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Review

A review of Tertiary climate changes in southern South America and the Antarctic Peninsula. Part 2: continental conditions

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ABSTRACT

Climate changes in southern South America and the Antarctic Peninsula during the Tertiary show a strong correlation with ocean warming and cooling events, which are in turn related to tectonic processes. During periods of accelerated sea-floor spreading and mid-ocean ridge activity, sea-levels rose so that parts of the continents were flooded and forests were destroyed. However, this was balanced by the large-scale release of CO_2 during volcanic outgassing and carbonate precipitation on the continental shelves, which caused rising air temperatures and the poleward expansion of (sub)tropical and temperate forests. Cooling episodes generally caused an increase in the north–south thermal gradient because of an equatorward shift in climate belts, so that the Westerly Winds intensified and brought higher rainfall to the lower latitudes. An increase in wind-blown dust caused temperatures to drop further by reflecting sunlight back into space.

The rising Andes Range had a marked influence on climate patterns. Up to the middle Miocene it was still low enough to allow summer rainfall to reach central and north-central Chile, but after about 14 Ma it rose rapidly and effectively blocked the spill-over of moisture from the Atlantic Ocean and Amazon Basin. At this time, the cold Humboldt Current was also established, which together with the Andes helped to create the "Arid Diagonal" of southern South America stretching from the Atacama Desert to the dry steppes of Patagonia. This caused the withdrawal of subtropical forests to south-central Chile and the expansion of sclerophytic vegetation to central Chile. However, at the same time it intercepted more rain from the north-east, causing the effect of the South American monsoon to intensify in northwestern Argentina and southern Bolivia, where forest communities presently occur.

In Patagonia, glaciation started as early as 10.5 Ma, but by 7 Ma had become a prominent feature of the landscape and continued apparently uninterruptedly into the Pleistocene. The Antarctic Peninsula saw its first mountain glaciation between 45 and 41 Ma, with major ice sheet expansion commencing at about 34 Ma. Isolated stands of *Nothofagus* forests were still present in low-lying areas, suggesting that the glaciers were initially wet-based, but dry-based glaciers were established at around 8 Ma. Although temperatures rose briefly during the Messinian–Pliocene transition, causing sub-Antarctic flora to retreat to higher elevations of the Transantarctic Mountains, the present cold polar conditions were finally established by about 3 Ma.

1. Introduction

Climate changes, whether global or caused by regional events such as tectonic uplift, have a profound influence on all forms of life. Organisms are either forced to adapt to the changing environment, migrate to a more favorable habitat, or become extinct. All these alternative responses are recorded in the stratigraphic and sedimentary records, which can thus be used to reconstruct climate variations through time in any particular region. Shifting trends in the distribution and nature of flora and fauna constitute an important tool to track global events such as continental drift, the evolution of mountain ranges, sea-level oscillations, or changing ocean circulation patterns.

This paper focuses on continental conditions in the southern part of South America (SSA) and the Antarctic Peninsula (AP), with the aim to investigate the causes of climate changes in these subcontinents during the Tertiary. A second objective is to provide core information (within the wider context of SSA and the AP) to climate researchers working in particular areas and chronostratigraphic units. For this reason, the discussion is according to regions, which are defined by the present topography and climatic conditions rather than political or administrative subdivisions.

Lengthwise, SSA is divided by the Andean Range, which forms a natural frontier between Chile to the west and southern Bolivia, Paraguay, Uruguay and Argentina to the east (Fig. 1), except in the southernmost part where Chilean territory extends across the Patagonian Andes. Chile has been divided into northern Chile, north-central Chile, central Chile, south-central Chile, and southern Chile, all of these regions lying west of the Andes drainage divide. Southern

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Fig. 1. Topography of SSA showing main features mentioned in text.

Bolivia has a similar topography, climate and vegetation to that of north-western Argentina and is therefore discussed together with the latter, whereas northern Argentina and Paraguay also share the same topographic, climatic and botanical characteristics. North-eastern Argentina, in turn, is grouped with southern Brazil. The rest of Argentina north of 40°S is divided into central Argentina (dry pampas) and eastern Argentina (wet pampas), the latter extending into Uruguay. Chilean and Argentinean Patagonia are combined in what is here simply referred to as Patagonia, which lies entirely east of the Patagonian Andes watershed. The AP and neighboring islands such as the South Shetlands are also discussed as an entity. In total, 12 regions are thus described (Fig. 2a).

2. Present continental climate and vegetation

A generalized map of present vegetation patterns in SSA and the AP is presented in Fig. 2b.

2.1. Northern Chile (18°–27°S)

Except for the north-easternmost highland area bordering Bolivia, which is the only part of Chile that receives tropical summer rain, the northern third of the country is occupied by the Atacama Desert (Figs. 2, 3a). This region, locally known as Norte Grande, owes its present hyper-aridity to a combination of three factors: The presence of the semi-permanent South Pacific Anticyclone (SPA), which prevents the northward displacement of the rain-bringing South-westerly Wind Belt (SWWB); the rain-shadow effect of the Andean Range blocking the inflow of tropical or subtropical moisture from the east; and the generation of a temperature inversion at about 1000 m a.s.l. by the cold, north-flowing Humboldt Current (HC) that hinders the inland penetration of Pacific moisture over the coastal escarpment (Latorre et al., 2007). As a result, parts of the Atacama Desert receive hardly any rainfall at all. However, because the influence of the SPA is restricted to lower levels of the atmosphere, low-pressure cells originating in the SWWB cause occasional precipitation in the high Andes as far north as the Bolivian Altiplano. In this area, the collision of these cold, polar fronts with warm, tropical air masses of the Intertropical Convergence Zone (ITCZ) from the north-east can cause heavy precipitation events (Rutlland and Fuenzalida, 1991). Melting snow and glaciers on the high Andes provide underground water to the deep valleys or "quebradas" that cross the desert to the coast (Fig. 3a), supporting trees such as *Prosopis tamarugo* and *Prosopis pallida*. Mean annual temperatures at sea level in this region are about 19 °C (Miller, 1976).

2.2. North-central Chile (27°–31°S)

North-central Chile (Norte Chico) has a semi-arid, transitional climate between that of the hyper-arid northern and Mediterranean central Chile, with a mean annual temperature of about 15 °C at La Serena (Fig. 4). The mean annual rainfall averages between 30 and 100 mm, supporting mostly xerophytic shrubland and cactus species (Fig. 3b), with the exception of isolated stands of *Aextoxicon punctatum* (olivillo) forests receiving moisture from the frequent coastal fog or "camanchaca". During wet years, however, flowering bulbs and herbs transform the semi-desert into a colorful spectacle. The blocking effect of the SPA here causes occasional winter droughts that become more frequent toward the north (Van Husen, 1967). This system is strongly affected by El Niño-Southern Oscillation (ENSO) events (Aceituno, 1988; Holmgren et al., 2001). El Niño years are characterized by a decrease in the upwelling of cool ocean water along the west coast of South America associated with a weakening of the SPA, allowing the northward displacement of SWWB cold fronts and causing heavy winter rainfall events in the area. The opposite occurs during La Niña episodes.

2.3. Central Chile (31°–37°S)

Central Chile lies between the SPA and the SWWB. This region has a Mediterranean climate with an annual rainfall increasing from about 200 mm in the north to 700 mm in the south (Rundel, 1981). The mean annual temperature in Santiago (Fig. 4) is 13.5 °C. The vegetation varies from dry xerophytic thorn scrub dominated by deciduous shrubs and succulents (e.g. *Trevoa trinervis*, *Flourensia thurifera* and *Colliguaja odorifera*), to mixed subtropical, sclerophyllous forest or woodland (matorral), with species such as *Cryptocarya alba*, *Lithrea caustica*, and the Chilean wine palm *Jubaea chilensis* (Fig. 3c), extending from the coastal areas to the Andean foothills. Andean tundra occurs on the high cordillera. During summer, the SPA prevents the SWWB frontal systems from affecting the area so that very little precipitation occurs, but in winter it weakens and shifts northward allowing the influx of moist ocean air. The rain-shadow effect of the Coastal Range (Ramírez et al., 1990) causes a decrease in rainfall from about 460 mm at the coast to 360 mm in Santiago.

2.4. South-central Chile (37°–42°S)

The northern limit of this region is formed by the average northern summer extent of the SWWB, so that the area receives rain throughout the year. The mean annual precipitation increases from about 700 mm in the north to nearly 2000 mm at Puerto Montt (Fig. 4), which has an average yearly temperature of 11.4 °C (Schwerdtfeger, 1976). The modern vegetation is characterized by temperate forests, including mixed deciduous and temperate beech (*Nothofagus*) forests in the north, while Valdivian rain forests extend from Valdivia and Osorno south to Chiloé Island (Heusser, 1990). The Andes Range in this region is mainly characterized by broad-leaved, mixed *Nothofagus* and *Araucaria* forests (Fig. 3d).

2.5. Southern Chile (42°–56°S)

Southern Chile in this paper refers to the area west of the Patagonian Andes watershed and south of 42°S, which is under the influence of the

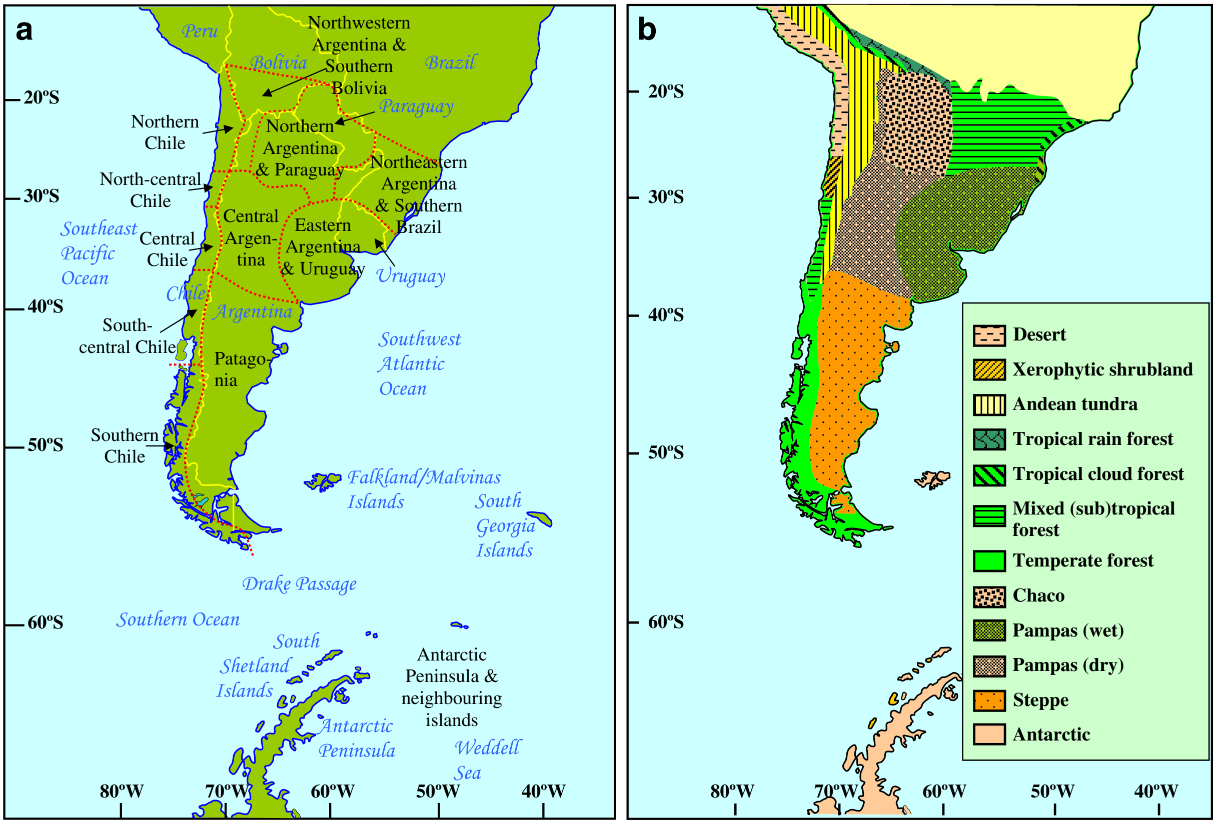

Fig. 2. a) Regional subdivision of SSA and the AP as discussed in text, based mainly on modern climate and vegetation zones. b) Present distribution of vegetation types in SSA and the AP. Modified from *The Edinburgh Atlas*, 1957, J. Bartholomew, Oxford University Press.

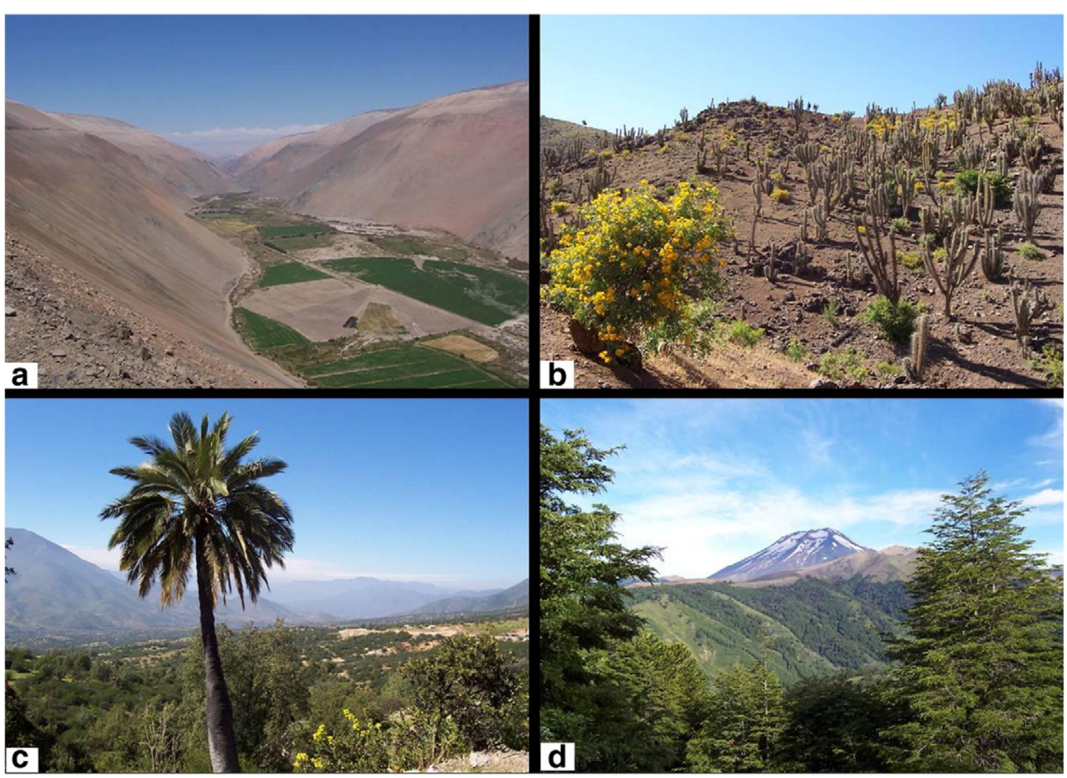

Fig. 3. a) Deep valley (locally known as a "quebrada") crossing the Atacama Desert from east to west; b) typical shrub-land and cactus vegetation in north-central Chile; c) subtropical woodland in central Chile with *Jubaea chilensis* (Chilean wine palm) in foreground; d) mixed deciduous forest of *Nothofagus* and *Araucariaceae* in south-central Chile.

Fig. 4. Main localities mentioned in text.

SWWB throughout the year. Geographically and politically most of this area lies within Chilean Patagonia, but its climate is markedly different from that east of the Patagonian Andes, being cold–temperate with a mean annual temperature of 5°–9 °C and much higher rainfall.

The Chiloé Archipelago (Fig. 1) presently has a mean annual temperature of about 11 °C and rainfall varying between 2000 and 3000 mm/yr (Schwerdtfeger, 1976). The temperate forests characterizing this area (Fig. 5a) are controlled by the latitude and local elevation above sea-level. Valdivian rain forest occurs up to about 200–250 m a.s.l., containing species such as *Eucryphia cordifolia*, *Amomyrtus meli*, *Nothofagus dombeyi*, and *Myrceugenia planipes*. These are replaced by north Patagonian rain forest species (e.g. *Laurelia philippiana*, *Myrceugenia ovata* and *Myrceugenia planipes*) between 350 and 450 m a.s.l. Above 600 m a.s.l., sub-Antarctic rain forest dominated by *Nothofagus betuloides*, *Nothofagus nitida* and other species including *Pilgerodendron uviferum* and *Podocarpus nubigena* occur together with sub-Antarctic Magellanic moorland, characterized by cushion bogs such as *Donatia fascicularis* and *Astelia pumila* (Heusser, 1990; Heusser et al., 1995).

At about 48°S the SWWB reaches its greatest strength, causing oceanic conditions that are excessively cloudy and wet, precipitation reaching 8500 mm or more at the coast and decreasing from here toward the north and south (Schwerdtfeger, 1976). Vegetation is characterized by sub-Antarctic rain forest where precipitation exceeds 800 mm. Further south, on the islands and along the coast, the forest is reduced to patches and bands of small trees and shrubs occupying protected slopes at less than 300 m a.s.l. The dominant vegetation is sub-Antarctic Magellanic moorland or Magellanic tundra. Most of the moorland consists of dwarf shrubs, wind-sheared trees, cushion plants (Fig. 5b), grasses and mosses. In more sheltered areas, small stands of *Nothofagus betuloides*, *Drimys winteri*, *Lepidothamnus fonkii*, and *Pilgerodendron uviferum* occur. Magellanic tundra occupies elevations above 600 m a.s.l., being composed of cushion-forming plants and tufted perennials such as *Bolax* and *Astelia* species (Heusser, 1995).

2.6. North-western Argentina and southern Bolivia (18°–27°S)

North-western Argentina, which includes the high Andes or Puna and its eastern foothills down to about 27°S, is generally characterized by an arid climate and large interannual variations in precipitation. While violent thunderstorms can occur in summer, the winters are cold and occasionally affected by the Zonda, a hot dry wind blowing from the west. In the northwestern part of this region, which extends into Bolivia, three forest communities belonging to the Yunga Province occur (Sirombra and Mesa, 2010). The transition forest is a microphyllous, monsoon forest occupying a discontinuous zone along the foot of the Andes, where the annual precipitation varies from 700 to 1000 mm. This community is typified by *Calycophyllum rhamnoides* and *Calycophyllum multiflorum*. The montane forest forms a more or less continuous strip between the transition forest and an elevation of about 1600 m, where precipitation may exceed 2500 mm. Typical trees are *Phoebe porphyria* and *Blepharocalyx gigantea,* with lianas, ferns, and epiphytes very abundant. The montane woodland occurs above 1600 m and consists of deciduous alder woodland with *Alnus*, and pine woodland with *Podocarpus parlatorei*. Above these woodland and forest systems are Andean grasslands or meadows with dicotyledonous herbs. These grasslands extend up to 3000 m, including typical taxa such as *Festuca hieronymi* and *Stipa tucumana*. The Altiplano in southern Bolivia and the equivalent Puna in northwestern Argentina are characterized by arid to semi-arid grassland with salt-flats occupying closed basins.

2.7. Northern Argentina and Paraguay (20°–31°S)

This relatively low-lying region, extending from Paraguay to about 31°S in Argentina, is known in both countries as the Chaco. It has a subtropical, continental climate with mild, fairly dry winters and humid, hot summers, the rainfall decreasing from about 1200 mm in the east to 200 mm in the west. A diverse array of vegetation includes xerophytic deciduous woodland, thornscrub, bushy and grass steppe, and savannas (Bucher, 1982). Characteristic genera include *Acacia, Larrea, Lithraea*, *Aspidosperma*, and *Zizyphus*. Large areas are also covered by lakes and swamps, especially after widespread flooding in summer.

2.8. North-eastern Argentina and southern Brazil (20°–34°S)

North-eastern Argentina lies east of the Paraná River (Fig. 1) and north of about 34°S. This region has a tropical climate, receiving more than 800 mm of rainfall per year. Winds are predominantly from the north, north-east and east. The temperature range is low and few night frosts occur in winter. The area has Brazilian biota with tropical genera such as *Dalbergia* (rosewood) and *Jacaranda* (Cabrera, 1976).

2.9. Central Argentina (27°–40°S)

Central Argentina includes western Buenos Aires Province and adjacent portions of the Santa Fe, Córdoba, and La Pampa Provinces (Figs. 2, 4). This region is semi-arid to arid with an annual precipitation of about 700 mm. Summer rainfall is torrential but scarce, whereas the winter season is long and dry. Mean annual temperatures are around 15–18 °C. Known as the dry pampas (Fig. 1), grass steppe is the principal variety of indigenous vegetation and trees are practically nonexistent. *Stipa* species such as *Stipa tenuissima*, *Stipa tricótoma*, and *Stipa filiculmis* are common, with some shrubs such as *Discaria longispina* also present (Anderson et al., 1970).

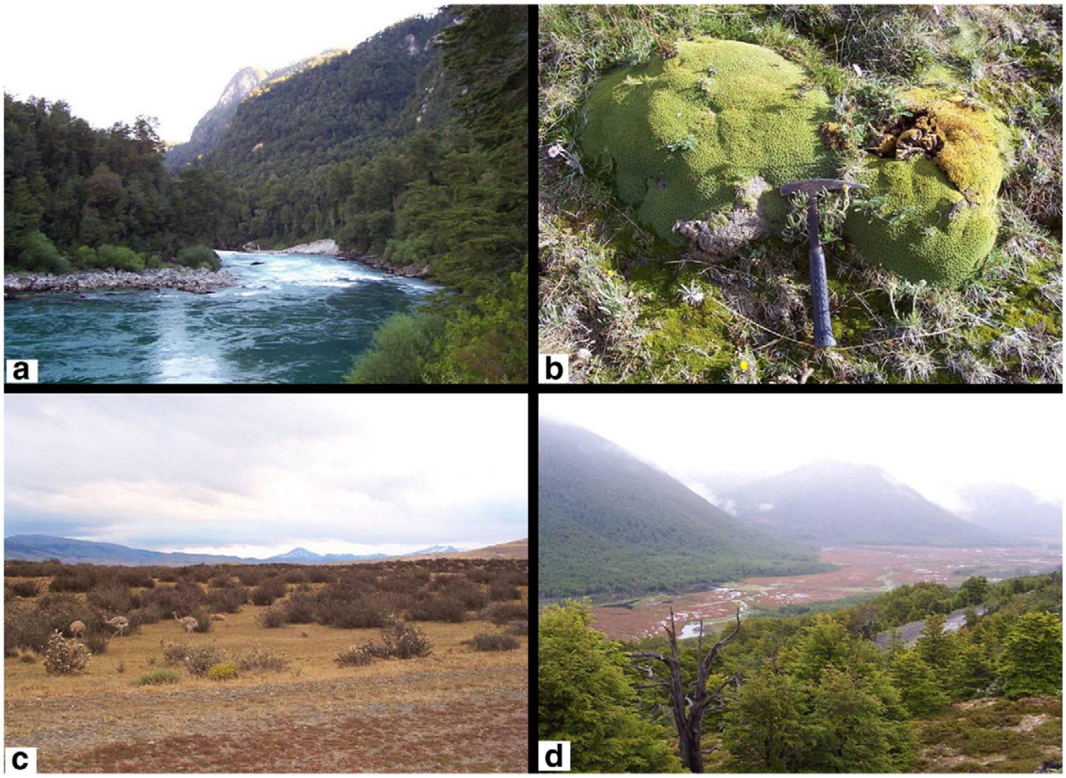

Fig. 5. a) Temperate forest in southern Chile; b) cushion plant of sub-Antarctic Magellanic moorland; c) bush and grass steppe east of Southern Patagonian Ice Fields; d) Magellanic woodlands in southern part of Tierra del Fuego.

2.10. Eastern Argentina and Uruguay (30°–40°S)

This region includes the Uruguayan savanna, which encompasses all of Uruguay and the southern portion of Brazil, and the wet pampas of eastern Buenos Aires and southern Entre Ríos Provinces (Figs. 1, 2). It has a generally mild climate with a precipitation of 600–1200 mm, more or less evenly distributed throughout the year. Winters are cool to mild and summers very warm and humid. The annual rainfall is heaviest near the coast, decreasing gradually further inland. Rain during the late spring and summer usually arrives in the form of brief, heavy showers and thunderstorms. More general rainfall occurs during the remainder of the year as cold fronts. The area is affected by the Sudestada, a cold southeasterly wind associated with the SPA that brings very heavy rains and flooding in late autumn and winter along the central coast and in the Río de la Plata Estuary (Fig. 1). The dominant vegetation types are grass prairie and steppe in which the genera *Stipa* and *Cortaderia* are particularly common (Cabrera, 1976).

2.11. Patagonia (37°–56°S)

There is no consensus on the geographic limits of Patagonia, especially between the two countries that share this region. Argentinean Patagonia is generally considered to lie south of the Colorado or Río Negro Rivers (Fig. 1), which flow into the Atlantic Ocean at about 40°S. The Pacific seaboard south of about 42° is commonly included in Chilean Patagonia, but excluding Chiloé Island that extends to below 43°S. In this paper, however, Patagonia is defined as the area south of 37°S and east of the Patagonian Andes watershed (Fig. 2a). The northern part of the region is semi-arid to arid with annual mean temperatures of about 15 °C and precipitation decreasing from 500 mm at Bahía Blanca in the northeast to 250 mm southwest of General Conesa (Fig. 4). The rainfall, with maxima during spring and autumn, relates to the seasonally varying influence of the SWWB and SAA (Schäbitz, 1994), whereas the vegetation changes from espinal dry forest in the northeast around the Colorado and Río Negro Rivers to xerophytic monte shrub in the northwestern and central parts (Hueck and Seibert, 1981). The southern areas have mild summers and cold winters with heavy snowfall, especially in mountainous zones. The Atlantic slope of the Patagonian Andes is much drier than the Pacific slope at the same latitude because of the rain-shadow effect, precipitation decreasing to less than 1000 mm in the Strait of Magellan (Fig. 1) and 200 mm on the Atlantic coast. Glaciers generally occur above 900 m a.s.l. in southern Patagonia (Lliboutry, 1956). The vegetation is here characterized by Magellanic tundra above 600 m a.s.l., changing to lower elevations into sub-Antarctic deciduous forest dominated by *Nothofagus pumilo* where rainfall decreases to between 500 and 800 mm. To the east this gives way to grass and bush steppe (Fig. 5c) where the rainfall is less than 400 mm, dominated by grasses such as *Festuca gracillima*, matorral shrubs, herbs, and brambles (Heusser, 1995). In the far south, cold Magellanic woodlands (Fig. 5d) are present. The eastern part of Patagonia is affected by the cool, northward-flowing Falklands/Malvinas Current (FMC), which meets the warm, south-flowing Brazilian Current (BC) opposite the Río de la Plata estuary at 34°–35°S.

The Falkland/Malvinas Islands (Fig. 1), presently have a mean temperature of about 6 °C and an annual rainfall of 600 mm (Birnie and Roberts, 1986).

2.12. Antarctic Peninsula and neighboring islands (56°–70°S)

The AP has a moderate polar climate with a short summer in which temperatures average about 2 °C, whereas mean winter temperatures drop to around −10 °C (Chapman and Walsh, 2007). The total yearly precipitation, generally falling as snow, is several thousand millimeters. Due to the snow cover trees or shrubs are absent and only two species of flowering plants, *Deschampsia antarctica* and *Colobanthus quitensis* occur along the western AP. The rest of the vegetation is formed by mosses, liverworts, lichens and fungi. The sub-Antarctic islands, including the South Shetlands, have a milder and wetter climate with more diverse floras, including a greater number of plant species such as ferns, tussock grass, herbs, and various kinds of bogs (Allison and Smith, 1973).

3. Continental climate changes during the Tertiary

Climatic warming and cooling events are referred to here using the same notation as in the companion paper by Le Roux (2012). These events include the Santonian–Danian Cooling (SDC), Thanetian–Ypresian Warming (TYW), Ypresian Cooling (YC), Lutetian Warming (LW), Bartonian–Rupelian Cooling (BRC), Chattian Warming (CW), Aquitanian Cooling (AC), Burdigalian–Langhian Warming (BLW), Serravalian–Tortonian Cooling (STC), Messinian–Pliocene Warming (MPW), and the Pleistocene cooling (PC).

3.1. Northern Chile (18°–27°S)

Tertiary sedimentation in northern Chile commenced during the middle Eocene as alluvial fans and evaporitic playa lakes deposited under arid to semi-arid conditions (Flint, 1985; Naranjo et al., 1994; Blanco et al., 2003; Charrier et al., 2007). These are represented by the Azapa Formation of northernmost Chile, the equivalent Sichal Formation in the Pampa del Tamarugal Basin (Fig. 6; Skármeta and Marinovic, 1981; Naranjo et al., 1994), and the evaporite-bearing Calama Formation in the Calama Basin (May et al., 2005). The generally arid conditions coincided with the LW recorded in the adjacent oceans.

A more humid phase followed during the late Eocene. Dunai et al. (2005) dated clasts by cosmogenic ^{21}Ne on erosion-sensitive landforms near Pisagua (Fig. 4), of which the oldest had an age of 37 Ma. This suggests a pluvial episode that more or less agrees with the supergene weathering of ore bodies between 35 and 34 Ma (Alpers and Brimhall, 1988; Sillitoe and McKee, 1996). This humid interval thus occurred within the BRC and coincided with a very sharp drop in temperature and sea level at about 34 Ma (Zachos et al., 2006).

Fig. 6. Approximate distribution of Tertiary basins with continental deposits, modified from Uliana and Biddle (1988), Aceñolaza (2004), May et al. (2005), Malumián and Nañez (2011), and other sources mentioned in text.

From the early to late Oligocene, arid to semi-arid conditions again prevailed (Dunai et al., 2005), which are also shown by lithological units in the Atacama region. The Lataguall a Formation at 19°15′S, which dates partly from the late Oligocene, was deposited in alluvial fans and braided rivers in a semi-arid climate (Pinto et al., 2004). In the Salar de Atacama Basin (Fig. 6), red sand- and siltstones with thick salt beds and minor conglomerate intercalations belonging to the San Pedro Formation (here of Oligocene age) also indicate an arid climate at the time (Naranjo et al., 1994). This dry period overlaps with the CW.

A significant pluvial phase in the Atacama Desert around the Oligocene–Miocene transition, probably related to the AC, was followed by the first establishment of hyper-arid conditions in the region (Dunai et al., 2005). However, these extreme conditions were interrupted by wetter spells. Clasts dated by Dunai et al. (2005) suggest a pluvial phase at 20 Ma, supported by the supergene weathering of orebodies ending at 21 Ma (Alpers and Brimhall, 1988; Sillitoe and McKee, 1996). Although these ages still correspond to the end of the AC, they suggest that the continental climatic transition was somewhat more irregular compared to oceanic conditions.

The recurrence of arid conditions during the early to middle Miocene is reflected by the presence of gypcretes around the basin margins of the Lataguall a Formation (Pinto et al., 2004). According to Watson (1985), gypcretes are restricted to areas receiving less than 250 mm of rainfall per year. However, the lithology of the lower to middle Miocene Tambores Formation in the Salar de Atacama Basin indicates that climatic conditions became somewhat less arid at times, as several debris flows were generated by an increase in rainfall and uplift of the Andes Range (Alpers and Brimhall, 1988). The aridification effect of the BLW was thus apparently somewhat mitigated by orographic precipitation caused by Andean uplift. Cosmogenic ^{3}He exposure ages of boulders on the Atacama Planation Surface between 16° and 27°S show that a widespread phase of surface abandonment occurred from 16.5 to 14.6 Ma, which possibly reflects the peak of the BLW coinciding with a hyper-arid climatic period (Evenstar et al., 2009).

Although Dunai et al. (2005) dated another humid phase at 14 Ma, corresponding to the beginning of the STC, climatic dessication generally intensified toward the late Miocene, which may be due to the increased blocking effect of the Andes to moisture from the east (Alpers and Brimhall, 1988). This is for example reflected in the Hollingworth Formation of the Salar de Atacama Basin, which was deposited under arid conditions with extensive pedimentation (Naranjo et al., 1994; Mpodozis et al., 1999). Pedogenic calcretes around the basin margins suggest an annual precipitation of 400–600 mm (Goudie, 1983). A pluvial phase was recorded by Dunai et al. (2005) at 9 Ma, whereas Evenstar et al. (2009) reported alluvial reworking of the Atacama Planation Surface between 7.6 and 6.8 Ma. The last event was also recorded in the Central Depression (Sáez et al., 1999; Hartley and Chong, 2002), the Lauca Basin on the western flank of the Altiplano (Gaupp et al., 1999), and in the Tariqua Formation of southern Bolivia (Uba et al., 2007). Le Roux et al. (2005) proposed an increase in Pacific sea floor spreading between 7.7 and 6.9 Ma that may have accelerated uplift of the Andes, leading to an increase in orographic rainfall from the west. Evenstar et al. (2009), however, attributed this event to decreasing global temperatures related to expansion of the West Antarctic Ice Sheet accompanied by pronounced cooling of the HC and deep Pacific Ocean water (Zachos et al., 2001b), which thus relates to the last part of the STC.

Based on the analysis of drainage patterns, Hoke et al. (2004) suggest that a changeover to hyper-arid climate conditions may have occurred along the western slopes of the Andes between about 10 and 5.8 Ma, the last age falling within the MPW. Gaupp et al. (1999) and Sáez et al. (1999) also reported sedimentary successions from spatially separate basins in the arid sector of the Chilean Andes that record a drastic switch to arid conditions between 6.4 and 3.7 Ma. This was followed by a return to more variable, semi-humid conditions that lasted until 2.6 Ma, after which the present hyper-arid conditions were established. However, according to Hartley and Chong (2002) and Hartley (2003) hyper-arid conditions already commenced between 4 and 3 Ma across the whole forearc region of northern Chile, based on the presence of up to 60 m of anhydrite, gypsum and halite belonging to the latest Pliocene–Pleistocene Soledad Formation. An extensive, up to 5 m thick saline crust composed of the same minerals also developed over lower Pliocene and older strata and blankets hill slopes, summits, valley floors and channel courses throughout northern Chile and southern Peru (Chong, 1988). Drainage abandonment at the same time suggests a regional climate change to the present hyper-arid conditions of the Atacama Desert (May et al., 2005).

The youngest alluvial activity was dated at 2.8 Ma on the Atacama Planation Surface by Evenstar et al. (2009), who linked this event to rapid global climate cooling during the late Pliocene (Raymo and Ruddiman, 1992), signaling the beginning of the PC.

Summarizing the evidence presented above, it thus appears that semi-arid to arid conditions generally dominated in this region between the Eocene and middle Miocene, but were interrupted by more humid phases at about 35 Ma (BRC), 25 and 20 Ma (AC), as well as at 14, 9 and 7 Ma (STC), undergoing a final change to hyper-aridity during the late Pliocene at ~3 Ma. The recorded pluvial episodes thus coincide with periods of global cooling across the Eocene–Oligocene and Oligocene–Miocene boundaries and during the middle Miocene (Zachos et al., 2001), as well as wetter periods in the Amazon Basin at 35–33, 24, and 20 Ma (Vasconcelos et al., 1994). This suggests that the rain came mainly from the east. However, a pluvial episode in the Amazon Basin between 17 and 12 Ma is not clearly reflected in northern Chile, overlapping with both the BLW and STC. Uplift of the Andes Range around 14–12 Ma in northern Chile may thus have caused an initial increase in sporadic orographic rainfall from the west, but finally ended the spill-over of moisture from the east onto its Pacific slopes.

3.2. North-central Chile (27°–32°S)

There are few detailed studies on Tertiary continental climates in north-central Chile, mainly because continental deposits are scarce in this region. Villagrán et al. (2004) observed that the woody components of paleoflora in the Fray Jorge National Park south of La Serena (Fig. 4), correspond to tropical lineages with Australasian links. They indicate warmer and more humid climates during the Paleogene than at present. The separation between subtropical and sclerophytic vegetation developed during the period leading up to the BLW, when the Mixed Paleoflora lost a large part of their cold Austral–Antarctic elements and became enriched in Neotropical lineages. The climate during this period was warm with well-developed seasonality, winter rains coming from the west and summer precipitation from the east. After the middle Miocene, a combination of events including glaciation in West Antarctica, the formation of the cold HC, and the final elevation of the Andes, caused the development of the "Arid Diagonal" of SSA, which incorporates the Atacama Desert and Patagonia. This in turn dismembered the tropical Tertiary forests and restricted them to the Pacific and Atlantic margins of the subcontinent. At the same time the northern limit of the subtropical forests along the Pacific withdrew to south-central Chile as a result of the aridification of the Atacama Desert, while sclerophytic vegetation expanded to central Chile.

3.3. Central Chile (32°–37°S)

Scattered relicts of olivillo forests between 30°30′S and Chiloé Island, together with phylogenetic relationships and the fossil record, suggest that subtropical rainforests occupied this area until the mid-Cenozoic (Villagrán, 1990; Villagrán and Hinojosa, 1997).

The palynology of the lower to middle Miocene Navidad Formation west of Santiago shows relationships with Australasian flora. The Mixed Flora association of *Nothofagus dombeyi*, *Podocarpaceae*, *Araucariaceae*, Myrtaceae and ferns suggests a humid climate, with precipitation exceeding 1100 mm and temperatures of about 16.5 °C for the basal part of the succession dated between 26 and 20 Ma by Sr (Gutiérrez, 2011; Gutiérrez et al., submitted for publication). This overlaps mainly with the AC. From 20 to 16 Ma, there was a decrease in *Nothofagus* and an increase in Subtropical Neogene taxa, *Nothofagadites* species dominating together with Podocarpaceae, which indicates dry conditions with temperatures reaching about 26 °C and rainfall of nearly 440 mm at the BLW (Troncoso, 1991; Hinojosa, 2005; Gutiérrez, 2011; Gutiérrez et al., submitted for publication). Between 16 and 12 Ma, there is a marked decrease in palynomorphs and especially *Nothofagadites* species, indicating that aridification continued, as also suggested by an increase in herbaceous species such as Chenopodiaceae (Gutiérrez, 2011). This aridification, which became more pronounced in the late Miocene, was attributed mainly to the rain-shadow effect of the rising Andes Range.

3.4. South-central Chile (37°–42°S)

Palynological studies in the Paleocene–Eocene Curanilahue Formation of the Arauco Basin (Fig. 6) have recorded spores of fungi and Pteridophytes, as well as pollen of gymnosperms and angiosperms, including both Dicotyledoneae and Monocotyledoneae. This palynological association indicates a humid, subtropical climate with mangrove forests (Collao et al., 1987; Palma-Heldt et al., 2009), probably coinciding with the TYW.

Middle Eocene beds of the San Pedro Formation in the Valdivia Basin (Elgueta et al., 2000) contain the fossil floras *Sabal ochseniusi*, *Tetracera ellipitica* and *Bennettia grosse-serrata*, together with abundant conifers (Illies, 1970; Di Biase and Lillo, 1973), which suggest a subtropical climate possibly coinciding with the LW. Oligocene coal seams higher up in the San Pedro Formation also contain an association of Microthyriaceae and *Cyathidites patagonicus* spores, together with pollen of *Araucariacites australis*, *Nothofagus cinta*, and *Podocarpidites* species, implying a mountain forest environment of high to very high humidity and a cold to temperate climate, similar to present-day conditions in the south of Chile (Palma-Heldt and Alfaro, 1982; Le Roux and Elgueta, 2000). This is supported by the presence of *Nothofagus subferruginia* and pollen of *Podocarpidites* species, *Nothofagadites* cf. *waipawaensis*, and *Proteacidites* cf. *symphyonmoides* in this formation (Elgueta et al., 2000). These cold–temperate conditions can be related to the BRC.

The broadly dated (Eocene–middle Oligocene) Chilpaco and Lonquimay Formations of the Cura-Mallín Basin (Fig. 6) yielded epiphyte fungi that are morphologically related to the Microthyriaceae and Meliolaceae families (Palma-Heldt, 1983), suggesting very humid, warm to temperate climates. Lacking more precise dating and stratigraphic control, these units are provisionally assigned here to the LW. *Podocarpidites mawickii*, on the other hand, has affinities presently occurring in the Valdivian rain forest, which suggest temperate–cold conditions possibly correlated with the BRC. Such a climate is also indicated by the presence of *Araucariacites australis* and *Nothofagadites cincta*, the closest relatives of which are typical of the Magellanic rain forest.

Marine transgression in this area during the late Oligocene, as reflected in parts of the Pupunahue and Santo Domingo Formations (Elgueta et al., 2000), probably correspond to the CW. This was followed by a short-lived regression during which a coal seam with intercalated tuff, dated at 23.5 Ma, was formed, coinciding with the AC. Pollen in the Cheuquemó Formation of the Osorno Basin (Troncoso and Barrera, 1980) suggests that it may be partly correlated with the Parga Formation of Chiloé Island (Elgueta et al., 2000), which was deposited under a cold to temperate climate with abundant rainfall (Torres et al., 2000).

The presence of the freshwater fish genus *Cheirodon* in the Cura-Mallín Basin (Fig. 6), suggests that tropical fauna had a wider southward distribution in South America during the early Miocene, as this genus presently occurs in the Brazilian ichtiobiogeographical subregion (Ringuelet, 1975; Weitzman and Weitzman, 1982; Rubilar, 1994). This reflects the southward expansion of tropical conditions during the BLW.

There is evidence that the climate cooled rather abruptly during the late Miocene, as glacial deposits of this age have been recognized in the Andean sector between 39°S and 41°S (Schlieder et al., 1988). Suárez and Emparan (1997) also reported erratic boulder and glacial striations at an elevation of about 2000 m around 38°30′S, possibly indicating the existence of an ice cap up to this latitude. These cold conditions probably reflect the STC.

In the late Miocene to Pliocene Ranquil Formation of the Arauco Basin (Le Roux et al., 2008), Schöning and Bandel (2004) described silicified wood of 10 different dicotyledonous tree families. All of these are presently found in the Pacific area and most have related species living in central Chile. The occurrence of certain Myristicaceae (angiosperms), however, indicates a stronger influence of Amazonia paleofloras in south-central Chile during the late Miocene. Schöning and Bandel (2004) thus deduced subtropical–tropical rainforest vegetation for the period, which coincides with the MPW. In the same basin, Palma-Heldt et al. (2009) reported the presence of *Haloragacidites harrisii* in strata possibly equivalent to the Ranquil Formation, which supports subtropical, warm and humid conditions during the MPW.

3.5. Southern Chile (42°–56°S)

During warming episodes, this area was mostly characterized by marine incursions, so that little information on continental conditions is available. In the Chiloé Basin (Fig. 6), the palynological record of the late Oligocene–early Miocene Parga Formation suggests a cold to temperate climate with abundant rainfall, giving rise to tree-thicket and marshy forests (Elgueta et al., 2000; Torres et al., 2000). A similar climate is indicated for this period by pollen records from the Cura-Mallín (Palma-Heldt et al., 1994), Valdivia (Palma-Heldt and Alfaro, 1982), and Osorno Basins (Troncoso and Barrera, 1980). This coincides with the AC.

North of Coihaique (Fig. 4), fluvioglacial conglomerates of the Galera Formation are interbedded with varves containing dropstones. These were dated at 12 Ma from an intercalated tuff bed (R. De la Cruz, M. Suárez, M. Fanning, pers. comm. to Lagabrielle et al., 2010), confirming earlier observations that middle Miocene glaciation occurred in the area (Suárez et al., 2007). This episode therefore correlates with the STC.

Climatic records in southern Chile thus suggest temperate-cold, wet conditions since at least the late Oligocene, but the absence of evidence for warmer spells may simply be because of a lack of continental outcrops. Glacial conditions were probably established first on the higher Andes, before the PC affected lower-lying areas.

3.6. North-western Argentina and southern Bolivia (18°–27°S)

Parts of northwestern Argentina are characterized by significant unconformities, as for example in the Puna, where the late Eocene Geste Formation directly overlies Ordovician strata and is in turn overlain by Pleistocene ignimbrites (Reguero et al., 2008). There are thus large gaps in the Tertiary continental record.

Studies on lake sediments in the Potosí Basin (Fig. 6) of Bolivia (Rouchy et al., 1993) show that this area was located in the ITCZ during the Paleocene, where arid conditions prevailed after a more humid period in the Maastrichtian. Carbonate deposition here during the early and middle Paleocene included coquinas, oolites, and microbialites characterizing a slightly more humid period (SDC), whereas hyper-arid conditions during the late Paleocene (TYW) are indicated by gypsum precipitation (Rouchy et al., 1983).

The presence of sebecid crocodile fossils in the Eocene Lumbrera Formation of north-western Argentina (Gasparini, 1984; Reguero et al., 2008) suggests a wet, tropical climate, which may coincide with the LW. However, upper Eocene to Pliocene successions on the Puna consist of alluvial fan, sand flat and eolian dune deposits, as well as evaporites such as gypsum, anhydrite and halite precipitated in playa mud flats, which indicate generally semi-arid to arid conditions over this period (Vandervoort et al., 1995; Voss, 2002).

The YC, BRC, CW and AC do not seem to be recorded in northwestern Argentina, but in the Puna, aridification leading up to the BLW is indicated by the appearance of evaporites dated between 24 and 15 Ma (Alonso et al., 1991; Vandervoort et al., 1995). However, $\delta^{13}C$ from tooth enamel samples of herbivores in south-western Bolivia suggests that these mammals fed on C_3 montane grasses and woody plants, which thrive in areas where sunlight intensity and temperatures are moderate and ground water is plentiful, until the BLW–STC transition (MacFadden et al., 1994). From 15 to 7.5 Ma (STC) this gradually changed to a mixed diet of C_3/C_4 plants, where C_4 includes temperate and tropical savanna-type grasses that are better adapted to environments with high daytime temperatures, intense sunlight, and drought. This might indicate that the area received both winter and summer rains from the west and east, respectively, until the end of the BLW, at which time the western source was diminished by the rising Andes barrier.

A change to wetter conditions is reflected in the variation of $\delta^{13}C$ values in pedogenic carbonates in the Yecua and Tariquia Formations in the north-western part of the Chaco–Paraná Basin (Fig. 6) between 12.4 and 7.9 Ma (Strecker et al., 2006, 2007), attributed by Uba et al. (2007) to a change in the relative abundance of C_3 and C_4 plants. Uba et al. (2007) noted a fourfold increase in sediment accumulation rates on fluvial megafans of the Andean-derived upper Miocene Tariquia Formation in southern Bolivia between 7.9 and 6 Ma, overlapping with the last part of the STC. This correlates with the uplift of the Bolivian Orocline (Ghosh et al., 2006) and intensification of the South American monsoon at the time (Kleinert and Strecker, 2001; Starck and Anzótegui, 2001; Strecker et al., 2007). These conditions persisted into the early Pliocene as indicated by endemism of *Eosclerocalyptus proximus* in north-western Argentina, which suggests somewhat more humid and hot environments than that of today (Zurita, 2007). At this time C_3 vegetation still prevailed at elevations exceeding about 2000 m. Clear evidence for C_4-dominated grasses only appeared in limited areas during the Plio-Pleistocene because of the effect of the rising Andes Range. The present-day biotic communities of the central Andes were established at around 3.5 Ma (MacFadden et al., 1994).

3.7. Northern Argentina and Paraguay (20°–31°S)

This region is largely covered by Quaternary deposits so that most information is obtained from petroleum exploration wells. Furthermore, the area was subjected to a major marine incursion during the middle to late Miocene (the Transcontinental Sea; see Le Roux, 2012), which left 200–300 m of marine sandstones and shales correlated with the Paraná Formation. Few boreholes penetrate to greater depths, so that the information on continental Tertiary climates is incomplete.

In the Chaco–Paraná Basin, evaporitic beds in the Mariano Boedo and Laguna Paiva Formations suggest at least temporary arid conditions during the early Paleocene (Padula and Minggram, 1968). However, in the Paleocene Lumbrera Formation of the Salta Basin (Fig. 6), the basal section reflects sandy, permanent fluvial systems and a perennial fresh-water lake, indicating more humid conditions. The upper section, on the other hand, is composed of sandstones and shales deposited in ephemeral fluvial and lake systems. Based on sedimentary features and the fossil record of both sections, an abrupt climate change is interpreted by Del Papa (2006), varying from temperate to humid at the base to hot and dry in the upper part. In the same basin, the development of a geosol in the Maiz Gordo Formation also indicates an overall aridification and decrease in seasonality leading up to the TYW, when maximum temperatures occurred, followed by fluctuating dry to seasonally wetter conditions in the YC (White and Brizuela, 2009).

Arid conditions during the Oligocene are indicated by gypsiferous units in the Salar de Antofalla region of the Salta Basin (Adelmann, 2001; Carrapa et al., 2005), which might coincide with the CW.

Franco and Brea (2008) described remains of the tree families Anacardiaceae, Leguminoseae and Solanaceae from the middle Miocene Paraná Formation. Together with species such as *Entrerrioxylon victoriensis* and *Anadenantheroxylon villaurquisense*, these suggest the existence of seasonally dry tropical forests, which presently occur only as relicts in isolated areas of northern Argentina, south-western Bolivia and Brazil. The climate was somewhat warmer than at present. The palynology and sedimentology of the Miocene Anta Formation in the Salta Basin also show transitional forest flora with Ulmaceae, *Rhoipites* species, Podocarpaceae and Anacardiaceae, indicating a saline lake environment within a montane paleocommunity. This reflects the first expansion of the steppe and a change to a relatively dry climate, which is supported by the disappearance of fungae (Quattrocchio et al., 2003). Although precise dates are not available, this period might coincide with the last part of the BLW.

In the Catamarca Province, Anzótegui et al. (2007a, 2007b) described leaf imprints from the Andalhuala Formation (dated at 5.2 Ma in this area), which are composed of Fabaceae and Anacardiaceae. The floral association suggests a hot climate with mixed xerophytic and riverine forest communities during the MPW. However, Rodríguez Brizuela and Tauber (2006), based on vertebrate fossil studies, concluded that these initially dry conditions changed to a somewhat more humid, temperate–warm climate with local arid sub-environments during the early Pliocene. The vegetation was generally characterized by open areas with herbs and shrubs, but local, closed tree communities also existed. In the Salta Basin (Fig. 6), Anzótegui (1998) and Starck and Anzótegui (2001) described the Angastaco, Palo Pintado and San Felipe Formations as containing mammal fauna, pollen, leaves and tree-trunks indicating a hot, semi-humid climate. The formation of thick calcretes in the upper part of the San Felipe Formation, however, suggests that conditions reverted back to aridity between about 3.4 and 2.4 Ma (Starck and Anzótegui, 2001).

3.8. North-eastern Argentina and southern Brazil (20°–34°S)

Due to scarce surface outcrops, little is known about the Tertiary geology of this region, except that it was invaded by the Transcontinental Sea (locally referred to as the Paranense Sea) during the middle Miocene. However, along the eastern border of this sea, a continental sector was exposed in north-eastern Argentina, western Uruguay and southern Brazil. This continental area expanded during marine regression in the late Miocene–early Pliocene, with vertebrate fauna and flora in the Ituzaingó and Puelches Formations indicating a warmer paleoclimate than that of today (Aceñolaza, 2004). This period coincided with the MPW.

3.9. Central Argentina (27°–40°S)

The central part of Argentina suffered intermittent uplift and subsidence before and during the Tertiary. The basement underlying Tertiary deposits, for example, is locally formed by Permian strata (Ezpeleta et al., 2006) and Paleocene–Eocene deposits are largely absent. Furthermore, toward the end of the Oligocene and during the early Miocene, the Transcontinental Sea (see Le Roux, 2012) invaded this part of the subcontinent, reaching the Paraguayan Chaco and the southern border of Bolivia. This intracontinental sea formed a biogeographic barrier between the Andean and Pampas regions at the time (Aceñolaza, 2004).

Sebecid crocodile fossils in upper Eocene deposits near Mendoza (Fig. 4) indicate a wet, tropical climate (Gasparini, 1984), probably overlapping with the last part of the LW.

A palynological study of lacustrine deposits of the late Oligocene–early Miocene Lileo Formation in north-western Neuquén Province (Leanza et al., 2002) indicates a relatively low diversity dominated by *Nothofagadites saraensis* and *Podocarpidites* species. The association of these two genera suggests forest communities in temperate to temperate–cold conditions, with more humid localities and the presence of shallow water bodies indicated by spores of Pteridophytes/Briophytes together with *Botryococcus* and *Azolla* species. These conditions indicate that the AC affected this area.

In the Famatina Range (Fig. 1), pollen and spore studies of the middle Miocene Del Buey Formation showed the presence of xerophytic and halophytic species as well as tropical elements such as *Magnaperiporites* and *Senipites*. Together with the development of calcrete and gypsum beds, these floras indicate that semi-arid, temperate–warm conditions reigned during the BLW (Barreda et al., 2006). The middle Miocene Santo Domingo Member of the Durazno Formation in the Bermejo–Vichina Basin (Fig. 6) was also deposited in eolian dunes and braided rivers under a semi-arid climate (Dávila and Astini, 2003). The orientation of the longitudinal dune system indicates winds predominantly from the north. The deposition of this formation coincided with uplift of the Famatina Range (Fig. 1), which formed an intermontane basin and prevented the influx of humid winds from the east (Dávila and Astini, 2003). In the same basin, magnetochronology reveals continuous accumulation from 19 to 17 Ma. The lower Río Salado Formation was deposited in a playa-lake while the four succeeding units (Quebrada del Jarillal, Huachipampa, Quebrada del Cura and Río Jáchal Formations) were deposited by sandy ephemeral rivers (Milana et al., 2003). This indicates generally arid conditions with seasonal droughts. In the central region of the Sierras Pampeanas (Fig. 1), the Los Llanos Formation is separated into fluvio-eolian and paleosoil-rich alluvial plain facies associations. The eolian deposits and calcretes confirm that a semi-arid climate reigned during the BLW.

Wetter conditions set in during the STC, as indicated by the presence of a silcrete capping the deposits of the Los Llanos Formation in La Rioja Province (Ezpeleta et al., 2006). Silcretes have been interpreted as reflecting seasonally dry and wet, alkaline conditions (Summerfield, 1983), which is also indicated by 12–10.7 Ma old vertic paleosols in the Santa María Group of the homonymous basin (Fig. 6; Kleinert and Strecker, 2001). Furthermore, a more humid climate is suggested by sedimentological, paleontological and stable isotope data from the Santa María Basin (Kleinert and Strecker, 2001; Starck and Anzótegui, 2001; Uba et al., 2005). This was attributed to the development of an orographic barrier along the eastern margin of the Altiplano/Puna intercepting moisture from the Atlantic Ocean and Amazon Basin, when the Altiplano rose 2.5–3.5 km between 10.3 and 6.8 Ma (Garzione et al., 2006; Ghosh et al., 2006). The end of the STC is reflected in the Andalhuala Formation of the same basin (7.1–3.4 Ma), which was deposited under semi-humid conditions with a pronounced seasonality. This is suggested by authigenic clays, fossils of *Paracacioxylon o'donelli* and *Mimosoxylon piptadensis* (Menéndez, 1962; Lutz, 1987), and fossil vertebrates including racoons, giant running birds, ground sloths, and a variety of ungulates (Marshall and Patterson, 1981). These are characteristics of subtropical tree savannas like those of the present Chaco region further east (Pascual et al., 1985). A southwestward radiation of the rodent subfamily Eumysopinae (Echimyidae), which presently inhabits the warm and humid savannas of Paraguay and central-east Brazil, was also recorded during the late Miocene–Pliocene in central Argentina (Vucetich and Verzi, 1996).

In the upper Miocene El Morterito Formation of the Santa María Basin (Fig. 6), Fabaceae fossil leaves include species such as *Senna* cf. *bicapsularis* and *Senna* cf. *obtusifolia*. Together with sedimentological data and vertebrate as well as invertebrate fossils, this suggests that dry, open spaces with xerophytic vegetation predominated in the area, while the presence of forested strips along river courses indicates a hot climate (Anzótegui et al., 2007a, 2007b). This is here correlated with the MPW. *Dasypodidae* in the Cerro Azul Formation of the Pampa Province also suggest a renewed zoogeographic connection of late Miocene–Pliocene fauna in central Argentina with coexistent species in the intermontane valleys of Catamarca, Tucumán and San Juan (Scillato-Yané et al., 1995; Urrutia et al., 2008), implying that the Transcontinental Sea retreated from this area. The presence of large Euphractini in this formation indicates relatively warm, semi-arid climatic conditions with seasonal rainfall, which is supported by sedimentological and paleopedological evidence (Melchor et al., 2000; Montalvo et al., 2008). Krapovickas et al. (2009) and Ciccioli and Marenssi (submitted for publication) also reported semi-arid conditions during deposition of the Miocene–early Pliocene Toro Negro Formation of the Bermejo–Vinchina Basin, as indicated by the presence of gypsum beds and eolian dune deposits.

During the middle Pliocene, Eumysopinae disappeared from central Argentina, indicating a northward shift of climatic systems (Goin et al., 1994; Cione and Tonni, 1995; Vucetich, 1995; Vucetich and Verzi, 1996; Vucetich et al., 1997) as the PC set in.

3.10. Eastern Argentina and Uruguay (30°–40°S)

Tófalo and Morrás (2009) studied paleosols in continental deposits of the Chaco–Paraná Basin in southern and western Uruguay, which indicate important climatic changes during the Cenozoic. Paleocene palustrine carbonates of the Queguay Formation, associated with phreatic calcretes indicate a seasonally contrasted, semi-arid climate which might coincide with the SDC.

In the early Eocene Asencio Formation of the Chaco–Paraná Basin, fluvial deposits that contain Ultisols developed under a warm and humid climate, which were indurated after periods of intense aridity marked by the formation of ferricretes. The upper portions of the latter were dismantled during episodes of increased precipitation. This warm period might overlap with the TYW, when subtropical conditions expanded to the south (Tófalo and Morrás, 2009).

The Oligocene–lower Miocene Fray Bentos Formation of the Chaco–Paraná Basin is composed of loess deposited under semi-arid conditions, with paleosols and pedogenic, tubular calcretes also indicating a seasonal, semi-arid climate (Tófalo and Morrás, 2009). These conditions might be linked to a northward shift of climate belts during the AC.

In eastern Argentina, a change to cooler and drier conditions took place between 16 and 12 Ma, as recorded by Frasian land-mammals. This was linked to the Quechua phase of uplift in the Andes by Pascual (1984), but is here associated with the STC as the Quechua phase peaked at about 18 Ma (Ramos, 2002).

Messinian freshwater fishes in the "Conglomerado osífero" beds of the Chaco–Paraná Basin are typically Brazilian, thus indicating tropical conditions during the MPW. This is supported by crocodiles, cetaceans and sirenids that can be correlated with those of the Andalhuala Formation of northern Argentina. Terrestrial vertebrates in this unit show a very high diversity, indicating a heterogenous landscape controlled by one or several rivers, together with swamps, woody lowlands and nearby savanna-type open spaces (Cione et al., 2000). Further south, fossil polyads of *Acaciapollenites acaciae* recovered from late Miocene–early Pliocene deposits in the Colorado Basin (Fig. 6) along the border between Patagonia and eastern Argentina are very similar to those of the extant *Acacia curvifructa*, which suggests drier and warmer paleoclimatic conditions in this area than today (Caccavari and Guler, 2006).

In the Buenos Aires Province, the upper part of the late Pliocene Puelches Formation reflects fluvial sands gradually overlain by backswamp and lake deposits, which formed on well-drained floodplains with oxidizing conditions. The absence of carbonate nodules in incipient soil profiles suggests a humid climate (Tófalo et al., 2005). The late Pliocene–middle Pleistocene Raigón Formation of southern Uruguay was also formed during a humid period, showing a paleosol at the top that developed in a seasonally contrasted climate (Tófalo and Morrás, 2009). In late Pliocene–Pleistocene strata of northeastern Buenos Aires Province, Pomi (2008) identified the large herbivores *Megatherium* and *Stegomastodon*, which require an abundant diet of tree and bush leaves. The only living related genus, *Tolypeutes*, presently inhabits forested areas. However, Pomi (2008) considered the presence of two possible groups of fauna, one associated with abundant arboreal vegetation, and the other preferring a more open habitat. The latter might be supported by the upper Pliocene San Andrés Formation of Buenos Aires Province, where fossilized nests of the termite *Barberichnus bonaerensis* occur in paleosols. Their presence suggests more arid and dry conditions (Laza, 2006). It is therefore possible that forest vegetation occurred along river courses traversing a savanna-type landscape subjected to seasonal droughts during the Pleistocene cooling.

3.11. Patagonia (37°–56°S)

Patagonian fossil plant and pollen records offer exceptional insights into the climatic evolution of this region, which are reinforced by vertebrate and invertebrate fossils.

Paleocene–early Eocene (TYW) floras in Patagonia were rainforest-dominated, including many angiosperms with temperate-warm affinities (Barreda and Palazzesi, 2007). Northern and central Patagonia were dominated by gymnosperms, *Classopollis* being the most important element (Archangelsky, 1973; Ruiz and Quattrocchio, 1997; Barreda et al., 2004) but Neotropical megathermal taxa were also abundant, including *Anacolosidites*, *Spinozonocolpites*, and *Senipites* species. Southern Gondwanean lineages were represented by Podocarpaceae, Araucariaceae, Cunionaceae, and Proteaceae. The regional climate was interpreted as warm and humid, with mangrove communities developing in coastal environments of Chubut (Petriella, 1972; Archangelsky, 1973; Petriella and Archangelsky, 1975). The limited information from southernmost Patagonia indicates the presence of some megathermal families such as Olacaceae, along with Myrtaceae and Proteaceae (Freile, 1972). Iglesias et al. (2007) collected specimens from the middle Paleocene Salamanca Formation from two localities in the Golfo de San Jorge Basin (Fig. 6). The samples revealed considerably greater richness than was previously known from this area, including angiosperm leaves, fruits, flowers, and seeds, together with conifer leaves, cones, and seeds. They indicate a humid, temperate-warm climate. High frequencies of megathermal taxa such as *Plicatopollis* and *Clavatipollenites* species have also been reported by Zamaloa and Andreis (1995). In the same formation, Brea et al. (2005) described fossil tree growth rings in gymnosperms. The presence of a great number of in situ trunks of large size (some more than 1 m diameter) suggests exuberant climatic conditions. The structural characteristics of the wood and growth rings indicate a temperate–warm, humid climate with spring rainfall and dry summers. This suggests that the TYW already began to affect this area during the middle Paleocene. Troncoso et al. (2002) studied leaf imprints and pollen records in the upper Paleocene Ligorio Márquez Formation south of Chile Chico (Fig. 4). The presence of Pteridophyta, Pinophyta and Magnoliophyta, as well as 14 different species of Lauraceae, also indicate a humid, tropical to subtropical climate at the time. The Lauraceae family, for example, presently occurs in tropical South Asia, Central America and Brazil. High mean annual temperatures are indicated by the dominantly entire margins of the leaves. This coincides with temperatures about 8° to 12 °C higher than today (Zachos et al., 1993) and the temperature maximum of the TYW observed in East Antarctica, Seymour Island and the AP (Dingle et al., 1998). In the Magellanes/Austral Basin, warm and humid conditions are also indicated by the clay mineralogy of upper Paleocene/ lower Eocene deposits (Malumián et al., 1998). In the Golfo de San Jorge Basin, the clay mineralogy of the Río Chico Group reflects changing paleoclimatic conditions that shifted from seasonal temperate-warm to tropical at the time (Raigemborn et al., 2009). Paleobotanical data suggest that the Paleocene vegetation underwent significant compositional and diversity changes from Mixed Temperate-Subtropical Forest to Mixed Subtropical–Tropical Forest. The Paleocene–Eocene climate thus changed from temperate–warm and humid with a highly seasonal precipitation to subtropical–tropical, year-round rainfall conditions (Raigemborn et al., 2009).

The YC does not appear to have led to significant cooling in Patagonia, although genera adapted to arid conditions such as *Striatricolporite*, *Celtis*, and *Cassia* reported from Laguna del Hunco and Río Pichileufú at the north-western extremity of the Golfo de San Jorge Basin (Wilf et al., 2003, 2005), suggest somewhat cooler and less humid conditions. In the same areas, the presence of middle Eocene megathermal families including palms, *Myrcia*, and *Gymnostoma* indicates an equable climate with winter mean temperatures warmer than 10 °C and abundant rainfall (Wilf et al., 2003, 2005).

The LW is probably recorded in lower and middle Eocene coal deposits in the Punta Torcida Formation of Tierra del Fuego (TDF) (Malumián and Jannou, 2010). Warm and humid conditions at the time are supported by the high index of fossil flora diversity reported from Laguna del Hunco and Río Pichileufú by Wilf et al. (2005).

The BRC was manifested from the latest middle Eocene in Patagonia, as indicated by land-living microgastropod fossils (Charopidae) in the Sarmiento Formation of the Golfo de San Jorge Basin. These are similar to taxa presently occurring in north-western Patagonia, indicating a temperate–cold but still humid climate (Miquel and Bellosi, 2007). In TDF, a new species of Araucariaceae recovered from late Eocene deposits (*Araucaria pararaucana*) has anatomical characteristics similar to *Araucaria araucana* (Panti et al., 2007), which is presently mainly restricted to southern Patagonia and elevations above 800 m in the Andes or Coastal Range of central Chile. This suggests cold, humid conditions in this area at the time. The BRC was also marked by the expansion of *Nothofagus* forests, with progressive replacement of megathermal communities by meso- and microthermal rainforest indicating a marked cooling trend (Barreda and Palazzesi, 2007). Assemblages were fairly homogeneous in composition, being dominated by Nothofagaceae, Podocarpaceae, Araucariaceae, Cunoniaceae, and Proteaceae (Fasola, 1969; Olivero et al., 1998) and an undergrowth of ferns and herbs, reflecting a high rainfall regime and temperate to temperate-cold climatic conditions. Evidence for aridity is scarce and restricted solely to the presence of Anacardiaceae (Barreda and Palazzesi, 2007). In TDF, coal-bearing, upper Eocene–lower Oligocene continental outcrops contain Podocarpaceae and Fagaceae with subordinate Pteridophyta. The palynological assemblage reflects a lacustrine or swampy environment with normal levels of moisture and a temperate climate (Rosello et al., 2004).

Late Oligocene (CW) floras in Patagonia were characterized by shrubby–herbaceous elements, while xerophytic species occupied coastal salt marshes and pockets in inland areas. Angiosperms of Rubiaceae, Combretaceae, Sapindaceae, Chloranthaceae, and Arecaceae indicate warmer temperatures. At this time forests of Nothofagaceae, Podocarpaceae, and Araucariaceae were still present in extra-Andean Patagonia (Barreda and Palazzesi, 2007). Shoreline communities included the first Asteraceae, Mutisiae and Convolvulaceae, along with Poaceae, Chenopodiaceae, and Ephedraceae, but in lower frequencies (Barreda and Palazzesi, 2007).

During the AC, the first expansion of shrubby elements of the Chenopodiaceae, Ephedraceae, and Convolvulaceae occurred in Patagonia, while forests were dominated by southern elements of the Podocarpaceae, Nothofagaceae, and Araucariaceae (Barreda and Palazzesi, 2007). Megathermal flora became scarce in southernmost Patagonia (Romero, 1970). Drier conditions prevailed in lowland areas, as shown by the abundance of Ephedraceae and Chenopodiaceae and the presence of sclerophyllous trees. The contraction of humid elements thus coincided with the expansion of xerophytic taxa. Rainforest trees, however, still contributed to pollen assemblages and may have developed gallery forests in central Patagonia (Barreda and Palazzesi, 2007).

The Burdigalian encompassed an important climate change from dry and hot to humid and temperate–warm. Barreda and Caccavari (1992) recorded the presence of polyads of *Acaciapollenites myriosporites* and *Polyadopollenites* species in the early to middle Miocene Chenque Formation of the Golfo de San Jorge Basin, which indicate a very mild to mild-temperate and humid climate. The spore/pollen sequences suggest a forest-dominated environment with tropical elements (Barreda and Palamarczuk, 2000a; Barreda et al., 2008). The BLW was also marked by an increase in megathermal *Cupania* and *Alchornea*, while aquatic herbs and hydrophytes such as Cyperaceae and Malvaceae were dominant, together with tree ferns (*Cyathea*). Coastal salt marshes were occupied by Chenopodiaceae, Convolvulaceae, and Asteraceae (Barreda and Palamarczuk, 2000b). Temperate–wet forests existed at higher elevations (Goin et al., 2007). In southern and central Patagonia, vertebrates of the so-called Colhuehuapian Mammal Age lived on a vast coastal plain with diverse vegetation as indicated by palynomorphs and phytoliths (Vásquez et al., submitted for publication).

Middle to late Miocene records show an increasing diversity and abundance of xerophytic taxa in Patagonia, including Asteraceae, Chenopodiaceae, and Convolvulaceae. Expansion of these xerophytic taxa, coupled with extinctions of megathermal/non-seasonal elements, indicate aridity and extreme seasonality. These late Miocene floras are closely related to modern communities, with steppe vegetation widespread across extra-Andean Patagonia and forests restricted to the western humid upland regions (Barreda and Palazzesi, 2007). At about 15 Ma, a change is also seen in the Frasian fauna where savanna–woodland species were replaced by typical pampa species, forming the Santacrucian–Colloncuran Land Mammal Age boundary (Marshall and Salinas, 1990). This suggests an abrupt cooling as climatic systems shifted to the north during the STC. Southern beech and podocarpaceous subtropical forests, which persisted to the southern tip of Patagonia throughout the Paleogene and early Miocene, were also replaced abruptly by colder, drier grassland vegetation in the middle Miocene, becoming extinct from the eastern steppe during the late Miocene–Pliocene (Barreda et al., 2008). At this time the subtropical–tropical environment shifted north to about 30°S (Pascual and Juareguizar, 1990). Subtropical woodland fauna, including platyrrhine monkeys, anteater-like armadillos and certain marsupials disappeared from Patagonia, while primitive tree sloths became extinct and were replaced by ground sloths (Webb, 1985). High-crowned ungulates now dominated for the first time (Pascual and Ordreman Rivas, 1971; Pascual, 1984). The spread of shrubs and herbs during the STC was probably triggered by tectonic and global paleoclimatic events. Uplift of the Patagonian Andes produced an important orographic rainshadow on its eastern side at about 16.5 Ma (Blisniuk et al., 2005), while the development of a major ice sheet on Antarctica in the late Miocene caused a general trend toward cooler conditions. This progressive increase in aridity was coupled with the worldwide late Miocene spread of grass-dominated ecosystems (Jacobs et al., 1999; Willis and McElwain, 2002). All these changes led to the expansion of cooler and drier climates throughout the Patagonian landscape, promoting the diversification of the Asteraceae (sunflower family) together with other xerophytic taxa (Barreda and Palazzesi, 2007).

In the late Miocene Puerto Madryn Formation of the Valdés Basin (Fig. 6), Barreda et al. (2008) described fossil pollen grains with morphological features unique in the Nassauviinae that suggest virtually xerophytic conditions. Nassauviinae comprise vines, shrubs and low trees endemic to America with a wide range of ecological preferences, the nearest living relatives of the fossil types being mostly confined to humid landscapes. The unusual occurrence of these groups during the arid late Miocene could be attributed to the complex interplay of mountain uplift and global circulation patterns. These forcing factors would have created a mosaic of different habitats with patches of forest and dry-adapted species developing in relatively small regions.

There is evidence that glaciation started in northern Patagonia during the late Miocene. Around Lake Cardiel (Fig. 1), Wenzens (2006) reported glacial deposits that may be as old as 10.5 Ma. More widespread evidence for glacial activity is found around Lake Buenos Aires (Fig. 1) in Argentina (known as Lake General Carrera in Chile), where lava beds intercalated with glaciofluvial conglomerates and tillites were dated between 6.85 and 2.96 Ma (Mercer and Sutter, 1982; Mercer, 1983; Ton-That et al., 1999; Guivel et al., 2006; Lagabrielle et al., 2007; 2010; Boutonnet et al., 2010). Rabassa et al. (2005) provided evidence for glaciation between 7 and 5 Ma in Patagonia, which is consistent with the onset of major Antarctic ice-sheet expansion at 7 to 5 Ma (Zachos et al., 2001). Malagnino (1995) identified 6 glacial events around Lake Buenos Aires, viz. Chipangue (7–3.2 Ma), Deseado, Primavera, Guenguel, Nacimiento and Felix. Various other proxies also indicate significant cooling since about 6 Ma (Lear et al., 2000). It thus appears that the MPW had little effect in certain parts of Patagonia, where the STC extended almost uninterruptedly into the PC.

3.12. Antarctic Peninsula and neighboring islands

In the Upper Cretaceous–lower Paleocene Dalmor Bank Formation of Dufayel Island (within Admiralty Bay, King George Island; Fig. 4), Birkenmajer and Zastawniak (1989) recorded fossil leaf species of *Nothofagus*, *Cochlospermum*, *Sterculia* and *Laurophyllum*, which presently occur in tropical–subtropical regions such as the forests of southern Brazil, together with some presently temperate climate species. The Paleocene Cross Valley Formation on Seymour Island (Fig. 4) contains ferns such as *Alsophila antarctica* and *Asplenium antarctica*, conifers that include *Araucaria imponense*, and the *Nothofagus* species *Nothofagus magellanica* and *Nothofagus pulchra*, in addition to *Laurophyllum nordenskjoldii* and *Lomatia antarctica*. Spore and pollen assemblages here also indicate podocarpaceous conifers, angiosperms and cryptogams (Askin, 1990). Such a mixed assemblage of warm, subtropical and cold, temperate species is typical of a warm and humid climate (Cranwell, 1959; Torres, 2002). Tree rings in fossil wood from Seymour Island also indicate climate warming during the early Paleocene (Francis, 1991). This is supported by lower Paleocene deposits on the Maud Rise in the Weddell Sea (Fig. 4), which contain eolian sediments from East Antarctica indicating a warm, semi-arid continental climate at the time (Barker and Kennett, 1988). On King George Island, Paleocene–Eocene formations have mixed flora associations including species such as *Nothofagus subferruginia*, *Nothofagus densinervosa* and *Nothofagus oligophlebia*, together with the *Podocarpus* species *Podocarpus tertiarius* and *Podocarpus andiniformis*, and Proteacea such as *Banksia antarctica*. This association suggests a humid, warm climate (Covecevich and Lamperein, 1970). It thus appears that the TYW may have started earlier in the AP and neighboring areas than further north, where it manifested only during the middle to late Paleocene.

Fossil wood from the Fildes Formation of the Collins Glacier region on King George Island provides evidence for the existence of cool temperate forests during the earliest Eocene (Poole et al., 2001), thus reflecting the YC.

The LW is manifested in the AP region by sedimentological, geochemical and clay mineral data from the La Meseta Formation of Seymour Island, which show that a warm, all-year round humid climate prevailed during the early Lutetian (~47 Ma), followed by seasonally wet conditions during the middle Lutetian (Dingle et al., 1998). The Lutetian Fossil Hill Formation of the South Shetland Islands also shows a mixture of both Antarctic and Neotropical elements (Reguero et al., 2002). Birkenmajer et al. (2005) reported the presence of a terrestrial, valley-type tillite between two basaltic lava sequences in the Punta Thomas Formation on King George Island. K–Ar dating of the lavas suggests that mountain glaciation occurred between 45 and 41 Ma, thus coinciding mainly with the LW, but also with the start of the BRC. The Punta Thomas Formation also contains *Nothofagus* and *Podocarpus* species as well as ferns dated by volcanic intercalations at about 37 Ma. It thus appears that glacial conditions already existed at higher elevations during the LW, while warmer temperatures on the lowlands allowed the persistence of *Nothofagus* during the BRC.

On Seymour Island, the La Meseta Formation paleoflora are dominated by Antarctic taxa such as *Nothofagus*, podocarps, and araucarian conifers, reflecting the BRC during the middle to late Eocene with a seasonal, temperate-cool, rainy climate (Reguero et al., 2002). The late Eocene–early Oligocene section of the La Meseta Formation is characterized by the presence of *Dacrycarpus tertiarius*, *Araucaria nathorati*, *Nothofagoxylon scalariforme*, and various other *Nothofagoxylon* and *Nothofagus* species typical of a temperate-cold, humid climate with seasonal changes. Similar floras have been recorded on King George Island for this time period (Torres, 2002), the BRC thus being clearly manifested in the AP and surrounding regions. These cold conditions peaked at around 34 Ma, when the climate finally became frost-prone (Dingle et al., 1999).

On King George Island, a regional ice sheet expansion occurred during the Oligocene Polonez Glaciation (32–26 Ma), shortly after the Oi-1 sea-level fall of the BRC (Zachos et al., 1996). At this time, East Antarctic glaciation was in full swing according to Birkenmajer and Zastawniak (1989), Barrera and Huber (1990), Barron et al. (1991), and Zachos et al. (1992b), although Ehrmann and Mackensen (1992) and DeConto and Pollard (2003) proposed that the East Antarctic Ice Sheet only began to develop during this abrupt global cooling event at the Eocene/Oligocene transition (Tripati et al., 2005). On Seymour Island, sedimentary deposits at the top of the Eocene La Meseta Formation, dated by Sr on dinoflagellate tests at 34 Ma, include glacial moraine deposits and lodgement till. This suggests the presence of a regionally extensive West Antarctic Ice Sheet during the earliest Oligocene. According to the nature of the conformable transition between the La Meseta Formation and glacial deposits, the onset of ice sheet growth was rapid (Ivany et al., 2006). This cooling event correlates with a $\delta^{18}O$ shift at about 35.9 Ma (Zachos et al., 1992a), which was attributed by Dupont-Nivet et al. (2008) to uplift of the Tibetan Plateau, causing an increase in rock weathering that lowered atmospheric CO_2.

The CW is registered in the AP region by a continent-wide interglacial stage between about 30 and 23 Ma, as shown by the strontium isotope stratigraphy of cryogenic strata (Dingle and Lavelle, 1998).

This was followed by regional ice sheet expansion on King George Island during the Miocene Melville Glaciation (23–20 Ma) (Birkenmajer, 2001; Troedson and Smellie, 2002), coinciding with the AC. Cryogenic strata in the northern AP also indicate that glacial conditions expanded at about 23 Ma (Dingle and Lavelle, 1998).

At the northern tip of the AP and on James Ross Island (Fig. 4), reworked, Sr-dated pectinid shells in the late Miocene Mendel Formation reveal open marine interglacial conditions between 20.5 and 17.5 Ma (Nývlt et al., 2011), which shows that the BLW was accompanied here by glacial retreat.

During the Miocene, Antarctica reached its present polar position. A large increase in IRD around Antarctica after about 15 Ma is shown by marine cores (Shackleton and Kennett, 1975; Kennett, 1977; Savage and Ciesielski, 1983), indicating the start of the STC. Initially, the glaciers were wet-based, but landscape analysis in northern Victoria Land suggests that they became dry-based (indicating colder temperatures) between 8.2 and 7.5 Ma (Armienti and Baroni, 1999). However, glaciation was apparently only established in West Antarctica during the late Miocene, as suggested by the fact that marine surface waters became inhospitable for calcareous nannoplankton at this time (Wise, 1988). A long hiatus in the sedimentary record from the Ross Sea was interpreted by Savage and Ciesielski (1983) to the expansion of the grounded Ross Ice Shelf, which removed much of the sedimentary record after about 10 Ma. Dingle and Lavelle (1998) also registered glacial expansion at about 10 Ma and during the latest Miocene.

Warm-based glacier deposits in the Mendel Formation in northern AP indicate that temperatures increased in the area between 5.9 and 5.4 Ma (MPW) (Nývlt et al., 2011). At about this time, sub-Antarctic flora found refuge at higher elevations in the Transantarctic Mountains (Torres, 2002). According to seismic reflection data on the continental shelf and slope of the AP, erosion and a change in sedimentation style occurred here during the late Pliocene, which suggests a change from wet-based to modern, cold polar dry-based ice regimes at about 3 Ma (Rebesco et al., 2006).

4. Discussion and conclusions

4.1. Summary of events

Fig. 7 summarizes the climatic events recorded in the different regions described above, together with a schematic representation of associated tectonic events (based on Table 1 of Le Roux, 2012).

In Chile, the TYW (60–55 Ma) is registered only in the south-central region, where a humid, sub-tropical climate prevailed. East of the Andean Range, this warming episode was marked by arid to hyper-arid conditions with maximum temperatures in southern Bolivia, north-western and northern Argentina, and Paraguay. Central Argentina apparently underwent erosion at the time, whereas eastern Argentina and neighboring Uruguay also had a warm and humid, sub-tropical climate, albeit with periods of acute drought. Patagonia at this time was mainly covered by temperate-warm rainforests, coastal areas being occupied by mangroves. The climate was humid and sub-tropical with high temperatures. A similar climate reigned in the AP during the TYW, but appears to have developed there already during the early Paleocene.

There is little information on early Eocene climates in SSA, which is probably due to the scarcity of continental outcrops of this age.

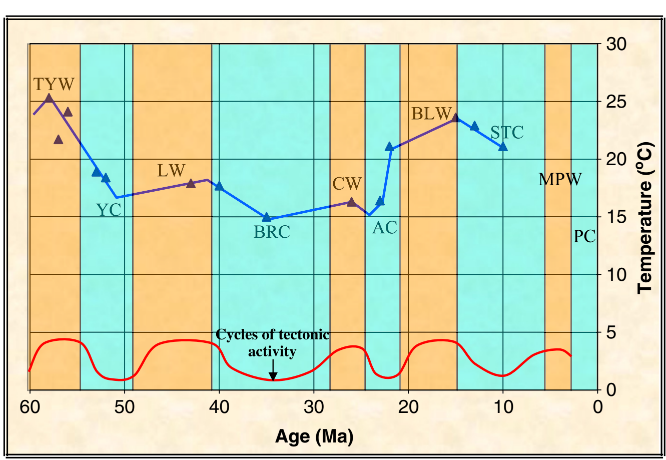

Fig. 7. Mean annual temperatures (blue/black line) in SSA during the Tertiary as derived from physiognomic analysis of Cenozoic taphofloras (modified from Hinojosa, 2005), as correlated with the different climatic and tectonic events described in this paper. Mean error in temperature ±1.5 °C, mean error in age ±2.5 Ma. Vertical orange color bands represent warm periods, blue bands cool periods. Red line at bottom indicates tectonic activity, rising with an increase in sea-floor spreading and related processes, and falling with ridge inactivity and tectonic extension. SDC: Santonian–Danian Cooling; TYW:Thanetian–Ypresian Warming; YC: Ypresian Cooling; LW: Lutetian Warming; BRC: Bartonian–Rupelian Cooling; CW: Chattian Warming; AC: Aquitanian Cooling; BLW: Burdigalian–Langhian Warming; STC: Serravalian–Tortonian Cooling; MPW: Messinian–Pliocene Warming; PC: Pleistocene cooling.

The YC (55–49 Ma) apparently manifested as somewhat cooler and less humid conditions in Patagonia (Laguna del Hunco), but is nowhere strongly reflected.

The LW (49–41 Ma) in northern Chile was characterized by generally arid conditions, whereas fossil floras in south-central Chile indicate a subtropical to humid, temperate–warm climate. Tropical, wet conditions existed in north-western and central Argentina, as well as southern Bolivia. Patagonia experienced a mild to warm climate with abundant rainfall. In the AP, the LW is also represented by a period of mild to warm, all-year round wet conditions which later became more seasonally wet, although mountain glaciers began to develop at higher elevations.

The BRC (41–28 Ma) in northern Chile was marked by a distinct pluvial episode, whereas a dry climate with seasonally wetter conditions existed in the Puna. In south-central Chile, humid, temperate–cold conditions predominated during this period. The BRC in Patagonia was mild to temperate–cold but still humid, marked by a significant expansion of *Nothofagus* forests. During the earlier part of the BRC, *Nothofagus* forests also persisted in the lowland areas of the AP and neighboring islands, but a marked change occurred at about 34 Ma when temperate-cold, seasonally humid conditions set in and wet-based glaciers began to expand.

Semi-arid to arid conditions prevailed in northern Chile during the CW (28–24 Ma). In Patagonia, the presence of certain angiosperm species also indicates warmer temperatures, whereas the spreading of xerophytic plants and inland sabkhas suggest drier conditions. A major interglacial stage was registered in the AP at this time.

The AC (24–21 Ma) was marked by an alternation of pluvial and hyper-arid phases in northern Chile, while central Chile had a temperate–cold and humid climate with a typical Mixed Flora association. In eastern Argentina and Uruguay, semi-arid conditions predominated. The climate in central Argentina was also somewhat drier with temperate to temperate–cold conditions, whereas Patagonia saw the disappearance of megathermal species and the expansion of shrubs and xerophytic plants. Only in southern Chile, abundant rainfall was registered in a cold to temperate climate. The AP was subjected to regional ice-sheet expansion at this time.

The BLW (21–15 Ma) was marked by arid conditions in northern Chile, although the rising Andes Range apparently caused sporadic, orographic rainfall events. In north-central Chile, subtropical vegetation was replaced by sclerophytic shrubs indicating a warm, seasonal climate receiving scarce rainfall from both the east and west. These conditions gave way to a dry, hot climate with Subtropical Neogene taxa in central Chile. The eastern part of south-central Chile apparently experienced tropical conditions, suggesting that the rising Andes Range caused microclimatological conditions in certain areas, as presently observed for example at Chile Chico on its eastern flank. A similar orographic effect is observed in central Argentina, where a change to semi-arid conditions is possibly related to uplift of the Famatima Range toward the end of the BLW. At this time, northeastern Argentina and Paraguay were characterized by seasonally dry, tropical forests and Patagonia became sub-humid to humid and temperate–warm. Forests containing tropical elements flourished in the lowlands, whereas temperate–wet forests existed at higher elevations. In the AP and surrounding areas, glacial retreat took place.

The STC (15–6 Ma) saw a general climatic dessication in northern Chile that reached hyper-aridity in the Atacama Desert, but pluvial phases occurred at 14, 9, and 7 Ma. The last event was also registered in southern Bolivia and north-western Argentina, probably related to the intensification of the South American monsoon and the development of an orographic barrier intercepting moisture from the Amazon Basin. At this time the Arid Diagonal was established across SSA, accompanied by the expansion of sclerophytic vegetation to central Chile. In south-central and southern Chile, temperate–cold conditions were dominant while mountain glaciers developed at higher elevations and across the Andes Range in northwestern Patagonia. In central Argentina, seasonally wet and dry conditions existed toward the end of the STC, indicating an increase in humidity in comparison with the BLW. However, eastern Argentina apparently became somewhat cooler and drier, at least during the early part of the STC. Patagonia also showed an increase in xerophytic taxa, implying increased aridity and seasonality. This led to the replacement of subtropical forests by grass or steppe vegetation. In the AP region, wet-based glaciers again expanded after 15 Ma, becoming dry-based at around 8–7 Ma.

The MPW (6–2.8 Ma) is registered in the Calama Basin of northern Chile by high $\delta^{18}O$ and $\delta^{13}C$ values between 6 and 5 Ma, indicating the onset of hyperaridity which was only fully established between 4 and 3 Ma. However, a pluvial event was registered in the Atacama Basin at about 2.8 Ma, marking the beginning of the PC. In south-central Chile, the MPW was marked by sub-tropical–tropical rainforest vegetation. Central Argentina was characterized by mixed xerophytic and riverine communities, which indicate a hot, semi-arid climate at the beginning of the MPW that later changed to somewhat more humid, temperate–warm conditions. However, during the middle Pliocene, conditions became cooler again. North-eastern Argentina, southern Brazil, Uruguay and eastern Argentina experienced drier, warmer climates than today during the early part of the MPW, but this was followed by a more humid, seasonally contrasted climate. The MPW was apparently not recorded in Patagonia, where glacial expansion continued during the Messsinian–Pliocene period. However, in the AP, the MPW is reflected by wet-based glacier deposits between about 6 and 5 Ma. At 3 Ma these glaciers became dry-based, indicating the onset of the PC.

4.2. Results of general climate studies

The results of these local to regional studies are supported in general terms by subcontinent-wide studies. Hinojosa (2005) undertook a physiognomic analysis of Cenozoic taphofloras from 15 different localities in Chile, Bolivia and Argentina. The results of his univariate and multivariate analyses, presented separately, are here combined in Fig. 7 (blue/black line). This shows that mean annual temperatures were around 23.5 °C during the late Paleocene (TYW), descending abruptly to 17 °C in the Eocene–Oligocene (YC), and jumping again to 22 °C during the early to middle Miocene (BLW). The mean annual rainfall varied between about 1500 and 2000 mm from the early Paleocene to mid-Eocene and then declined sharply to about 500 mm in the late Eocene. This was followed by a general increase to around 1000 mm that lasted until the middle Miocene, before dropping abruptly once more to about 500 mm between the mid-Miocene and earliest Tortonian (Hinojosa, 2005). In spite of the fact that latitudinal and elevation differences were not taken into account, there is a good correlation with general warming and cooling trends as recorded individually for the different regions, as well as cycles of tectonic activity. These are shown by the superimposed vertical color bands and the red line at the bottom of Fig. 7, respectively.

4.3. Relationship between continental climate change, oceanic and tectonic events

In the companion paper (Le Roux, 2012) it is shown that there is a correlation between spreading activity along the mid-ocean ridges and ocean water temperatures. A side-effect of ridge activity that has a strong influence on continental climates, and in particular on mean air temperatures and plant productivity, is an increase in CO_2 and other greenhouse gases such as CH_4. Creber and Chaloner (1985) examined worldwide records of fossil woods from the early Tertiary, finding that there is a zone between paleolatitudes 32°N and 32°S in which specimens are either without rings or have very weakly defined rings. This was interpreted as an indication of a much broader belt of seasonless climate than that of modern low latitudes (23°N–23°S). Fossil wood occurrences also extended into very high paleolatitudes where tree growth is not possible today, while wider tree rings in these areas show that the wood productivity was of a high order. These observations were attributed by Creber and Chaloner (1985) to a worldwide increase in CO_2, which enhanced plant productivity and raised temperatures, thus compensating for the low light intensity at high latitudes.

The release of CO_2 is related to four different processes, namely degassing during the outflow of basalts along the mid-ocean ridges, dissociation of sea-floor methane hydrates or organic-rich sediments heated by the basalts, chemical precipitation of carbonates on continental platforms made wider by sea-level rise, and outgassing at subduction-related volcanoes on the adjacent continents. Carbonate precipitation is enhanced by warmer water temperatures and releases CO_2 into the atmosphere through the reaction $Ca(HCO_3)_2 \rightarrow CaCO_3 + H_2O + CO_2$. Berner et al. (1983) estimated that the present rate of precipitation of carbonate in the ocean by this reaction releases enough CO_2 to the atmosphere to double its content every 3100 years. Studies by Augustsson and Ramanathan (1977), Manabe and Wetherald (1980), and Washington and Meehl (1984) have shown that a doubling in the atmospheric CO_2 will result in the mean global temperature increasing between 1.5 °C and 3.4 °C, with a larger increase at higher latitudes. With a rise in temperature, evaporation increases from the oceans, precipitation increases in the tropics, and the rate of decomposition of soil organic matter increases, releasing more CO_2. Methane (CH_4) is also liberated on a large scale by permafrost thawing (Skinner and Porter, 1995).

In a CH_4- and CO_2-enriched, warm atmosphere, therefore, plant productivity will increase and forests will expand toward the poles. However, longitudinally these forests will shrink because higher sea-levels will take up more continental space. At the same time, although increased plant productivity would consume more CO_2, this would be partly balanced by the release of CO_2 from decaying leaves and wood. The role of forests in absorbing excess CO_2 may thus be less than generally assumed. Furthermore, the amount of carbon present in the atmosphere is only 0.001% of the amount of carbon in carbonaceous rocks (Baes et al., 1977). Therefore, the release of CO_2 by carbonate precipitation in the ocean, as well as outgassing at the mid-ocean ridges and subduction-related volcanoes, would be far more than that produced by the decaying of plants.

In conclusion, long-term climate changes seem to be driven mainly by plate tectonics, with mid-ocean ridge activity leading to higher sea-levels and warmer ocean water, together with an increase in atmospheric CO_2 and CH_4 as a result of volcanic degassing, carbonate precipitation, and permafrost thawing. During these events, vegetation and climate belts expand toward the poles and there is a decrease in the north–south thermal gradient. This debilitates the Westerly Winds and causes a decrease in precipitation in south-central and central Chile. However, the southward expansion of the ITCZ may cause increased winter rainfall on the Altiplano/Puna and in northern SSA. During periods of tectonic inactivity, sea-levels and temperatures fall, climate belts shift equatorward as glacial expansion takes place in Antarctica, and higher wind velocities entrain more dust into the atmosphere, reflecting sunlight back into space. Intensification of the Westerly Winds brings higher rainfall in central and north-central Chile, while summer droughts may occur on the Altiplano/Puna and in northern SSA.

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