict sediments); most of the Patagonian shelf is of this type
Outer shelf	From around 90 m depth to the shelf break.	Close to the shelf edge where sediment dynamic is associated with the shelf–slope transition zone; boundary currents and upper-slope to submarine canyon-head processes (such as turbiditic and debris flows) occur there
Regions according to balance between continental and marine processes		
North	Offshore the eastern Pampas	Fluvial activity dominates over marine processes owing to the presence of the de la Plata fluvial–estuarine environment, active since the Pliocene
Central	Offshore the southern Pampas and most of the Patagonian regions	Predominance of wave action in the north and tidal action in the south Fluvial influence is of minor and local importance as the sediment provider to the shelf The coastal retreat occurred as a result of the balance between post-glacial sea-level rise and isostatic uplifting. A ravinement surface was produced with the consequent formation of a relict sandy mantle
South	Southern tip of Patagonia and Tierra del Fuego	The very narrow continent was almost completely covered by ice during LGM times, when glaciers reached positions close to the sea. Glacial and glacio-fluvial deposits were covered by the sea during the post-glacial transgression

from the open sea by sills, the tops of which are at water depths of 50–70 m. The origin of the gulfs was attributed to aeolian activity in continental depressions, later flooded by marine waters during the Quaternary transgressions and, consequently, lacustrine facies could have probably occupied the depressions during sea-level lowstands.

- Patagonian inner shelf – this sector, located between the Nuevo Gulf and the Santa Cruz River, shows a strong relief marked by coastal lobate morphologies probably related to small deltaic environments associated with the Patagonian rivers.
- Patagonian outer shelf – this is the largest province of the ACS that comprises terraces II, III and IV. On most of its surface, a partially buried drainage system develops, which constitutes incised valleys excavated by subaerial processes during pre-transgressive times.
- Tierra del Fuego shelf – this has a predominant gravelly composition and the presence of moraine-like topographies, resulting from glacial processes, occurred around LGM times.
- Malvinas islands shelf – this is a flat feature whose upper part constitutes the islands, and represents a morphological and geological extension of the Patagonian outer shelf.

Terraces in the ACS show different regional distributions, with deeper (older) terraces disappearing in the northern part of the shelf and very little development of TI in the south (Fig. 6.3). It is considered that the present conditions of Patagonian coasts (cliffed reliefs, high-energy) have also characterized previous stages of the late-glacial evolution, in such a way that deeper terraces have been shaped in the same way and therefore reached a more significant development. However, northern (Pampean) coastal regions, today characterized by low-energy coasts with lowlands, coastal plains and estuaries, have evolved with the same features in the past, and therefore no relicts of significant terraces remain recorded in the shelf, except for TI. This terrace represents a particular case as it probably responded to more complex and energetic interactive processes, among which the most significant can be attributed to the deep erosive processes driven by a stationary sea level during the Younger Dryas, and the influence of large estuarine and deltaic environments (the de la Plata and Colorado rivers) during the last stages of the regional evolution.

It can be synthesized that the modelling of the ACS, depending on the interaction between global, regional and local factors, such as sea-level fluctuations, climate, subaerial and subaqueous processes, isostasy and tectonism, originated in different geomorphological regions. Three distinct sub-environments are recognized: the inner, the middle and the outer shelf. However, regional differences due to the balance between continental and marine processes allow three geographical regions to be considered: North, Central and South. Table 6.6 gives the main characteristics of all three regions.

Conclusions

The ACS is one of the most extensive shelves in the world, showing diverse geological characteristics as a result of its emplacement in different geotectonic and oceanographic settings. Owing to its enormous size, knowledge of the ACS is uneven and still incomplete and, to learn more about it, is a short- to mid-term challenge for present and future generations of marine scientists.

The main conclusions arising from our present knowledge of the ACS can be summarized in the following points.

- The shelf has developed mainly on a passive continental margin, although it is also influenced, particularly in the southern regions, by other (active) types of margins. Consequently, northern regions of the shelf (adjacent to the Pampas and northern Patagonia) show different morpho-sedimentary features to those in the southern regions (southern Patagonia).
- Four terraces with different extensions and characteristics, as well as several geomorphological provinces of complex origin, constitute the main reliefs of the shelf.
- Morpho-sedimentary features and sediment facies document the increasing influence of hydro-isostasy to the south.
- Sedimentary cover of the shelf is terrigenous and siliciclastic, constituted by sediments mainly sourced in Andean Patagonian regions. Sediments are considered as relict and palimpsest as a result of reworking by marine processes by means of the progressive sweeping of the shelf surface during the post-LGM transgression.
- Although the post-LGM sea-level rise was relatively uniform, some fluctuations are evident through the disposition of morpho-sedimentary features, the most important ones probably being associated with the Younger Dryas event.

Many regional geological aspects related to the evolution of the ACS during post-LGM times still remain incompletely solved, particularly: (a) the origin and evolution of terraces and related steps, incised valleys and north Patagonian gulfs; (b) the real significance of cold events (i.e. Younger Dryas, Antarctic Cold Reversal and neoglacial periods) and the evidence for this; (c) why the shelf border changes greatly in depth in different regions; (d) better interpretation of features resulting from relative sea-level fluctuations, particularly the lowstand deposits present in the shelf edge and upper slope; and (e) the processes that regulated the last subaerial exposure of the shelf.

To solve these problems a significant effort must be made in order to organize multidisciplinary projects aimed at carrying out research activities on the entire shelf based on geophysical–geological surveys focused on Late Quaternary sequences, in a continuous and systematic way, and with the objective of progressively covering successive areas until the entire shelf has been surveyed. It is necessary to do this under 'sea–land correlation' and 'source-to-sink' integrated perspectives. A programme initiated in the 1980s by the Group of Marine Geology and Geophysics of the Argentine Hydrographic Survey, and still continuing today, was the starting point for such a research line.

The summary that this contribution represents must serve as a framework for further studies and to encourage future –and essential – research in the region.

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