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The Late Cretaceous–Cenozoic transgressions in Patagonia and the Fuegian Andes: foraminifera, palaeoecology, and palaeogeography

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In southernmost South America, several ephemeral Atlantic transgressions flooded the Patagonian Platform: in the Maastrichtian-Danian, late Mid-Eocene, Late Oligocene-Early Miocene, and Middle Miocene; only in the Fuegian Andes did marine conditions remain continuously from the Maastrichtian up to the Middle Miocene. In the Maastrichtian, the calcareous foraminiferal benthic assemblages contain endemic species, and most of them disappear in the Cretaceous–Palaeogene transition. The Palaeocene carries the extinct cosmopolitan Midway type assemblage with few endemic taxa such as *Buliminella isabelleana*, and the genera *Antarcticella* and *Boltovskoyella*. The Palaeocene/Eocene turnover gives room to assemblages of modern and marked Austral aspect: Elphidiidae dominates in shallow environments, including genera endemic to high and mid-high southern latitudes such as *Cribrorotalia*. The Late Middle Eocene transgression is characterized by large nodosarids in the Fuegian area and the spreading of *Elphidium saginatum*. The Late Oligocene transgression is of limited extension and shallow waters, with abundant *Buccella* and the conspicuous genus *Discorotalia*. The Early Miocene transgression carries the extinct and typical Antarctic genus *Ammoelphidiella* and witnesses the origin of the modern Patagonian coastal assemblage, characterized by its pauperism and the dominance of the genus *Buccella*. The Middle Miocene transgression covers mainly northern Argentina. Considering that the late Middle Eocene and Middle Miocene transgressions are coeval with relative climatic optima, and in comparison with assemblages at similar palaeolatitudes elsewhere in the Southern Hemisphere, the absence of larger foraminifera or thermophilic forms in the Patagonian and Fuegian assemblages is outstanding.

ADDITIONAL KEYWORDS: Argentinean continental Platform – Austral geobioprovince – Endemism – foraminiferal turnover – Maastrichtian – Tertiary – sea level change – palaeoceanography.

En el extremo austral de América del Sur, varias transgresiones efímeras inundaron la Plataforma Patagónica: en el Maastrichtiano-Daniano, Eoceno Medio Tardío, Oligoceno Tardío-Mioceno Temprano, y en el Mioceno Medio; sólo en los Andes Fueguinos las condiciones marinas permanecieron desde el Maastrichtiano hasta el Mioceno Medio. En el Maastrichtiano, las asociaciones de foraminíferos bentónicos contienen especies calcáreas endémicas, que en su mayoría desaparecen en la transición Cretácico/Paleógeno. El Paleoceno porta la asociación cosmopolita extinta del tipo Midway, con pocos taxones endémicos tales como *Buliminella isabelleana*, y los géneros *Antarcticella* y *Boltovskoyella*. El recambio del límite Paleoceno/Eoceno da lugar a asociaciones de aspecto moderno y marcadamente austral: los Elphidiidae dominan en los ambientes someros, incluyendo géneros endémicos de altas y medias altas latitudes australes tales como *Cribrorotalia*. La transgresión del Eoceno Medio Tardío está caracterizada por grandes nodosáridos en el área fueguina y por la dispersión de *Elphidium saginatum*. La transgresión del Oligoceno Tardío, de limitada extensión y de aguas someras, contiene abundante *Buccella* y el conspicuo género *Discorotalia*. La transgresión del Mioceno Temprano porta el extinto y típico género antártico *Ammoelphidiella* y testimonia el origen de las asociaciones costeras patagónicas modernas, caracterizadas por su pobreza y la dominancia del género *Buccella*. La transgresión del Mioceno Medio cubre principalmente el norte de la Argentina.

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En consideración a que las transgresiones del Eoceno Medio Tardío y Mioceno Medio son coevas con óptimos climáticos relativos, y en comparación con otras asociaciones en palaeolatitudes similares del Hemisferio Sur, es notable la ausencia de foraminíferos grandes o formas termofílicas en las asociaciones patagónicas y fueguinas.

PALABRAS CLAVE: cambios del nivel del mar – endemismo – geobioprovincia austral – Maastrichtiano – paleoceanografía – Plataforma Continental Argentina – recambio de foraminíferos – Terciario.

INTRODUCTION

The aim of the present study is to provide palaeogeographic maps for the main Atlantic transgressions on the Patagonian Platform and on the island of Tierra del Fuego. A succinct synthesis of the major foraminiferal palaeobiogeographic and palaeoecological features of these transgressions is also provided; these features comprise the basic data used to construct the maps. We have searched, with uneven intensity, the foraminiferal contents of almost all the outcropping and subsurface stratigraphical entities in all basins (Figs 1, 2). This has been carried out mainly in their type localities, distributed along 20° of latitude. This search was recently accomplished upon description of the foraminiferal contents of the rather complete Upper Campanian–Miocene marine episodic succession of the Fuegian Andes (Olivero & Malumián, 2008; Malumián & Jannou, 2010). Although a relative large number of new taxa still await formal description, the most typical of them are illustrated in the present study.

THE ATLANTIC TRANSGRESSIONS

Shallow and ephemeral transgressions from the Atlantic have flooded Patagonia during the Maastrichtian–Danian, late Middle Eocene, Late Oligocene–Early Miocene, and the Middle Miocene. During each of these transgressions, the continental shelf, developed on a passive margin and one of the widest in the modern world, largely increased its extension towards the West, conforming the Patagonian Platform, and giving room to extended shallow seas of peculiar palaeoecological conditions. These conditions affected the distribution of the planktonic foraminifera acting as filter for deep dweller species and larger or adult forms, and also promoted the endemism of the benthic foraminifera.

The coastal shape and, to some degree, the extension of the transgressions were modulated by the major positive areas (Fig. 1): in the northern part of the study area, the Somuncura and Deseado Massifs and a main dorsal on the shelf, known as the Patagonian Oriental Dorsal or Patagonian Atlantic Dorsal. In the southern part, the main feature responsible for the coastal shape is the Fuegian orocline that existed at least since the Eocene (Maffione *et al*., 2010). This orocline includes the Fuegian Andes, the active border of the Austral or Magallanes Basin. The Fuegian Andes have one of the few nearly complete upper Cretaceous–Middle Miocene marine sections exposed at high southern latitudes (Fig. 2).

Two extreme contrasting environments are recognized in most of the transgressions: the extended shallow to marginal environments of the Patagonian Platform with dominant low diversity endemic calcareous assemblages; and the turbiditic and/or deep environments localized in the Fuegian Andes with dominant cosmopolitan flysch-type agglutinated foraminifera, which are commonly related to turbiditic and/or below compensation calcite depth and tectonically active settings.

THE MAASTRICHTIAN TRANSGRESSION (FIGS 3, 4, 5)

The first and greatest Atlantic transgression occurred during the Maastrichtian, a period of tectonic quiescence and low magmatic activity, and it was the origin of the Patagonian Platform landform. The sea remained in most part of Patagonia until the Danian. At its maximum flood, the sea reached mid platform depths in central northern Patagonia, carrying relatively diverse assemblages. Otherwise, low diverse assemblages representing very shallow waters of extreme environments are widespread in northern Patagonia. Some of them are quasi monospecific, composed of endemic calcareous taxa, whereas deltaic agglutinated assemblages, also of low diversity, are restricted to the Lefipán Formation (Chubut Province).

Typical Austral foraminifera originally described from New Zealand such as *Notoplanulina rakauroana* and the very conspicuous '*Frondicularia*' *rakauroana* also occur in southernmost South America. The first species reached latitudes as low as those of the offshore Colorado Basin, and the second one is known from Antarctica and the Malvinas Basin (Fig. 5). The neritic *Coryphostoma incrassata gigantea* assemblage occurs in the northern Austral Basin (Malumián & Náñez, 2002a).

Noteworthy, the marine Maastrichtian is not recorded from the Península Valdés and Rawson Basins. These basins were part of a huge positive

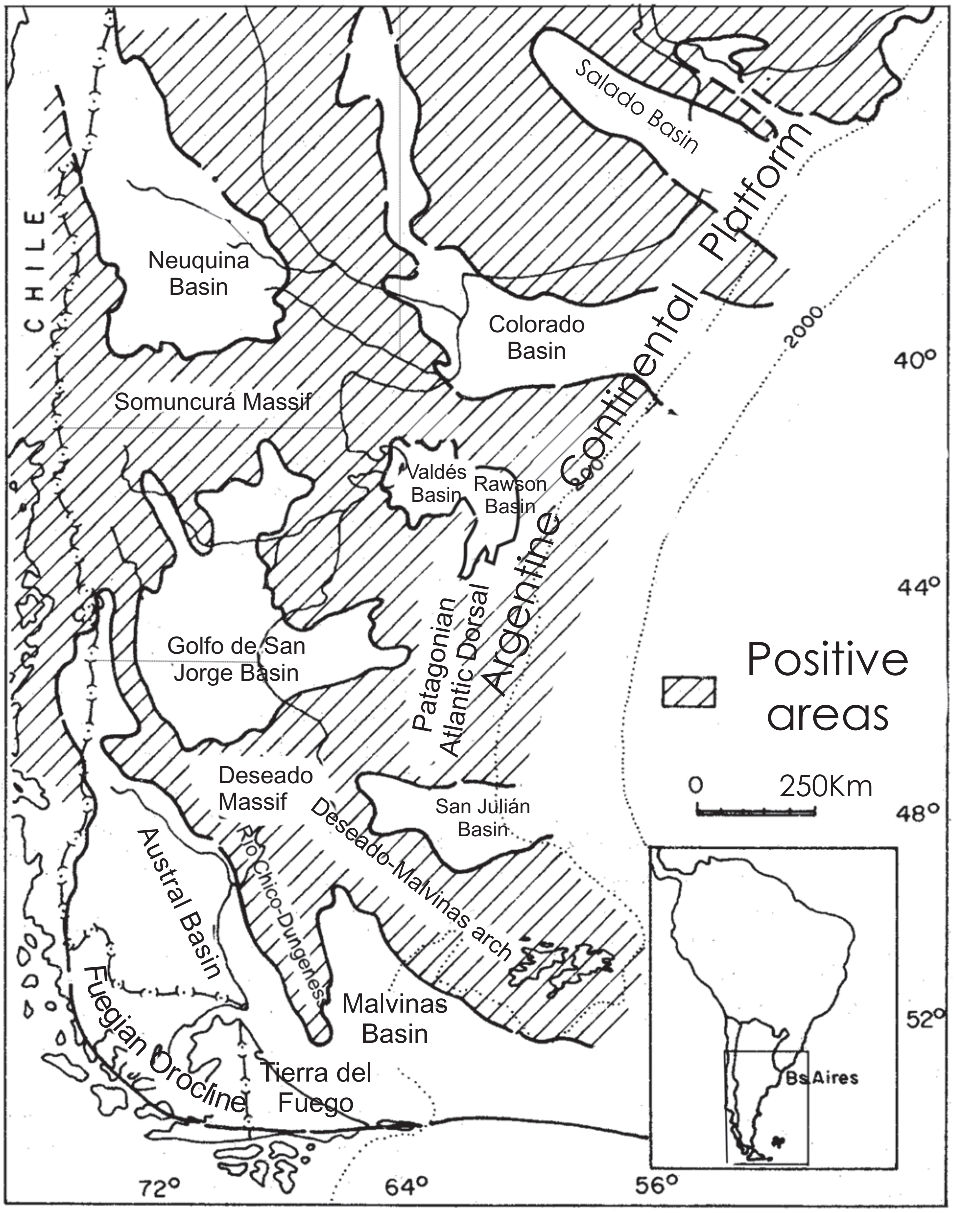


Figure 1. Main morphostructural units in the Late Cretaceous–Cenozoic of Patagonia and Tierra del Fuego Island. The positive areas include the Somuncura 'Massif', a Precambrian basement complex that acted as a stable rigid block during the Andean orogeny. The Deseado Massif also has a cratonic behavior; southwards it composes the Río Chico–Dungeness high that separates the Austral from the Malvinas Basin, and south-eastward, the Deseado–Malvinas arch. The Patagonian–Fuegian Andes conform the Andean range south of 39°S, and are characterized by dominant marine Late Cretaceous–Palaeogene sediments. At approximately 52°S, a dramatic change in the structural trend from north–south to west–east is known as the Patagonian or Fuegian orocline. It is uncertain whether this orocline was formed as a curved or a rectilinear orogen comprising the Southern Patagonian–Fuegian Andes and the Antarctic Peninsula, which subsequently was bent (Ghiglione & Cristalini, 2007; Gombosi *et al*., 2009). The Fuegian Andes as a principal component of the Scotia Arc have implications associated with the opening of the Drake Passage, oceanic circulation, and polar glaciations. The Argentinean Continental Platform has its own attributes and peculiarities that led to consider its northern and central parts as the paradigm of a lower plate passive margin, including a relative high, the Patagonian Atlantic Dorsal, whereas the southern part is a complex area where different margin types converge.

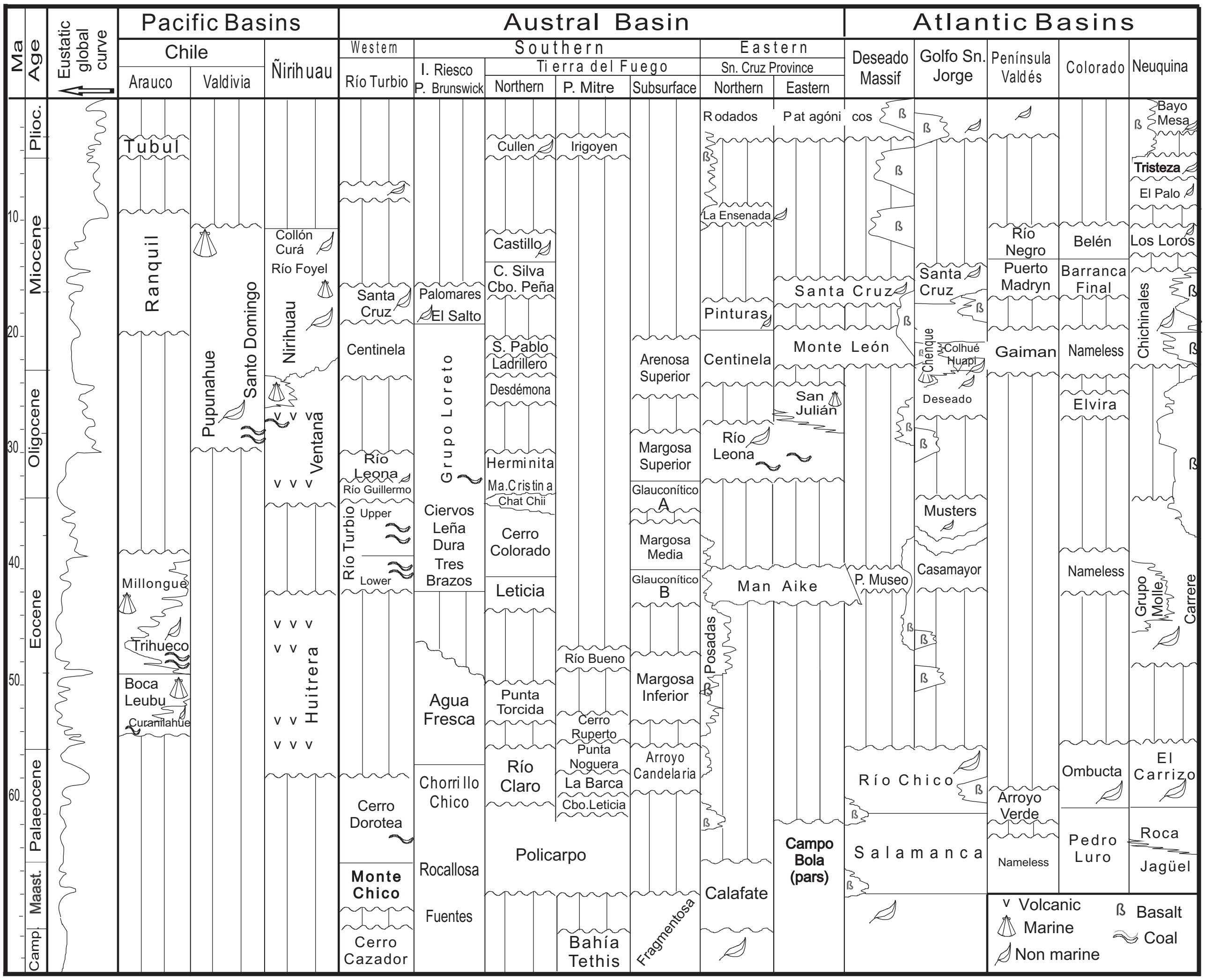


Figure 2. Late Cretaceous–Cenozoic marine formations correlation chart (the Cenozoic data modified from Malumián, 1999). The correlation is based on the foraminiferal content, taking the Andean Fuegian marine pile as a general biostratigraphic reference (Northern and Península Mitre columns). This pile is a rather complete but strongly episodic upper Cretaceous–Miocene succession, accumulated in a complicated structural setting where numerous contacts among formations are tectonic. The eustatic curve is *sensu* Haq, Hardenbol & Vail (1987); the megasequences exhibit a strong similarity between the southern Australian shelf (McGowran, 1979, 1991) and Patagonia-Tierra del Fuego (Malumián, 2002).

area, mainly conformed by the Patagonian Atlantic Dorsal and the Dungeness–Malvinas High, which separate the northern and the southern Maastrichtian sea (Náñez & Malumián, 2008).

In the Maastrichtian/Danian transition (Fig. 5), almost all of the Maastrichtian endemic taxa disappeared, giving place to the Midway type cosmopolitan assemblage. In the Golfo San Jorge Basin, tidal assemblages of very low diversity are dominated by *Buliminella isabelleana*, one of the few Austral Danian endemic taxa that survived up to the Early Eocene. However, this species is a potential synonym of *Buliminella westraliensis* Parr, well known in Australasia. Remarkable are the appearances in the Danian of *Antarcticella* and *Boltovskoyella*, endemic to high southern latitudes and Patagonia, respectively. The low percentage of agglutinated foraminifera (12%) in the Danian of the Neuquina–Colorado Basin is attributed to hypersaline waters, exposed by sculptured forms such as *B. isabelleana*, forma *tuberculata* (Malumián & Caramés, 1995).

In the Fuegian Andes, the Cretaceous/Palaeogene transition is not manifested into the dominating agglutinated flysch type assemblages of a Maastrichtian–Lower Eocene succession that contains *Rzehakina* (Caramés & Malumián, 2006).

A general withdrawal occurs during the Middle Palaeocene in the Patagonian Platform. The marine Upper Palaeocene–Lower Eocene remained restricted to the Fuegian Andes, where the Palaeocene/Eocene transition is evident by the great turnover of the benthic foraminifera. The Palaeocene Midway type assemblage disappeared, and was replaced mostly by a typical Austral assemblage with genera such as *Cribrorotalia* and discoidal *Elphidium*.

The Late Middle Eocene transgression (Figs 6, 7)

A generalized unconformity encompassing the Upper Palaeocene and Lower Eocene developed in the Patagonian Platform. It was followed by the late Middle Eocene transgression, recorded only in the Austral Basin and offshore of the Colorado Basin in the study area, although it is extensively recognized in the Southern Hemisphere. Apparently, the Patagonian Atlantic Dorsal precluded the income of marine waters into the Golfo San Jorge and Península Valdés basins.

In the Austral Basin, the transgression is characterized by endemic foraminifera. Among them, *Boltovskoyella*, a genus that had appeared in the Danian, exhibits a clear evolutionary trend towards the test elongation and the reduction in the number of chambers in the last whorl: five–six in the Danian forms, to only two in the Late Eocene forms (Náñez, 1998). This genus achieves its maximum abundance in the Eocene, and is thus used as biostratigraphic marker, giving name to the *Boltovskoyella* beds.

Westward in the basin, the coal measures, the scarce miliolid foraminifera and the abundant ostracods reflect an estuarine circulation and a coal generating period. This period had already started in the Maastrichtian, culminating with exploited coal measures in the Middle Eocene, and remained until the Oligocene represented by the extensive deposit of lignite of the Río Leona Formation (Fig. 8). Northward, the extreme record of this transgression is a briozoal limestone outcropping at the locality of Puesto del Museo (Panza, Náñez & Malumián, 1998); southward, on the island of the Tierra del Fuego, it is characterized by a retrograde assemblage with large-sized nodosarid foraminifera (Figs 3–6, 7) associated with a high abundance of crinoidal remains, constituting an event shared with Antarctica (Malumián & Olivero, 2005a).

As a noteworthy feature, *Elphidium saginatum* Finlay, originally described from New Zealand and abundant in the Austral Basin, reached a wide distribution during this transgression: it is recorded up to latitudes of the Colorado Basin off shore, on the Atlantic Ocean side; and up to the Talara Basin, in Peru, on the Pacific side of South America.

The appearance of typical Antarctic taxa such as *Antarcticella antarctica* in the late Middle Eocene, followed by the appearance of the characteristic Antarctic genus *Ammoelphidiella* in the Early Miocene, reveals a pattern of decreasing temperatures.

In general, an increased abundance of borings and boring types is apparent on the Middle Eocene foraminifera, affecting genera also known to be intensely bored from the Antarctic Pliocene. This increased bioerosion gives a polar aspect to the assemblages because intense bioerosion have been recorded in both a typical polar genus such as *Ammoelphidiella* and in modern Antarctic assemblages (Malumián *et al*., 2007). All this suggests that Fuegian foraminifera are part of an Antarctic province, which is consistent with findings of *Elphidium* species common to both Tierra del Fuego and to Antarctic boulders (Quilty, 2001).

The Late Oligocene transgression (Figs 8, 9)

The transgression of the Late Oligocene in Patagonia is of limited extension and very shallow waters. It is characterized by calcareous assemblages, with rare miliolid foraminifera in the Austral Basin suggesting hyposaline conditions (Bertels, 1979). Such hyposaline conditions are the result of the rainy climate presumed prevalent at the time, which generated seven millions of tons of lignite in the Río Leona Formation.

By contrast, in the Península Valdés Basin, the transgression is represented by beds with abundant miliolids in assemblages of very low diversity and devoid of planktonic foraminifera, suggesting shallow hypersaline waters disconnected from the open ocean (Caramés, Malumián & Náñez, 2004). In the Colorado Basin, this transgression is represented by the Elvira Formation and its shallow-water and poorly preserved assemblage. All these very shallow environments are characterized by *Buccella* spp. and similar genera (Figs 1, 3, 9) with umbilical areas covered by tubercles, with rather infrequent records of *Discorotalia*, a typical genus originally described from New Zealand.

On the island of Tierra del Fuego, in the Early Oligocene, the generation of the deepest Cenozoic foredeep (Scarpa & Malumián, 2008) facilitated the income of corrosive Antarctic waters. Conditions

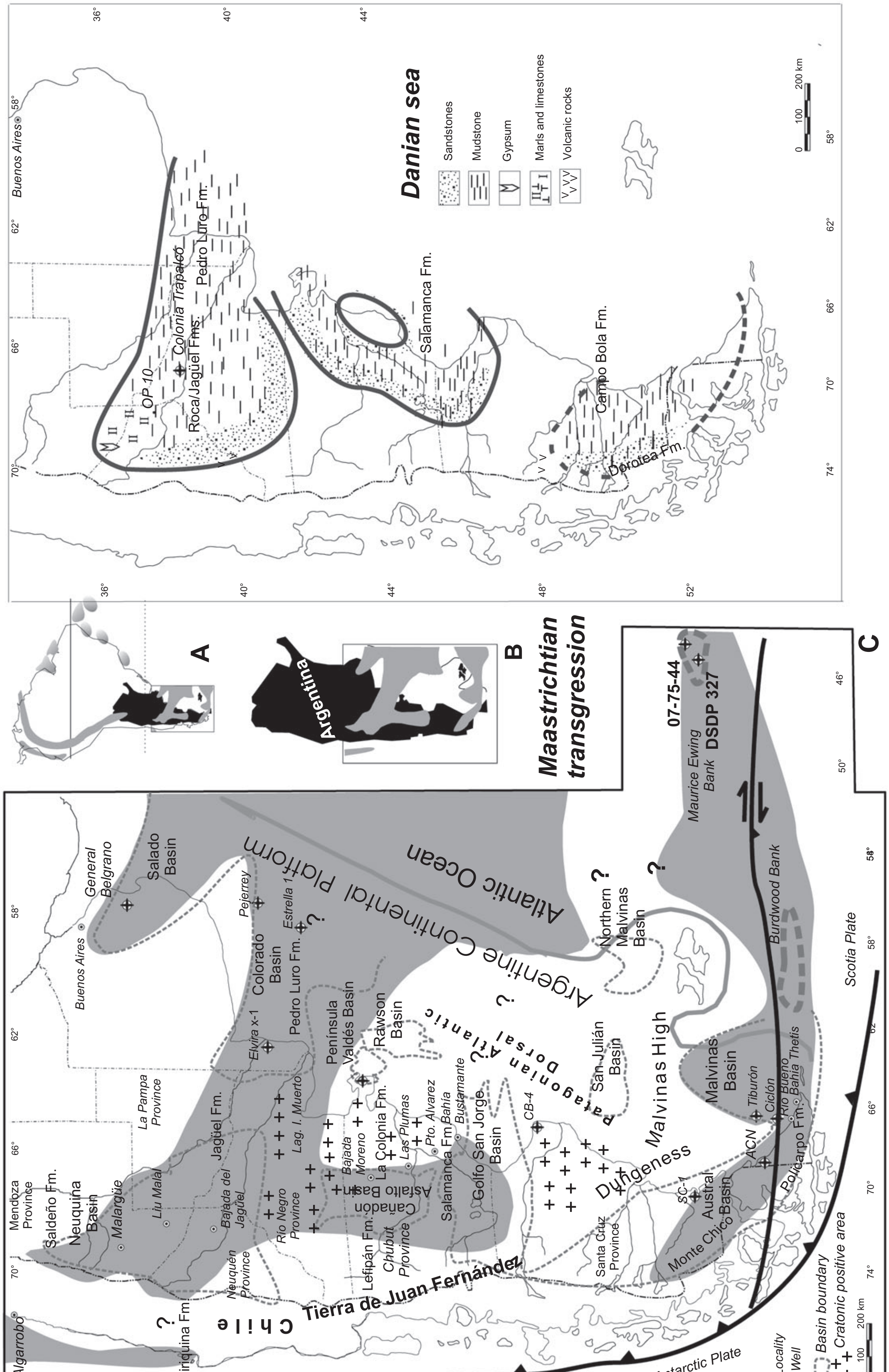

Danian sea
Sandstones
Mudstone
Gypsum
Marls and limestones
Volcanic rocks
Salamanca Fm.
Pedro Luro Fm.
Colonia Trapalco
Roca/Jagüel Fms.
OP 10
Campo Bola Fm.
Dorotea Fm.
Buenos Aires
A
B
C
Argentina
Maastrichtian transgression
07-75-44
DSDP 327
Maurice Ewing Bank
Atlantic Ocean
Argentine Continental Platform
Patagonian Dorsal Atlantic
Northern Malvinas Basin
Malvinas High
Malvinas Basin
Burdwood Bank
Scotia Plate
Antarctic Plate
Nazca Plate
Chile
Tierra de Juan Fernández
Colorado Basin
Salado Basin
Neuquina Basin
Golfo San Jorge Basin
San Julián Basin
Austral Basin
Rawson Basin
Península Valdés Basin
Cañadón Asfalto Basin
Dungeness
Locality
Well
Basin boundary
Cratonic positive area

Figure 3. The Maastrichtian transgression marks the origin and the maximum extent of the Patagonian Platform. Type localities of the formations, studied localities, basins, and positive areas (Náñez & Malumián, 2008). This is the first expansion of the marine shelf and the concomitant reduction of the non-marine Late Cretaceous environments. The distribution of the Maastrichtian marine sediments raises several palaeogeographic questions, such as the existence of a sea connection with the Pacific Ocean at the latitude of Central Chile, as well as the existence of the Patagonian–Fuegian orocline. A, Study area relative position in South America; B, relative position in Argentina; C, Maastrichtian transgression.

below the calcite compensation depth remained up to the Early Miocene (Malumián & Olivero, 2006).

The Early Miocene transgression (Figs 10, 11)

The transgressive stage of this major flooding carried the *Spirosigmoilinella–Martinottiella* association, mainly composed of agglutinated foraminifera, eventually with *Transversigerina* or *Antarcticella*, reflecting the income of Antarctic corrosive waters (Malumián & Náñez, 1991; Náñez, Quattrocchio & Ruiz, 2009). The latter genus along with *Ammoelphidiella* reached latitudes as low as those of the Colorado Basin. Only in the Paiva Formation, at 32°S latitude, out of the study area, the finding of *Peneroplis* sp. indicates warm waters (Marengo, 2006).

The regressive stage comprises an assemblage of mostly calcareous rotaliid foraminifers (Fig. 11), regarded as the origin of the modern assemblage of the Argentine inner shelf, the so-called *Buccella* kingdom (Boltovskoy, 1976). This assemblage is characterized by its poverty and the abundance of the genus *Buccella*.

The Middle Miocene transgression (Fig. 12)

The Middle Miocene transgression is of minor extent in Patagonia, although pervasive into central and northern Argentina. On the Atlantic coast, the southernmost record of warm-water indicators is found at the latitudes of the Uruguayan coast. In Chile, *Transversigerina transversa* (Cushman) is very abundant in the Cholchol Formation, Temuco Basin, and in the Hueyusca Formation, Catamutún Basin (Marchant, 1990). These Chilean formations have been assigned to the late Middle Miocene. They are just in front of the Ñirihuau Basin, on the Argentine side of the Andes, which carries the probably conspecific *Transversigerina* cf. *transversa*, found in the Foyel Formation (Malumián *et al*., 2008). Recently, Finger *et al*. (2007) assigned the classic Navidad Formation, along with the Ranquil and Lacui formations from central Chile, to the Late Miocene and Early Pliocene.

General biogeographical, palaeoecological, and biostratigraphic features (Fig. 13)

The Patagonian transgressions were coincident with relative climatic optima, with the remarkable exception of the Palaeocene/Eocene optimum: the Late Palaeocene–Early Eocene sea was reduced and confined to the depocenters of the Fuegian-Austral Patagonian Andes.

Notoriously, despite this coincidence, there are no records of larger foraminifera or other taxa indicative of warm waters in any Fuegian or Patagonian assemblages. In modern seas, the larger foraminifera are distributed between 25 °C isotherms at maximum depths of 100–200 m. On the West Atlantic coast, the southernmost record of Cenozoic larger foraminifera is in the Santos Basin, at the modern latitude of the Tropic of Capricorn (de Abreu & Viviers, 1993). The absence of fossil larger foraminifera is the main palaeoecological characteristic of the Patagonian Platform assemblages. These warm-water indicators are recorded at similar palaeolatitudes elsewhere in the Southern Hemisphere, including Southern Australia, New Zealand, and South Africa. Despite the fact that the Southern Australian shelf had similar and even higher palaeolatitudes than the Austral Basin (Malumián & Náñez, 2002b), it has Late Eocene larger foraminifera. This occurrence can be explained by the existence of a forerunner current of the modern Leeuwin Current (Quilty, 1981; Li *et al*., 1996; McGowran *et al*., 1997). New Zealand, from the Late Cretaceous up to the Early Eocene, was at palaeolatitudes of 50°–65°S and, subsequent to the Early Eocene, it has larger foraminifera such as *Asterocyclina*, which, along with keeled planktonic foraminifera, are the first Cenozoic indicators of warmer waters

Figure 4. The Danian sea experimented a retreat with respect to the Maastrichtian transgression in the Neuquina–Colorado Basin; however, in the Valdés Basin and parts of the Golfo San Jorge Basin, new areas were flooded by a very shallow sea. Most likely, the Fuegian area was covered by the sea, although the lack of Danian foraminifera suggests that Danian sediments could have been eroded.

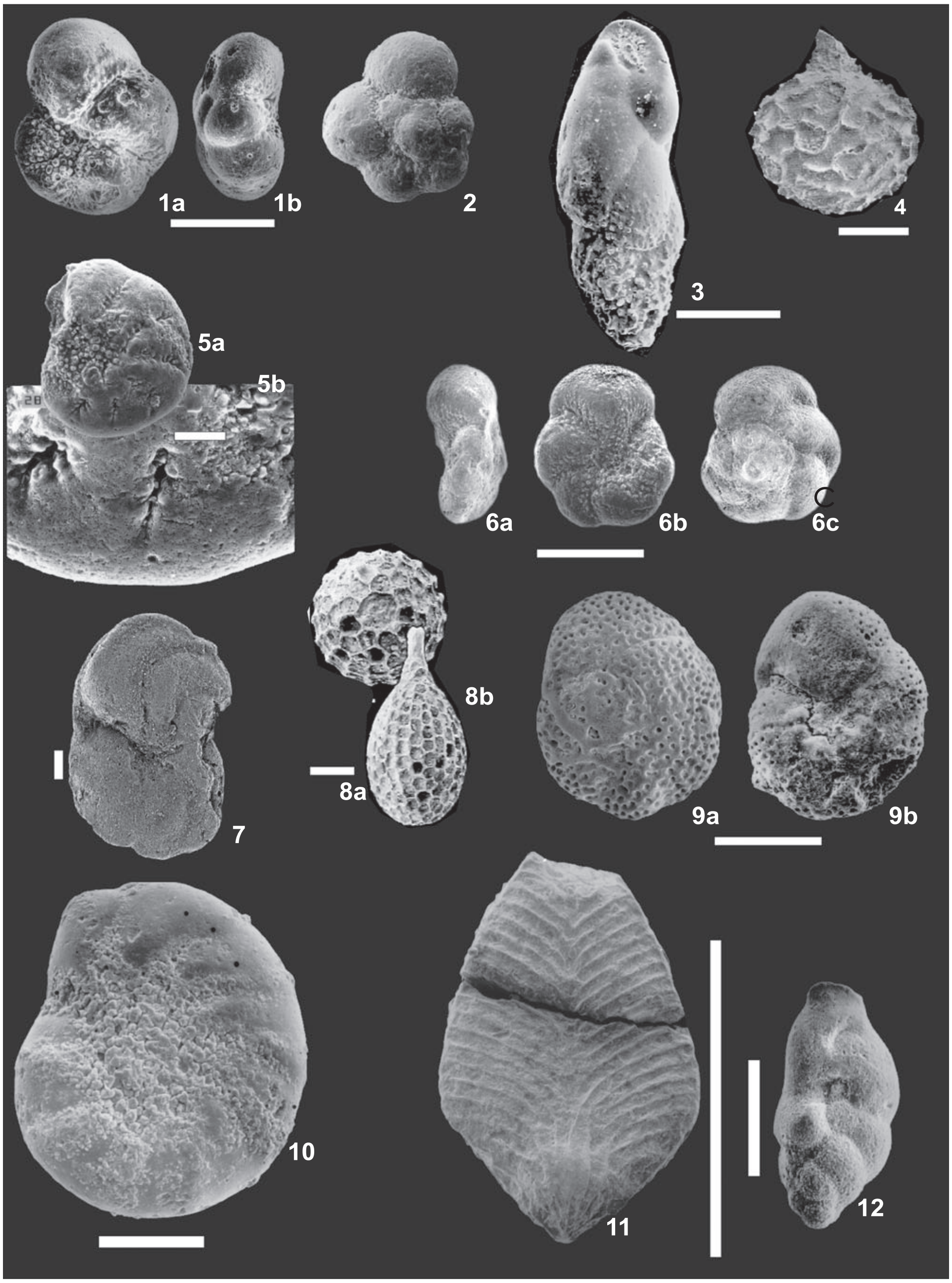


Figure 5. Maastrichtian–Danian endemic and conspicuous species. Scale bars = 100 μm, except otherwise stated. Danian: 1, *Antarcticella pauciloculata* (Jenkins, 1966) forma *primitiva*; a, umbilical view; b, peripheral view. Salamanca Formation, Golfo San Jorge Basin; 2, *Antarcticella pauciloculata* (Jenkins, 1966) forma *typica*; spiral view, Jagüel Formation, OP 10 sample, Neuquina Basin; 3, *Buliminella isabelleana* Camacho, 1954 forma *tuberculata*; Neuquina Basin; 4, *Favolagena atilai* (Bertels, 1964); Colonia Trapalcó borehole, Roca Formation, Neuquina Basin. Maastrichtian: 5, *Protelphidium primitivum* Náñez & Malumián, 2008; a, lateral view; b, enlargement, scale bar = 10μm; Liu Malal, Jagüel Formation, Neuquina Basin; 6, **Gen. nov.** and **sp. nov.** a, peripheral view; b, umbilical view; c, spiral view; Jagüel Formation, Neuquina Basin; 7, *Notoplanulina rakauroana* (Finlay, 1939); Pejerrey well, 1823 m; Colorado Basin off shore; 8, *Favolagena ardolinoi* Malumián, Náñez & Caramés, 1991; a, lateral view; b, enlargement basal view, La Colonia Formation; 9, *Rosalina patagonica* Náñez & Malumián, 2008; a, spiral view, b, umbilical view; Liu Malal, Jagüel Formation, Neuquina Basin; 10, *Tehuelchella caminosi* Náñez & Malumián, 2008; umbilical view; Laguna del Indio Muerto, Río Negro Province, Neuquina-Colorado Basin; 11, '*Frondicularia*' *rakauroana* (Finlay, 1939); Tiburón x-1 well, 850–60 m, Malvinas Basin. Scale bar = 1 mm; 12, *Hiltermannella kochi* (Bertels, 1970); Bajada del Jagüel, Jagüel Fm., Neuquina Basin.

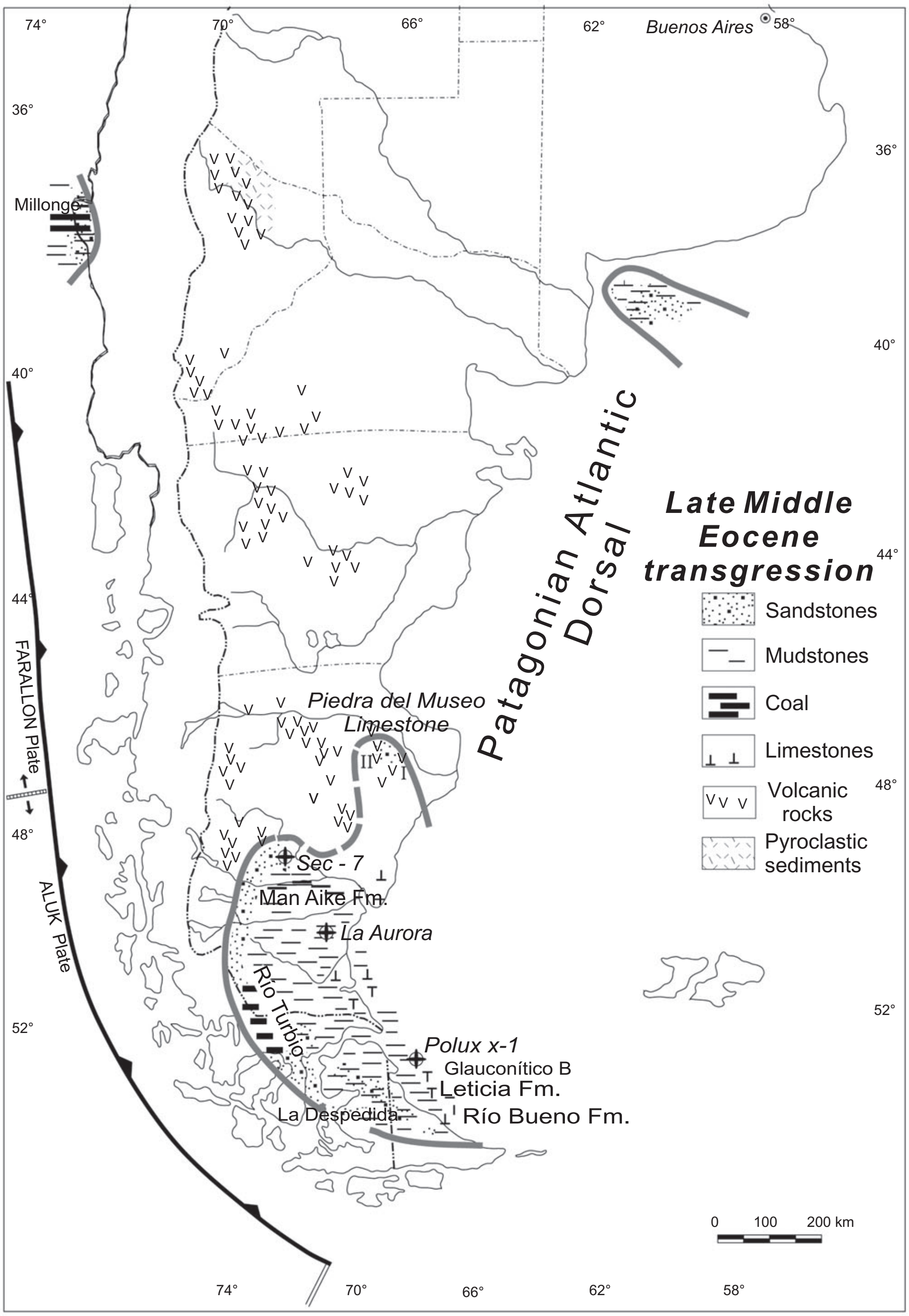


Figure 6. Late Middle Eocene transgression. After an extended non-marine and/or erosive period with the exposure of new terrestrial habitat, a minor eustatic Atlantic transgression is recorded in the late Middle Eocene in the Austral Basin and offshore of the Colorado Basin. On the Pacific side, in central Chile, there are records of planktonic thermophilic foraminifera such as the genus *Hantkenina*, and also there are records of abundant reworked marine Eocene foraminifera in upper Miocene–Pliocene sediments (Finger & Encinas, 2009).

Figure 7. Late Middle Eocene endemic and conspicuous species. All specimens from the Austral Basin. Scale bars = 100 μm, except otherwise stated. 1, *Cribrorotalia manaikense* Malumián, 1990; a, spiral view; b, peripheral view; c, detail of the spiral side. SEC-7 well, 320–325 m; 2, *Cribrorotalia* **sp. nov.**; a, peripheral view; b, umbilical view; Polux x-1 well; 3–4, *Marginulina* ex gr. *M. hochstetteri* (Stache, 1864); Leticia Formation, La Despedida section, 69 m; 5, *Marginulina* ex gr. *M. hochstetteri* (Stache, 1864); Cerro Colorado Formation, La Despedida section 533 m; 6, *Marginulina knikerae* Cañón & Ernst, 1974; Leticia Formation, La Despedida section, 69 m; 7, *Elphidium deferrariisi* Malumián, 1990; Cerro Colorado Formation, La Despedida section, 540 m; 8, *Elphidium saginatum* Finlay, 1940; La Despedida section, 242 m; 9, *Nummodiscorbis novozealandicus* Hornibrook, 1961; Cerro Colorado Formation, La Despedida section, 535–540 m; 10, *Astrononion manaikense* Malumián, 1990; Man Aike Formation, SEC-7 well, 332 m; 11, *Wellmanella kaiata* Finlay, 1947; Cerro Colorado Formation, La Despedida section, 540 m; 12, *Astrononion pseudorusticum* Malumián, 1994; Cerro Colorado Formation, La Despedida section, 533–540 m; 13, *Uvigerina manaikense* Malumián, 1994; Man Aike Formation, SEC-7 well, 332 m; 14, *Caucasina selknamia* Malumián, 1994; Cerro Colorado Formation, La Despedida section, 540 m; 15, *Chiloguembelina ototara* (Finlay, 1940); Cerro Colorado Formation, d member; 16, *Bulimina fueguina* Malumián, 1994; a, lateral view and enlargement showing pore mounds; b, apertural view; Leticia Formation, La Despedida section, 247 m; 17, *Boltovskoyella patagonica* Malumián & Masiuk, 1972; a, peripheral view; b, spiral view; c, umbilical view. SC-1 well, 571–630 m, Man Aike Formation; 18, *Boltovskoyella argentinensis* Malumián & Masiuk, 1972; a, umbilical view; b, lateral view; La Aurora well, 665–675 m.

(Hornibrook, de Brazier & Strong, 1989). This suggests that there would have been local conditions of anomalous high temperatures for the latitude (Nicolo *et al*., 2007), which are necessary to support philothermic taxa. The southern coast of South Africa, located at an estimated palaeolatitude of 48°S in the Palaeocene and at 34°S at present, bears the first Cenozoic larger foraminifera in the Late Palaeocene (McMillan, 1986). In the Northern Hemisphere, the larger foraminifera reached latitudes as high as Alaska in the Eocene (Berggren & Prothero, 1991).

The lack of larger foraminifera in the study area can be attributed to a cold current along the Patagonian Platform, well expressed during the Early Miocene, and related by Lagabrielle *et al*. (2009) to a narrowing of the Drake Passage or else to some other obstruction that could have injected cold water into the Patagonian platform, as it indicated earlier by Malumián & Náñez (1991).

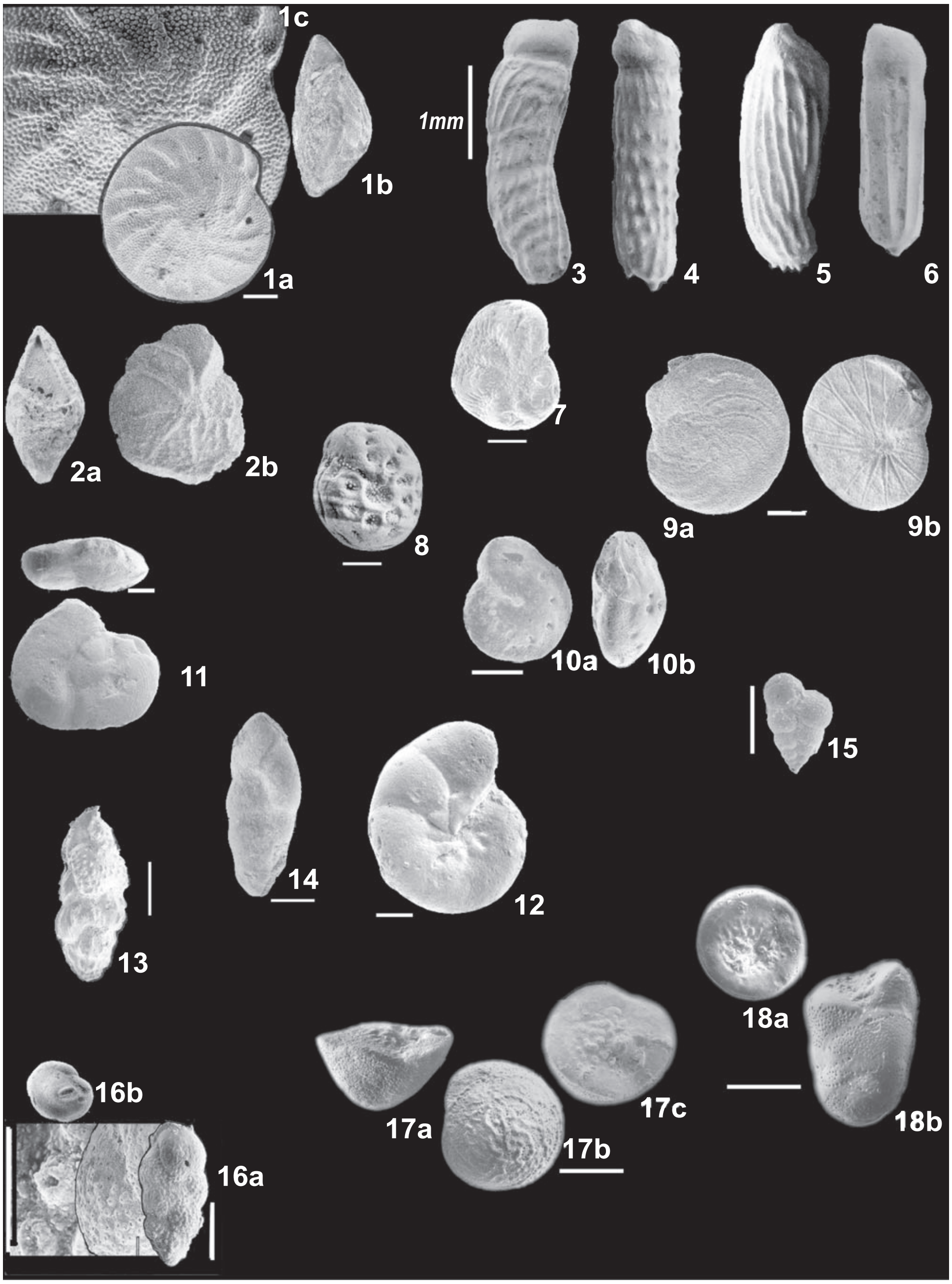
This current is not manifested during the Middle Miocene, when the existence of tropical mollusks at the Golfo San Jorge Basin was first indicated by Windhausen (1931). In the Middle Miocene, *Amphistegina*, a clear subtropical–tropical foraminiferal genus, is found in the Uruguayan coast, although it is not recorded in the Salado Basin of Argentina, where microfossil briozoa such as *Cupuladria canariensis*, considered to be of equatorial distribution, are common in subsurface samples. None one of them is recognized in the more austral Colorado Basin, thus providing evidence consistent with a clear thermal gradient (Malumián, 1999).

Assemblages from the Fuegian Andes, the active margin of the Austral Basin, show some particular features. From the Late Maastrichtian up to the Late Eocene, planktonic foraminifera are rare, suggesting some kind of isolation from the open sea (Malumián, Jannou & Náñez, 2009). A sudden deepening of the foredeep after the latest Eocene–earliest Oligocene unconformity, is clearly shown by the abundance of planktonic foraminifera (Scarpa & Malumián, 2008), indicating the end of the isolation. This deepening is a result of tectonic causes given that the Early Oligocene is a period of low global sea level.

The marine Upper Palaeocene–Lower Eocene sediments, preserved only in the Fuegian Andes, records the greatest turnover in the Cenozoic calcareous benthic foraminifera, between the Late Palaeocene cosmopolitan assemblages of the La Barca Formation (Malumián & Caramés, 2002), and the mostly endemic assemblages of the Punta Noguera Formation, of Early Eocene age, not younger than 53.39 Mya. The latter formation includes the appearance of the genera *Cribrorotalia* and discoidal *Elphidium*, and the first record of new serial planktonic foraminifera (Malumián *et al*., 2009).

Cribrorotalia becomes the most common, widespread, and typical genus of the shallow Patagonian Cenozoic palaeoenvironments, recorded up to southern Brazil during the Miocene (Malumián & Jannou, 2010). Its abundance also characterizes the shallow water assemblages of the modern southern South American Pacific coast, from Tierra del Fuego up to the Peruvian offshore. This southern distribution suggests an Antarctic origin for *Cribrorotalia*. Precisely, the Fuegian Neogene in the Irigoyen Basin, on the Atlantic coast, contains a particular assemblage of benthic foraminifera of marked Pacific aspect, including abundant *Cribrorotalia*, suggesting an Atlantic–Pacific oceans connection similar to the modern Beagle Channel (Malumián & Scarpa, 2005; Malumián & Olivero, 2005b).

Another remarkable aspect of *Cribrorotalia* is its disjointed distribution. In New Zealand, the genus



has nine species known from the Late Eocene up to the Early Miocene. In southern South America, the genus is known since the Early Eocene, and has five species but none in common with New Zealand.

Discoidal *Elphidium* includes forms difficult to separate from *Discorotalia*, a genus originally described from the Mid Tertiary of New Zealand, being the modern *Discorotalia clathrata* (Brady) a common species in southern high latitudes.

Morphologically, many of the endemic Austral foraminifera have a complete to partially tuberculate test wall, persistent retral processes, and/or complex canal systems. Among the most conspicuous genera of the Patagonian Platform and Tierra del Fuego are the extinct typical Antarctic genera *Antarcticella* and *Ammoelphidiella*, and the extant *Cribrorotalia*. *Antarcticella* was originated immediately after the Cretaceous/Palaeogene mass extinction; *Cribrorotalia*, at the Palaeocene/Eocene benthic foraminiferal turnover; the appearance of *Ammoelphidiella* is apparently associated to the Mi-1 glacial event; and the extinctions of *Antarcticella* and *Ammoelphidiella* may be related to the Pliocene optima. Thus, the

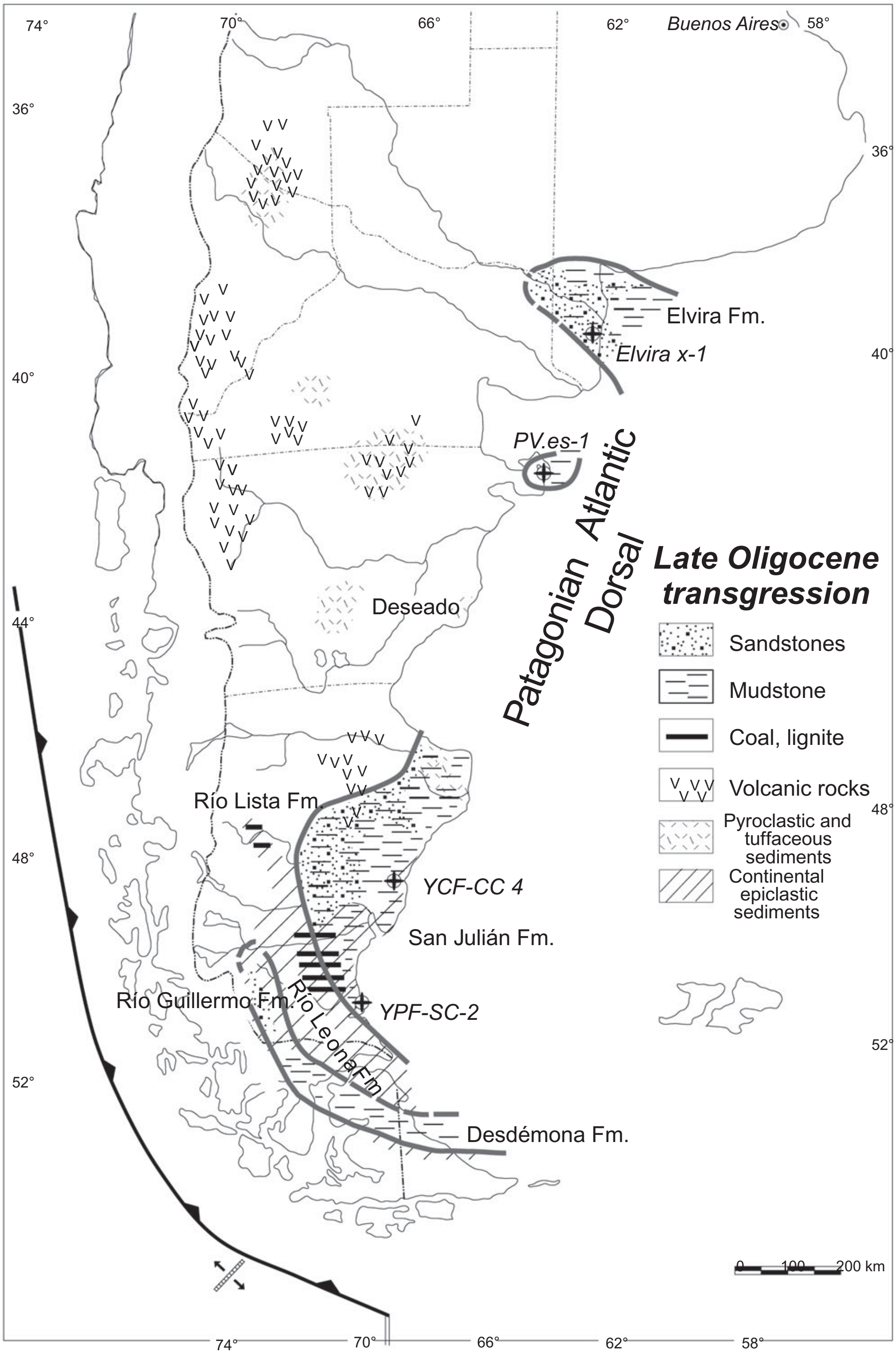


Figure 8. Late Oligocene transgression. This is another minor and very shallow transgression spatially and temporally related to extensive lignite deposits in the subsurface of the Santa Cruz Province. By contrast, it is represented by sediments deposited near the lysocline or below the Calcite Compensation Depth in the foredeep of the Fuegian Andes, where deep environments have been established since the Early Oligocene.

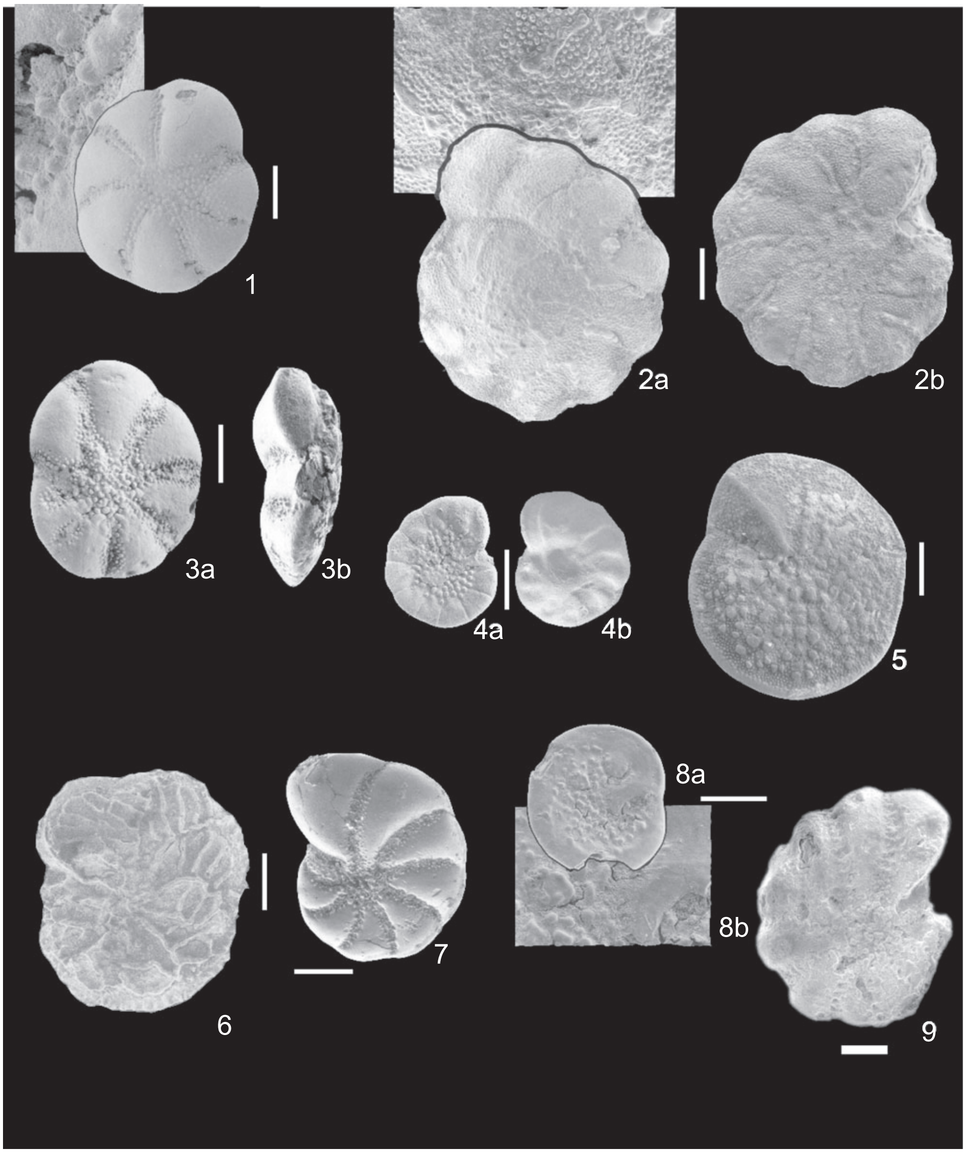


Figure 9. Late Oligocene endemic or conspicuous species. Scale bars = 100 μm, except otherwise stated. 1–8, San Julián Formation, Austral Basin (from Náñez, 1989, 1990): 1, '*Buccella*' sp. 1049; SC-2 well, 493 m; 2, *Cribrorotalia* **sp. nov.**; a, spiral view, and enlargement; b, umbilical view; SC-2 well, 449 m; 3, *Buccella* sp. 9532 cf. *B. lotella* Hornibrook, 1961; Gran Bajo de San Julián, sample 123; 4, *Pileolina* **sp. nov.**; a, umbilical view; b, spiral view; RSC-1 well, 427–429 m; 5, *Cribrorotalia hornibrooki* Malumián & Masiuk, 1971, f. *typica*, *sensu* Bertels (1979); SC-2 well, 497–499 m; 6, *Discorotalia* sp.; Gran Bajo de San Julián, sample 135; 7, *Nonion* cf. *depressulus* (Walker & Jacob, 1798); RSC-1 well, 413–415 m; 8, '*Discorbis*' *malovensis* Heron-Allen & Earland, 1923; RSC-1 well, 415–417 m. Elvira Formation, Colorado Basin: 9, *Elphidium* **sp. nov.**; Elvira 1 well, 762–64 m.

origin of these three conspicuous Austral genera appears to be strongly related to major global events, whereas their extinctions apparently occurred in association with minor climatic optima.

The migration of the thermophilic biota to high latitudes and the evolutionary turnover caused by the climatic optimum of the Palaeocene/Eocene transition, the Early Eocene warm period, and the global cooling from the end of the Early Eocene up to the early Middle Eocene (Fig. 13), have occurred in a scenario of expanded terrestrial environments as a result of a major regression taking place from the Late Palaeocene up to the early Middle Eocene. A minor Atlantic transgression is recorded in the Austral Basin and offshore of the Colorado Basin after an extended non-marine and/or erosive period in the late Middle Eocene. This eustatic transgression, clearly recognized in the southern Australian shelf, is

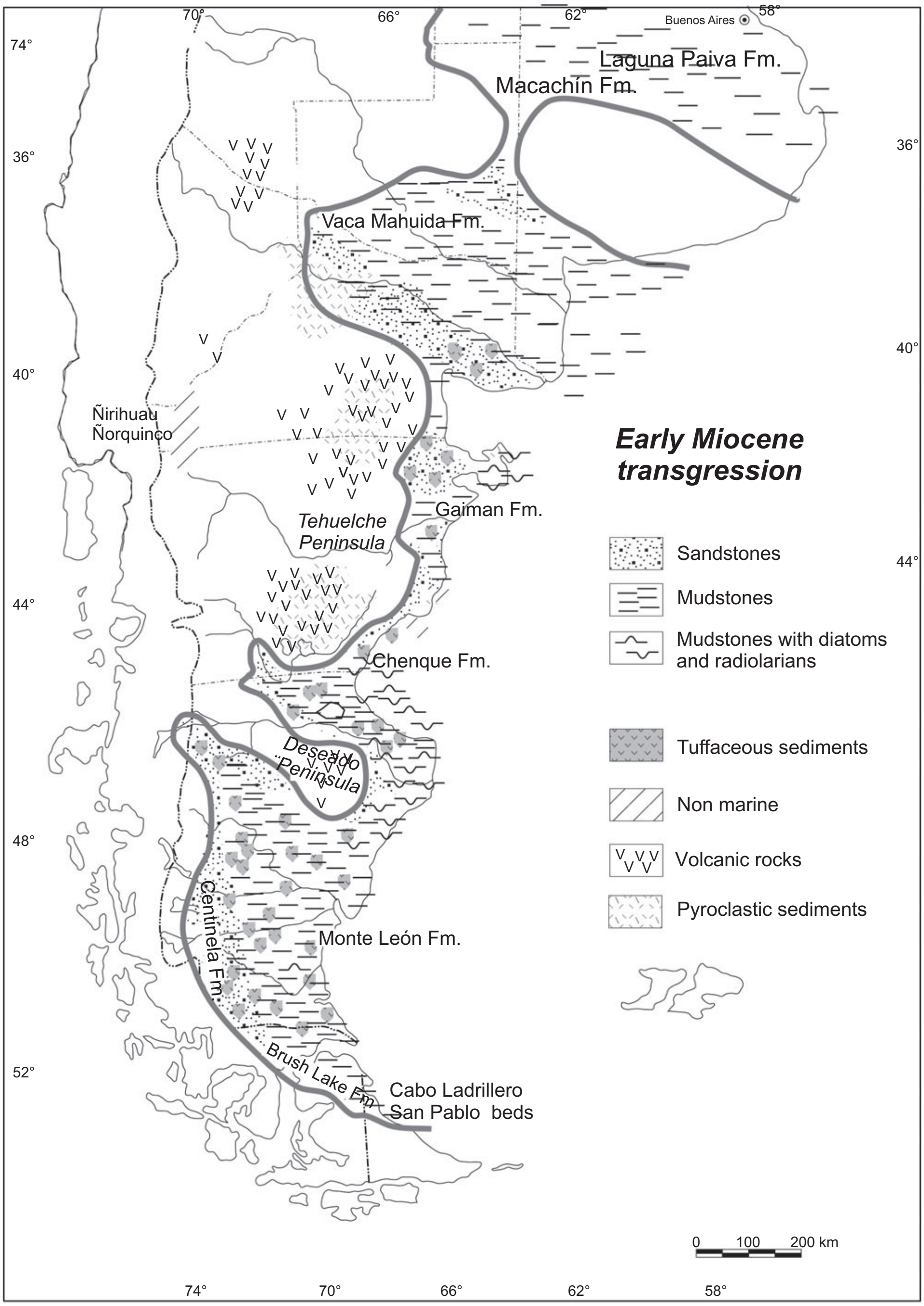


Figure 10. The Early Miocene transgression, the second transgression in magnitude, is characterized by extensive very shallow water tuffaceous deposits, barren or of very poor foraminiferal content in Patagonia; and contrasting foredeep deposits below the calcite compensation depth, in the Fuegian Andes. A Pacific transgression in the Northern Patagonian Andes is recorded by Early Miocene foraminifera in the Argentine Río Foyel Formation, common to the foraminifera of the Chilean Temuco and Catamutún basins but in disagreement with isotopic ages (Asensio *et al*., 2010; Ramos & Bechis, 2010).

coeval with a relative optimum and the influx of shallow Pacific sea water as a result of a connection forerunner of the Drake Passage, based on the Neodymium isotope ratios (Scher & Martin, 2006).

GENERAL CONCLUSIONS

The first transgression from the Atlantic Ocean over Patagonia occurred in Maastrichtian times, giving

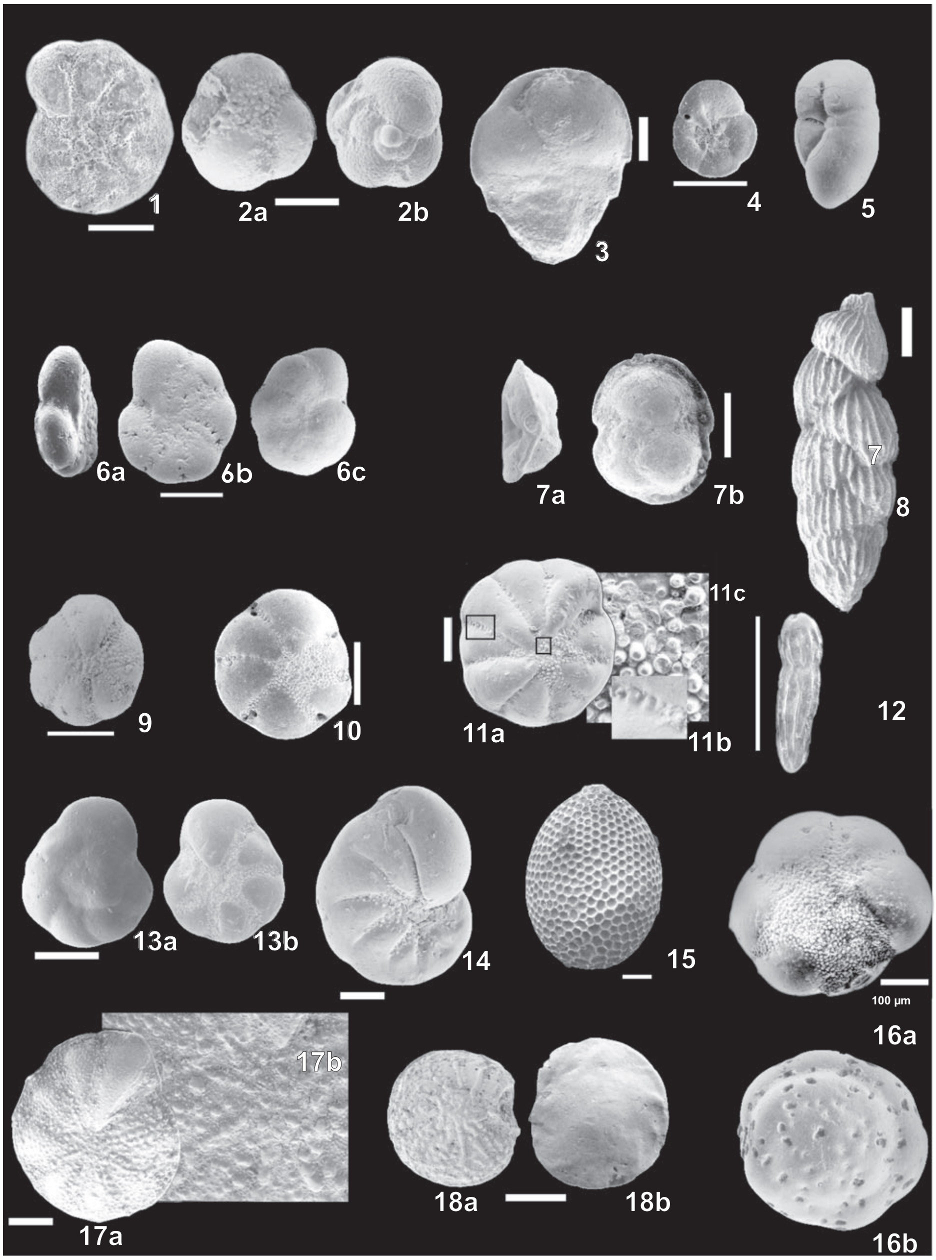


Figure 11. Miocene endemic and conspicuous species. Bars equal 100 µm, except otherwise stated. Middle Miocene: 1, *Protelphidium tuberculatum* (d'Orbigny, 1846); Barranca Final Formation, Colorado Basin; 5, *Robertinoides australis* Malumián 1982; Carmen Silva Formation, Austral Basin; 9, *Buccella* sp.; Carmen Silva Formation, Austral Basin. Early Miocene, Monte León Formation, Austral Basin, from Náñez (1989, 1990) except otherwise indicated: 2, *Antarcticella antarctica* (Leckie & Webb, 1990); a, umbilical view, Island of Tierra del Fuego; b, spiral view, CB es-6 well, 610–620 m; 3, *Ehrenbergina glabra* Heron-Allen & Earland, 1922; CB es-6 well, 610–620 m; 4, *Biapertorbis* sp.; umbilical view, Cte. Piedra Buena (LP 2); 6, *Ammoelphidiella* **sp. nov.** 9551; a, peripheral view; b, umbilical view; c, spiral view; Cañadón Pallán (CP 2); 7, '*Discorbis*' sp. cf. *D. tricamerata* Heron-Allen & Earland, 1932; a, peripheral view; b, spiral view, LP 2; 8, *Uvigerina bifurcata* d'Orbigny, 1839; SC-2 well, 381 m; 10, *Buccella peruviana* (d'Orbigny) f. *carinata*; LP 2; 11, '*Buccella*' sp. 9544; a, umbilical view, b and c, enlargement showing small ponticulus on the ventral sutures; R es-1 well, 270–280 m; 12, *Transversigerina tenua* (Cushman & Kleinpell, 1934); Golfo San Jorge Basin, Chenque Formation, scale bar = 1 mm; 13, *Buccella* sp. 923; a, spiral view; b, umbilical view; LP 2; 14, *Nonion* sp.; R es-1 well, 270–280 m; 15, *Favolagena digitalis* (Heron-Allen & Earland, 1932); Cabo Blanco 4 well, 6.86–7.05 m; 16, *Ammoelphidiella* **sp. nov.**; a, umbilical view; b, intensely bored spiral view; RC-4 well, 415 m; 17, *Cribrorotalia hornibrooki* Malumián & Masiuk, 1971, forma *planoconvexa*; CP 2; 18, *Cribrorotalia meridionalis* (Cushman & Kellet, 1929); a, umbilical view; b, spiral view, R es-1 well, 140–150 m.

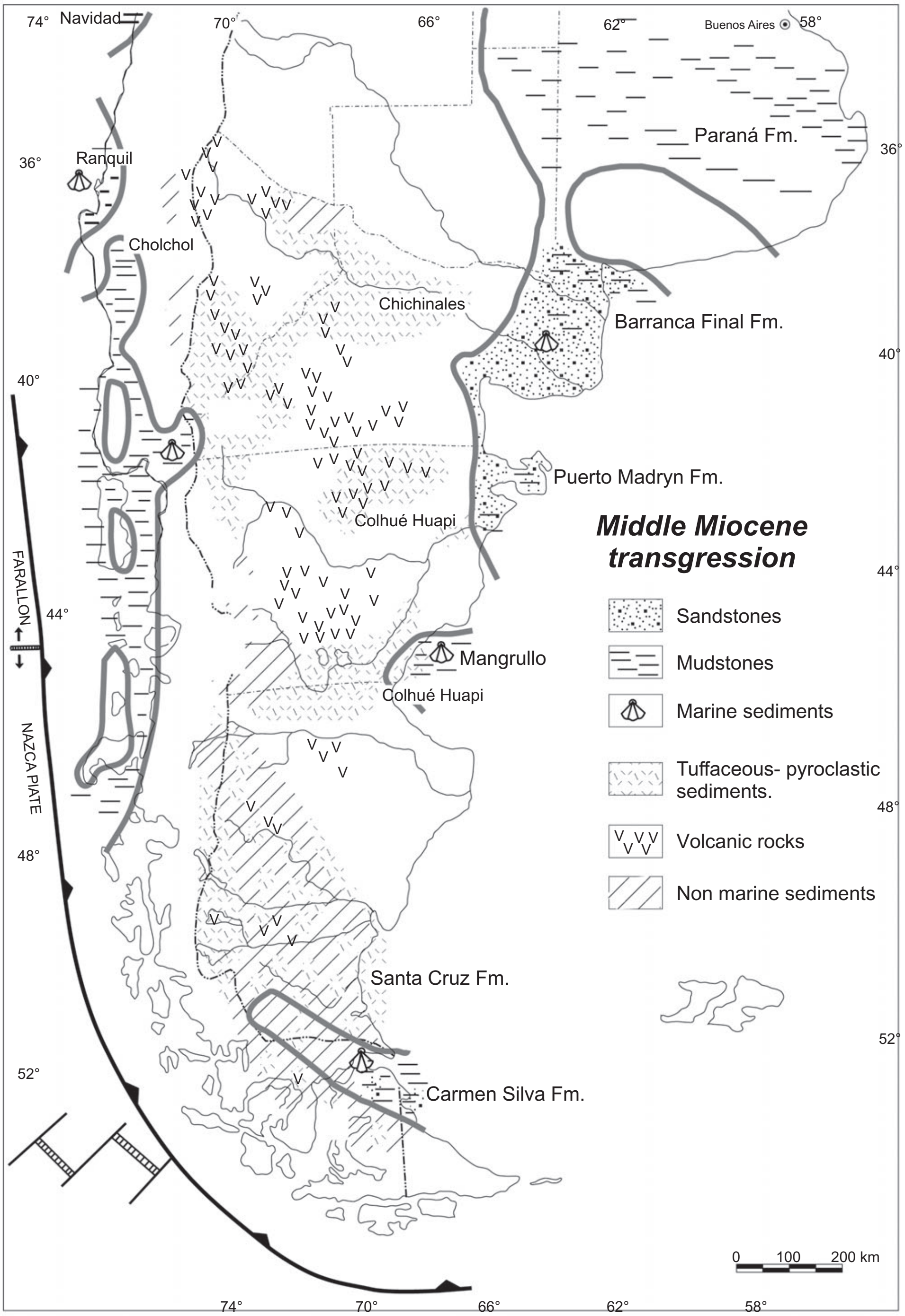


Figure 12. Middle Miocene transgression. On the Pacific side, reworked foraminifera found in Neogene sediments, indicate the existence of marine Palaeogene.

origin to the Patagonian Platform. Subsequently, several ephemeral Atlantic transgressions flooded Patagonia forerunning the modern Argentine continental shelf. Main transgressions occurred in the Maastrichtian–Danian, in the late Middle Eocene, the Late Oligocene, the Early Miocene, and the Middle Miocene. By contrast, the more prolonged permanence of the sea in the Fuegian Andes area is testified by an almost complete marine Upper Cretaceous–Middle Miocene column.

In each transgression, a shallow and extended sea covered Patagonia, carrying foraminiferal assem-

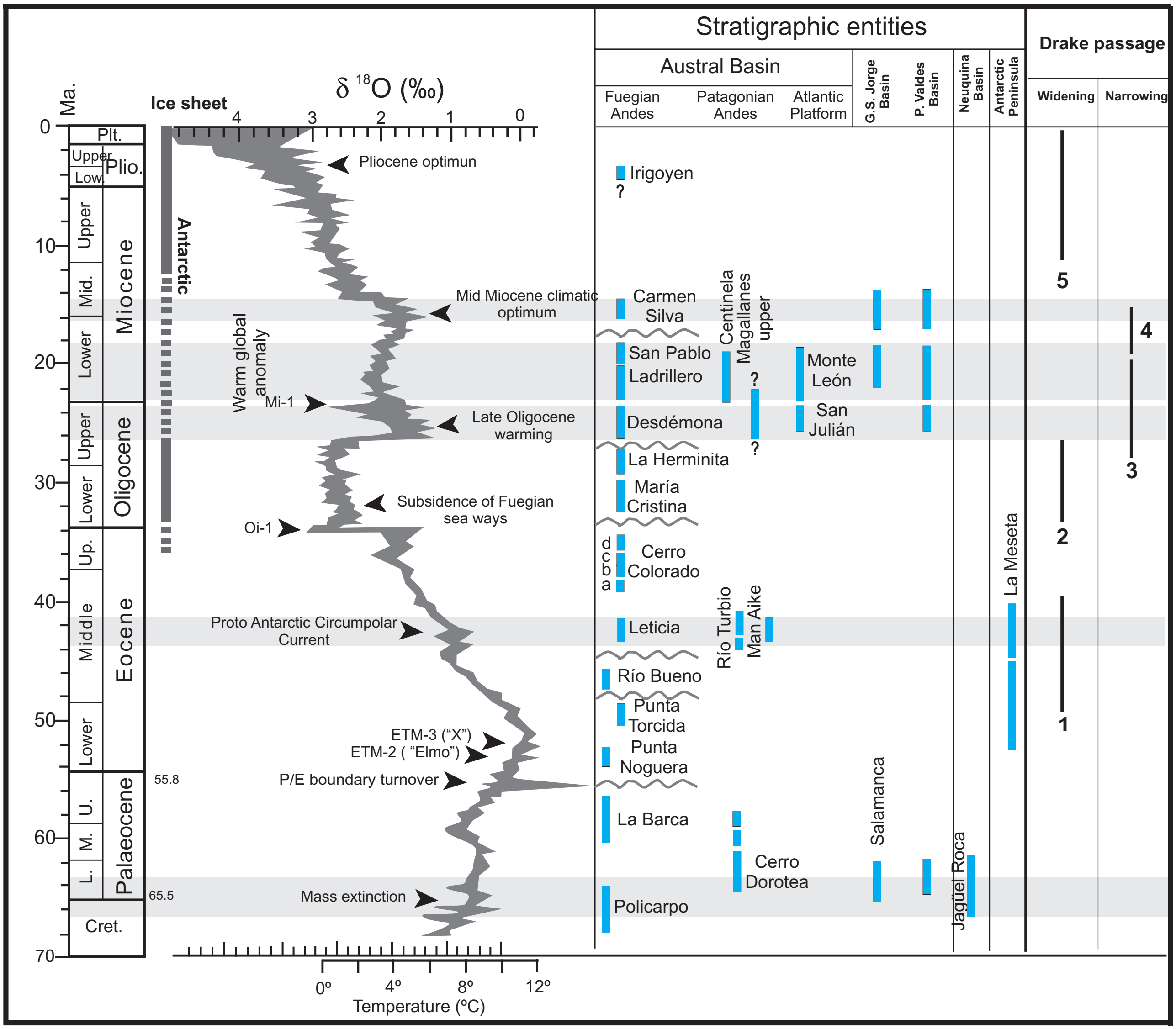


Figure 13. Relationship among transgressions, temperature and most relevant formations; *sensu* Zachos *et al*. (2001), Lagabrielle *et al*. (2009), and Malumián & Jannou (2010). Dark grey bands correspond to transgression periods.

blages of peculiar palaeoecological and biogeographical features. A major and common feature to all of these transgressions is given by the extraordinarily wide Patagonian Platform, which acted as a filter for planktonic foraminifera, typical of open ocean environments, and, at the same time, promoted the endemism of the benthic foraminiferal assemblages.

The Maastrichtian transgression, the largest in flooded surface, carried mainly calcareous foraminiferal benthic assemblages, including several and frequent endemic taxa. Most of them disappeared in the Cretaceous–Palaeogene transition. The Palaeocene sea carries the extinct cosmopolitan Midway type assemblage with few endemic taxa such as *B. isabelleana*, and the genera *Antarcticella* and *Boltovskoyella*. In northern Patagonia, a warm and arid climate is reflected in the ornamentation of *B. isabelleana*, and the record of miliolids suggests an anti-estuarine circulation; whereas, in the Austral Basin, the record of coal seams and the absence of miliolid foraminifera suggest hyposaline waters and an estuarine circulation.

The Palaeocene/Eocene turnover (an event known to have profoundly affected deep-sea benthic foraminifera from tropical areas) is also noticed in the shallow and extratropical environments of the Fuegian Andes, giving room to Eocene shallow assemblages of modern and marked Austral aspect: Elphidiidae are dominant, and include genera endemic to high and mid-high southern latitudes such as *Cribrorotalia*.

The late Middle Eocene transgression is of reduced extension, without records of marine sediments in the Golfo San Jorge Basin, where continental sediments were deposited. Instead, the transgression flooded the Austral Basin, where it is related to coal measures reflecting an associated humid climate. These conditions, together with the abundance of ostracods, indicate an estuarine circulation for this basin.

In Patagonia, the Late Oligocene transgression is of limited extension and shallow waters, carrying abundant *Buccella* spp. and the conspicuous genus *Discorotalia*. It is partially coeval with the extended and lignite-rich Río Leona Formation. The Early Miocene transgression, in its early stage, is characterized by the *Spirosigmoilinella–Martinottiella* assemblage, a residual assemblage of mainly agglutinated foraminifera with occasional solution-resistant calcareous tests, which is recorded up to the Colorado Basin and reveals the existence of a cool water current. This northward current has dispersed the extinct and typical Antarctic genera *Ammoelphidiella* and *Antarcticella*; the first one up to the Colorado Basin, and the second up to the Península Valdés Basin. In a later and widely represented stage, the Early Miocene transgression witnesses the origin of the modern Patagonian coastal assemblage, characterized by its pauperism and the dominance of the genus *Buccella*. The Middle Miocene transgression covers mainly northern Argentina. These three transgressions are clustered and their sediments separated mostly by ravinement surfaces. Thus, they could be considered as pulses of a major transgression, despite the fact that they possess distinctive foraminiferal assemblages.

By marked contrast to Patagonia, in the Fuegian Andes, the marine conditions remained continuously from the Maastrichtian up to the Middle Miocene. Their foraminiferal assemblages are mainly of flysch-type, characteristic of turbiditic and/or below compensation calcite depth, and tectonically active settings. However, Maastrichtian–Late Eocene planktonic foraminifera are scarce or absent, suggesting restricted and/or relatively shallow settings. From the Early Oligocene up to the Early Miocene, deep and below compensation calcite depth environments become dominant; thus, planktonic foraminifera are abundant and of large size, whenever they escape dissolution conditions.

Considering that the late Middle Eocene and Middle Miocene transgressions are coeval with relative climatic optima, and in comparison with assemblages at similar palaeolatitudes elsewhere in the Southern Hemisphere, the absence of larger foraminifera or another thermophilic foraminifera in the Patagonian and Fuegian assemblages is outstanding. This absence may be related to a cold current moving along Patagonia and, together with the occurrence of several taxa in common to New Zealand and Antarctica, it gives, in general, an Austral character to the Patagonian–Fuegian assemblages and, in particular, an Antarctic character to the Fuegian assemblages.

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