DID THE CONTINENT AND SEA HAVE DIFFERENT TEMPERATURES IN THE NORTHERN ANTARCTIC PENINSULA DURING THE MIDDLE EOCENE?

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ABSTRACT:
The Seymour Island beds include a remarkable representation of the continental flora and fauna and marine fauna of Eocene in southern high latitudes. We suggest that, at least during the deposition of the best sampled unit, the *Cucullaea* I Allomember of the La Meseta Alloformation in the Seymour Island area, a cold temperate terrestrial environment co-existed with relatively warmer temperatures in the adjacent shallow shelf sea. This is suggested by the fish and invertebrate fauna and could have been due to the presence of warmer waters of a current reaching the region from the north. The temperature drop proposed for the time of deposition of the uppermost part of the La Meseta Formation (Submeseta Allomember) appears to correspond to the global drop of the end of the Eocene and beginning of Oligocene and not to the establishment of the Antarctic Circumpolar Current.

Keywords: *Climate, Eocene, Antarctica, La Meseta Formation, Seymour Island, Marine, Continental.*

RESUMEN: *Eran diferentes las temperaturas continentales y marinas durante el Eoceno Medio en el norte de la Península Antártica?*
Los estratos de la Isla Seymour incluyen una notable representación de flora y fauna continentales y fauna marina del Eoceno de altas latitudes australes. En este trabajo sugerimos que, un ambiente terrestre templado frío coexistió al menos durante la depositación de la unidad mejor muestreada, el Alomiembro Cucullaea I de la Aloformación La Meseta en el área de la Isla Seymour, con un ambiente marino costero y somero con temperaturas más cálidas. Esto es sugerido por la fauna de peces e invertebrados y pudo deberse a la presencia de una corriente de aguas cálidas que alcanzó el norte de la península. La caída de temperatura propuesta para el momento de depositación de la parte más superior de la Formación La Meseta (Alomiembro Submeseta) parece corresponder con la caída global a fines del Eoceno y comienzos del Oligoceno y no al establecimiento de la corriente circumpolar antártica.

Palabras clave: *Clima, Eoceno, Península Antártica, Formación La Meseta, Isla Seymour, Marino, Continental.*

INTRODUCTION

There is currently some debate about the climatic transition from the Cretaceous "greenhouse" to modern-day "icehouse" conditions (Pfuhl and McCave 2006). A fundamental record for this discussion is included in the Paleogene rocks of Seymour Island in Antarctica (Fig. 1). These beds are highly fossiliferous and yielded a remarkably diverse assemblage of plants, invertebrates and vertebrates that have provided the most detailed record of high-latitude southern Eocene organisms to date (e.g., Feldmann and Woodburne 1988). Nearly all phyla commonly preserved in the fossil record have been described from the unit (Schweitzer *et al.* 2005). Both continental and marine organisms indicate that the environment was completely different to that present in Antarctica today.

Zinsmeister (1979, 1982) proposed a biogeographic unit of shallow marine waters (the Weddellian Province) that encompassed the coasts of Australia, Tasmania, Antarctica and southern South America during the late Cretaceous through Eocene. The sea around Seymour Island was considered to be cold temperate during the Eocene by some authors (e.g., Case 1992, Long 1992a) although Long (1992c) noted the presence of some shallow water tropical migrants that occasionally entered the area. Case (1988) included in this biogeographic province the continental flora and fauna. These latter were characterized by the association of megafloral assemblages dominated by the Southern Beech, *Nothofagus* sp. and marsupials of the family Polydolopidae. Later, some new floral and faunal taxa were reported (see Reguero *et al.* 2002).

The Eocene rocks from Seymour Island contain a record of marine (and continental) organisms representing ecosystems with no Recent parallels, as they developed in relatively warm environments in a sunlight/darkness-stressed setting (Parras *et al.* 2005).

Indeed, we found that proxies suggest large differences among the temperature preferences of marine and continental organisms present at least in some levels of the Eocene La Meseta Formation. We discuss them and propose a cause for explaining these differences in the oceanographic pattern present at that time.

METHODS

The fossil record in the La Meseta Formation is extremely diverse. In this paper we refer only to the *Cucullaea* I Allomember of that formation (Marenssi *et al.* 1998

a, b).
We selected some organisms as proxies due to their abundance and significance as indicators. Among fishes, the extreme abundance of neoselachians in the record is due to taphonomic reasons, as it is the case in other shallow marine deposits (see Cione 1988). For neoselachian we considered only the better sampled localities (IAA 1/90 and IAA 2/95, both close and correlative). Most of the material comes from IAA 1/90 which yielded by dry screening more than 8000 teeth in different campaigns.
Many sharks are highly mobile animals. They can (and do) follow the optimal environmental conditions by migrating along the coasts, crossing ocean stretches or displacing to deeper or shallower waters (see discussion in Long 1992a). Concerning migrating species, fossil representation corresponds to those that present their optimum in summer or in winter. This is a radical difference with fossil sessile or non-migratory organisms (most invertebrates, rays) which indicate tolerance to winter conditions in the area (Cione and Barla 1997, Cione et al. 2005). Migratory individuals from warm waters indicate summer temperatures (e.g., odontaspidid and isurid sharks; see Cione *et al.* 1994; Cione and Azpelicueta 2002). Migratory individuals of taxa from cold areas indicate winter temperatures (e.g., the porbeagle shark *Lamna*).
There is some debate about what is called warm temperate and cold temperate water in littoral populations. Stephenson (1953) as summarized by Knox (1960; also adopted by Briggs 1974) proposed that warm temperate waters have a minimal temperature (average for the warmest month) of between 12° and 20°C and a maximum summer range (average for the warmest month) near or somewhat exceeding 25°C. In cold temperate waters the temperature (average for the coldest month) should fall below 12°C in the winter, but usually not to zero; summer mean temperatures may approach 20°C. The Cold temperate region is divided into two sub-regions: Subantarctic cold temperate, with a mean temperature range from 3 to about 14-15°C and Cold temperate mixed waters with a mean temperature range of 7 to 18°C. Knox (1960) commented that thermal boundaries are not equal everywhere. Knox (1960) suggested that in the Antarctic waters the temperatures fall below zero in the winter and do not exceed 3-5°C in the summer (see also Charnock 1996).
In the southwestern Atlantic, the shelf Argentinian Province (Fig. 2; see below) reaches waters of about 8°C or less (in the coldest month). Knox (1960) considers this area as cold temperate. However, species present there are clearly different from those of the Magallanian Province and are similar to those inhabiting waters to the north of the Rio de la Plata that are identified as warm temperate by Knox (1960). Argentinian zoologists consider the Argentinian Province as warm temperate (e.g., López 1964, Menni 1981).

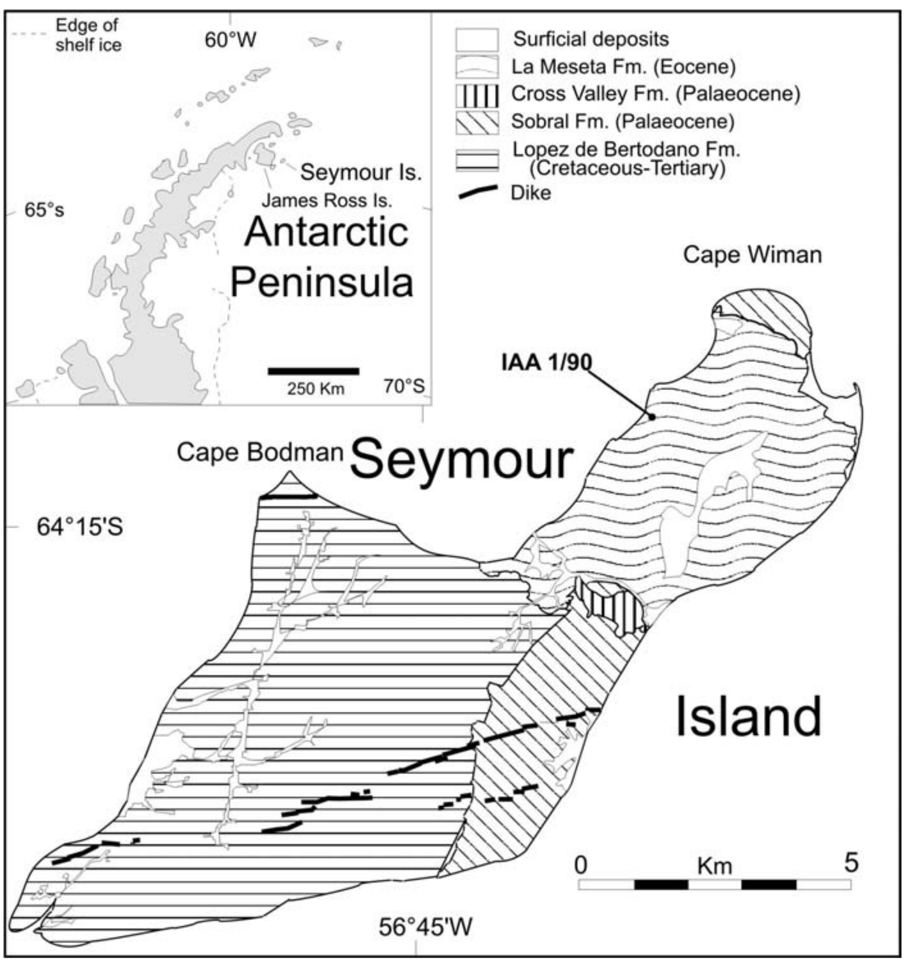

Figure 1: Map of Seymour (Marambio) Island showing locality IAA 1/90.

Abbreviations
ACC, Antarctic Circumpolar Current; DP, Drake Passage; LMF, La Meseta Formation; TG, Tasman Gateway.

SEYMOUR ISLAND GEOGRAPHIC AND PALEOGENE STRATIGRAPHIC SETTING

The early Eocene/early Oligocene La Meseta Alloformation is an unconformity-bounded unit (La Meseta Alloformation of Marenssi *et al.* 1998a, 1998b). This unit has a maximum composite thickness of 720 meters filling up a 7 km wide valley cut down into the older sedimentary rocks of the island after the regional uplift and tilting of the Paleocene and Marambio Group beds (Fig. 3).
It comprises mostly poorly consolidated siliciclastic fine-grained sediments deposited in deltaic, estuarine and shallow marine en-

vironments as a part of a tectonically-controlled incised valley system (Marenssi 1995, Marenssi *et al.* 1998b). This unit is made up of several lens-shaped unconformity-bounded members representing different sedimentation stages (Marenssi *et al.* 2002).

Paleoenvironmental reconstructions indicate that the La Meseta Alloformation accumulated at the seaward end of an incised valley during an overall rise in sea level (Marenssi 1995, Marenssi *et al.* 1998a). Recent studies of the geometric relationships in the La Meseta Alloformation (Sadler 1988, Marenssi 1995, Marenssi *et al.* 1998b) show that the steep erosional boundaries are the margins of a large channel some 7 km in width that originated farther west. The head of the La Meseta incised valley was placed almost 60 km to the northwest, at the toe of the Antarctic Peninsula (Stilwell and Zinsmeister 1992).

$^{87}Sr/^{86}Sr$ ratios of bivalves from the highest shell-bearing marine bed in the Submeseta Allomember yield ages of 33.57-34.78 Ma (Ivany *et al.* 2006), and are the youngest documented ages from the La Meseta Alloformation and confirm that the unit extends to the E-O boundary (33.9 Ma; Gradstein *et al.* 2004). The oldest dates, 52-54 Ma (based on $^{87}Sr/^{86}Sr$ isotopic ratios after Reguero *et al.* 2002), in the formation come from the 150 m level in the boundary of the Valle de las Focas and Acantilados allomembers of Marenssi and Santillana (1994). Consequently, the base of the La Meseta should be close to the beginning of the Eocene at 54.8 Ma (Gradstein *et al.* 2004).

The unit is unconformably overlain by Pliocene-Pleistocene till of the Weddell Sea Formation (Zinsmeister and DeVries 1983, Gazdzicki *et al.* 2004).

RECENT OCEANOGRAPHY AND CLIMATE

Figure 2: South American shelf marine biogeographic units (modified from López 1964) and the Subantarctic Province (modified from Cabrera and Willink 1973). Note that both units scarcely overlap in latitude.

The dominant feature of the current system of the southern region is the Antarctic Circumpolar Current which influences the greatest part of the Antarctic oceanic region and the whole of the temperate oceanic region (Knox 1960, Fig. 4). It branches into currents flowing northerly off the coast of the major land masses. On the western part of South America it becomes in the Humboldt Current (also Peru Current). In the Drake Passage, the Antarctic Circumpolar Current is named Cape Horn Current which, after passing the southern tip of the continent, divides into two branches. The west branch passes on both sides of the Malvinas (Falkland) Islands and is called the Malvinas Current. It finds the warm southward Brazil Current at about 43°-46° S and turns east (López 1964). The Humboldt Current is much stronger than the Malvinas Current and its influence extends to near the Equator (Sverdrup *et al.* 1942). The combined effect of the northerly transport and upwelling is to produce that the average surface temperatures off the coast of Peru are something like 10°C lower than the theoretical values for the latitude (Knox 1960).

Warm currents are prevented (by the offshoots of the Antarctic Circumpolar Current) from circulating the sun´s heat away from tropical and temperate latitudes into the polar region (Pielou, 1992).

The southern ocean is divided into several regions on the basis of surface temperatures (Fig. 5). With increasing distance from the Antarctic continent temperature increases slowly until a region within which an

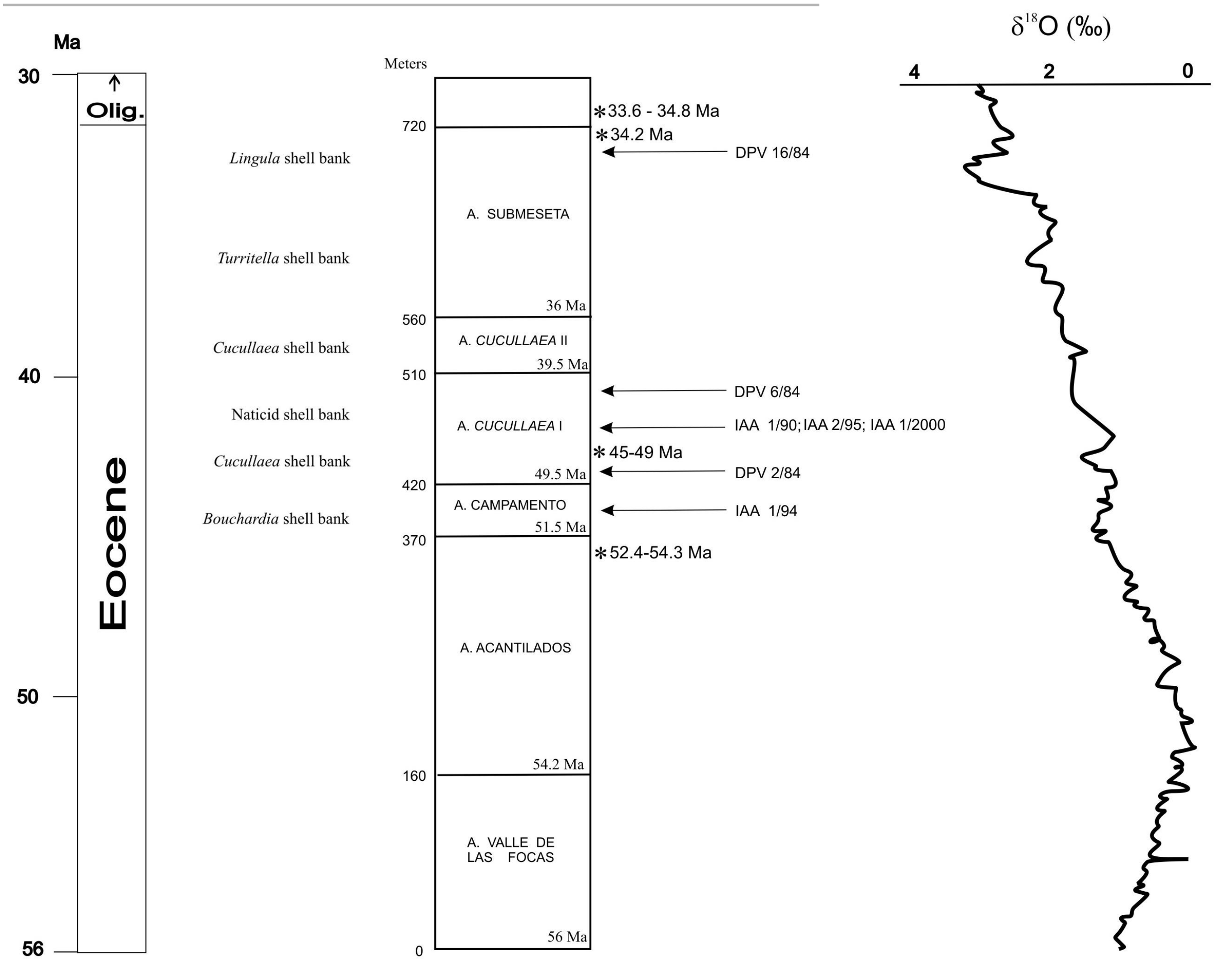

Figure 3: Comparison of temperature curve (according to Zachos *et al.* 2001) with La Meseta Formation unconformity-bounded internal units and ages (after Marenssi 2006).

increase of 2 or 3°C takes place in a very short distance (Knox 1960). This region is called the Antarctic Convergence. Further to the north, the surface temperature rises slowly until another region of rapid increase of about 4 or 5°C, the Subtropical Convergence. Both convergences limit the Antarctic region and the Subantarctic region (Knox 1960).

RECENT BIOGEOGRAPHY OF ANTARCTICA AND SOUTH AMERICA

a) Marine

Different authors have divided the coastal marine waters of South America into biogeographic areas. Regan (1914) distinguished that the fishes determined a Temperate Zone with Argentinian and Chilean Districts and a Subantarctic Zone with the Magallanian and Antipode Districts (also an Antarctic Zone). Eckman (1953) distributed the whole marine fauna into Shelf Warm Waters Faunas, Temperate Waters Faunas, Warm-Temperate Waters Faunas and Antarctic Faunas.

López (1964) considered the following icthyogeographic units in South America: Magallanian Province (cold-temperate waters) with two districts, South Chilean and Patagonian; Argentinian Province (warm-temperate waters) with two districts, Bonarian and South Brazilian; West Indian Province (warm waters) with three districts, Gulf of Mexico and Caribbean, Antillean, and Brazilian (Fig. 2). Balech (1964) proposed a rather different scheme. Menni (1981, 1983) commented the biogeography of fishes and Martínez and del Río (2002) that of mollusks.

The Magallanian Province occupies the southernmost part of South America. According to López (1964), in the Atlantic coast it reaches 42°S and in the Pacific 40-41°S (Fig. 2). According to Balech (1964), it reaches 43°S and 40°S respectively. However, in the outer platform and talud the Magallanian Province reaches about 34°S. At latitude of 43º to 45ºS separates from the coast.

The Argentinian Province ranges from about 42°S to 23°S according to López

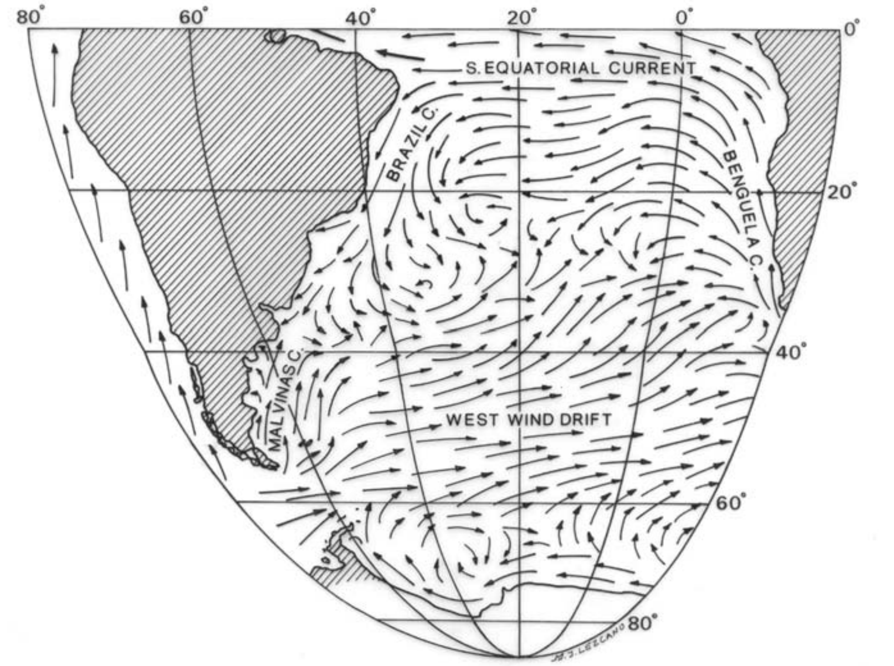

Figure 4: Recent marine circulation in southern Atlantic Ocean (modified from Sverdrup *et al.* 1942).

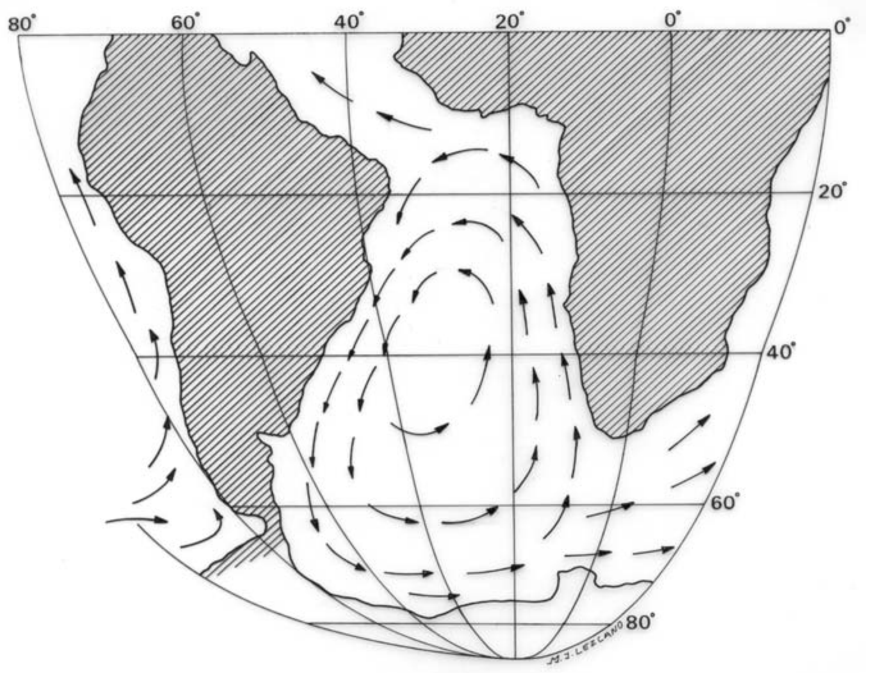

Figure 5: Antarctic and Subantarctic convergences (modified from Knox 1960).

(1964).

However, boundaries between the Argentinian and Magallanian provinces could be presently changing due to the global temperature changes (see Góngora *et al.* 2003).

Waters around Antarctica, beyond the Antarctic Convergence, have a distinctive fauna.

b) Continental

Botanists and some general biogeographers consider an austral Recent biogeographic unit called Antarctic Region that encompasses part of South America and New Zealand (Cabrera and Willink 1973). Most zoogeographers do not accept that parts of South America were not included in the Neotropical Region (e.g., Ringuelet 1961). In South America, the Subantarctic Province of the Antarctic Region is recognized in southern Chile and westermost southern Argentina between 37°S and 55°S (Fig. 2). The climate is cold temperate and wet. Evergreen conifer/broad-leaf forests dominate, but there are also open areas. Rainfall in these areas is very high, mainly in summer and spring seasons, with an average precipitation from 1000-3000 mm/y and freezing temperatures can prevail during several months of the year. The unit is characterized floristically by the predominace of genera (or even families) of austral distribution. Genera most important are *Nothofagus, Dacrydium, Laurelia, Lomatia* and others (Cabrera and Willink 1973). The endemic taxa are a family (Misodendracea) and several genera (*Fitzroya, Austrocedrus, Pilgerodendron, Macrachenium, Combera*).

TAXA AND CLIMATE

The paleobotanical record of Paleogene Antarctic vegetation indicates the loss of warm-temperate vegetation and the increased dominance of other types more typical of high latitude environments (Askin 1997, Birkenmajer and Zastawniak 1989, Francis 1999).

Paleofloral data sets show that the middle late Eocene was warmer than present, but not as warm as the late Paleocene (Cross Valley Formation) through early Eocene (Acantilados Allomember, La Meseta Alloformation). Paleoflora from the middle part of the La Meseta Alloformation (RV 8200, IAA 1/90, and DPV 3/84 = C/88, from *Cucullaea* I Allomember) indicate a drop in temperature (Case 1988, Gandolfo *et al*. 1998) with respect to lower levels of the sequence.

Nothofagus is considered to be of critical importance as an paleoclimate indicator. *Nothofagus* is the predominant angiosperm taxon in each of the three paleofloras from the La Meseta Alloformation mentioned above. Gandolfo *et al.* (1998) reported *N. serrulata* and two indeterminate species of the same genus from the late early Eocene

Acantilados Allomember (A/88). The former species is now restricted to southern South America, where it grows in a cool temperate climate. *Nothofagus serrulata* extends from southern Chile (Carmen Silva, Loreto, and Brush Lake Formations) and Argentina (Río Turbio, Río Guillermo, and Ñirihuau formations) to the southern shores of Tierra del Fuego Province (Cullen Formation), and thus provides a stronger geographical link to Antarctica than is suggested by other South American species (Fig. 2) (Reguero *et al.* 2002).

EVOLUTION OF CLIMATE DURING THE PALEOGENE

Paleoclimatic interpretations of the Paleogene of the James Ross Basin were proposed using different lines of evidence (sedimentology, fossils and stable isotope analysis). The idea of a temperate marine environment from the late Cretaceous through the late Eocene has been proposed some time ago based on the presence of particular taxa of marine mollusks (Weddellian Province of Zinsmeister 1982). It was recently confirmed by stable isotope analysis (Gazdzicki *et al.* 1992, Dichfield *et al.* 1994; Pirrie *et al.* 1998, Dutton *et al.* 2002). Francis (1991) interpreted a marked cooling of the climate during the Cretaceous-Paleocene transition on Seymour Island based on the study of growth ring patterns of tree trunks collected from the López de Bertodano and Sobral formations. By the time of deposition of the Cross Valley Formation (Upper Paleocene) the climate had returned to a warmer level (Francis 1991). Gandolfo *et al.* (1998) indicate the presence of subtropical forests based on the percentage of entire margin leaves (43%) from the same unit. Likewise, several lines of evidence point to indicate a seasonal cool-temperate rainy climate for the Middle Eocene of the Seymour Island with a cooling trend through the Eocene till the earliest Oligocene (Case 1988, Francis 1991, Torres *et al.* 1994, Gandolfo *et al.* 1996, 1998). Case (1988) suggested that the nothophyllous leaves of the lower part of the La Meseta Alloformation indicate a period of climatic amelioration with respect to the middle and upper part of the unit where microphyllous leaves were recovered. The palynoflora presents austral characteristics (Zamaloa *et al.* 1987) while taxonomic analysis indicates a mixture of Antarctic (dominant) and neotropical megafloral elements (Gandolfo *et al.* 1998). Morphological analysis of the leaves led Gandolfo *et al.* (1998) to interpret the presence of a mixed mesophitic forest (32% of entire margin leaves) developed under a seasonal cool-temperate climate with dry and rainy seasons. Mean annual paleotemperatures were calculated to be between 11º and 13ºC and the mean of the coldest months between -3º and 2ºC.

The marine temperature of the Seymour Island area, on the basis of oxygen isotope ratios of late Eocene invertebrate shells, was estimated as 8°C for the minimum winter temperature and 12°C for the minimum summer temperature (Kennett and Barker 1990).

Geochemistry and clay mineralogy of sedimentary rocks from Seymour Island were used to interpret the climatic evolution of the northern Antarctic Peninsula area since the Late Cretaceous (Dingle and Lavelle 1998). A cool period is indicated during the Early Paleocene before the climatic optimum of the Cenozoic (late Paleocene-early Eocene) followed by a climatic deterioration from very warm, non-seasonally wet conditions (early middle Eocene) to a latest Eocene cold, frost-prone and relatively dry stage (Dingle *et al.* 1998).

The sudden, widespread glaciation of Antarctica and the associated shift towards colder temperatures at the Eocene/Oligocene boundary (~34 million years ago) (Zachos *et. al.* 1996, 2001, Barrett 1996, Lear *et al.* 2000) is one of the most fundamental reorganizations of global climate known in the geologic record. The glaciation of Antarctica has hitherto been thought to result from the tectonic opening of Southern Ocean gateways, which enabled the formation of the Antarctic Circumpolar Current and the subsequent thermal isolation of the Antarctic continent (Kennett 1977).

The earliest Oligocene (ca. 33.5 Ma) is marked by a rapid and significant positive shift in the oxygen isotope value of marine carbonates, and the appearance of ice-rafted debris in the Southern Ocean that corresponds to the first major expansion of Antarctic ice in the Cenozoic (Zachos *et al.* 1992).

The opening of Southern Ocean gateways and the formation of the Antarctic Circumpolar Current undoubtedly cooled high southern latitudes. However, the simulated effect of a 20% change in ocean heat transport associated with the opening of Drake Passage is shown to have a smaller effect than that expected in the transition from a 'greenhouse' to an 'icehouse' climate. In our model, the opening of Drake Passage can only be a potential trigger for glacial inception when atmospheric CO2 is within a relatively narrow range, reinforcing the importance of pCO2 as a fundamental boundary condition for Cenozoic climate change (DeConto and Pollard 2003).

ESTABLISHMENT OF THE DRAKE PASSAGE

A highly debated issue is the establishment of the modern circulation around Antarctica. Actually, the Antarctic Circumpolar Current is a strong, wind-driven current, which in parts reaches the ocean-floor and significantly limits meridional heat-exchange in the Southern Hemisphere (Barker and Thomas 2004, Pfuhl and McCave 2006). The Antarctic Circumpolar Current inception depended on changes in atmospheric circulation patterns but was determined by the separation of Antarctica after the establishment of the Tasman Gateway south of Australia and the Drake Passage south of America to deep throughflow (Lawver and Gahagan 2003, Pfuhl and McCave 2006).

Major plate motions based on dated seafloor spreading anomalies and distinct fracture zone lineations constrain the age of the opening of a seaway between the South Tasman Rise and Antarctica as very close to the Eocene/Oligocene boundary, with an unrestricted opening deeper than 2000 m dating from ~ 32 Ma.

Timing of the opening of Drake Passage is more circumstantial because the exact motions of certain micro-continental fragments are not known. Uncertainty of motion of the South Georgia and South Orkney microcontinents and other possible continental fragments make an exact time for opening of Drake Passage difficult to ascertain. Even so, the early Oligocene position of the Antarctic Peninsula with respect to South America requires a throughgoing, deepwater seaway to have been open at Drake Passage prior to 28 Ma, even given the unconstrained motion of various highstanding crustal fragments in the Scotia Sea. With reasonable assumptions concerning motion of the crustal fragments in the western and central Scotia Sea, it is likely that Drake Passage or passage through Powell Basin was open to deep water circulation by ~ 31 ± 2 Ma. Recent investigations in the Leg 189 to the Tasman Gateway, suggest that a homogenous Southern Ocean water mass did not exist prior to the mid-Oligocene interval (Pfuhl and McCave 2006, see also Beu *et al.* 1999).

MARINE AND CONTINENTAL TEMPERATURES DURING THE DEPOSITION OF CUCULLAEA I ALLOMEMBER

Global temperatures during the Eocene were in general much higher than today (see above).

Warm temperate conditions during the deposition of the *Cucullaea* I Allomember are suggested by the presence of typically warm-water taxa such as *Cucullaea*, *Poli-nices, Autratoma, Ringicula,* ficids and ranellids (Stilwell and Zinsmeister 1992). Additional support for relatively warm temperatures is provided by the presence of a number of extinct austral taxa such as the bivalve *Lahillia*, and the gastropods *Struthiolarella*, *Taioma* and *Struthioptera*, which are known from early Tertiary warm-temperate facies of Australia and New Zealand. Shells of the bivalve *Cucullaea* are very abundant and form banks in the Cucullaea I and II allomembers. Shells of brachiopods *Glottidia* and *Bouchardia* form banks in several levels of the La Meseta Alloformation including *Cucullaea* I Allomember (Emig and Bittner 2005). Two fossil species of *Bouchardia* appears to occur in most localities cited in La Meseta Alloformation (Wiedman *et al.* 1992). A close relative of these two species, *B. rosea*, is currently found living in shallow waters off the South American coast at the latitude of Rio de Janeiro and perhaps to the south (Manceñido and Griffin 1988). These waters correspond to the Sudbrazilian District of the Argentinian Province (Fig. 2).

Cirripeds also indicate warm waters. *Austrobalanus* is represented by a single extant species restricted to the warm, temperate southeast coast of Australia. Extant *Scoliodobalanus* achieves its greatest diversity in the tropical and subtropical Indo-West Pacific region, but species are also known from warmer regions of the Atlantic Ocean (Zullo *et al.* 1988).

We only considered neoselachian proportions from the best sampled locality (IAA 1/90; and in part IAA 2/95) which correspond to a bank of naticids (mostly *Polynices*) in the *Cucullaea* I Allomember. Actually, most of the fish taxa mentioned here are found in many different levels of the La Meseta Alloformation excepting the upper levels; however, they are currently being restudied. The most abundant (according to tooth number) taxa are *Squatina* (37.89%), *Pristiophorus* (22.45%), Odontaspididae (17.24%), *Myliobatis* (6.70%), *Squalus* (6.81 %), Rajidae (4.72) and Holocephali (2.68 %). The other taxa are present in a much smaller proportion (*Centrophorus, Stegostoma fasciatum, Cetorhinus, Dalatias licha, Carcharocles auriculatus, Isurus praecursor, Lamna, Scoliodon*). The shark assemblage suggests shallow waters (discussed in Long 1992c. There are some species with affinities to deeper waters but these taxa have also been found into shallow water deposits from other parts of the world (e.g., Miocene of Patagonia; Cione 1988). Most neoselachian families and genera that dominate are typical of the Argentinian province of central Argentina, Uruguay and Brazil: odontaspidids (represented in La Meseta Alloformation

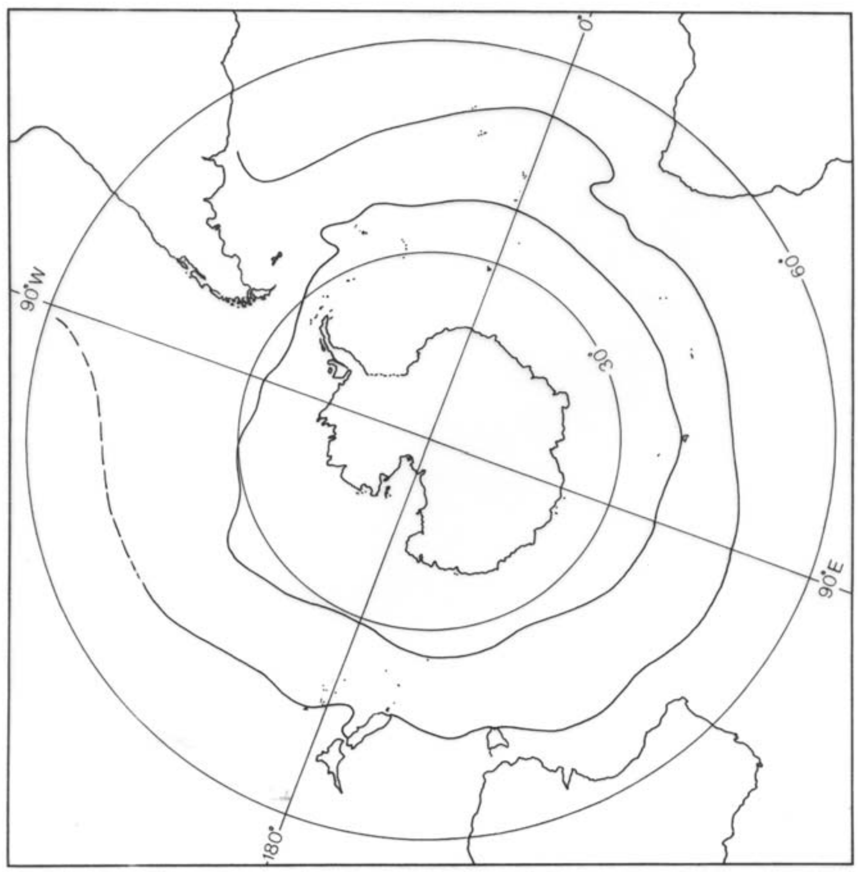

Figure 6 A land connection between South America and Antarctica was suggested for the Cretaceous (Case et al. 1988). Does it persist until the Early Eocene as mammal evidence suggest? A model of marine circulation during Eocene times previous to the establishment of the Antarctic Circumpolar Current is depicted.

mainly by *Striatolamia macrota*, *Odontaspis rutoti and Odontaspis winkleri*), squatinids (*Squatina*), and myliobatids (*Myliobatis*) (see Menni 1981, Cousseau and Perrotta 1992). These families have almost no representation in the Magallanian province. Other common taxa such genus *Squalus* (represented by *Squalus woodburnei* and *S. weltoni*) and pristiophorids are wide-ranging in warm and cold temperate seas (Compagno *et al.* 2005). Pristiophorid sharks became extinct in southern Atlantic after the Miocene (Cione and Azpelicueta 2002). Remarkably, there are several taxa that presently inhabit warm temperate to tropical areas (e.g., the sharks *Stegostoma, Isurus,* the carcharhinids *Carcharhinus* and *Scoliodon*) and Pristis, the teleosts *Oplegnathus*, and Trichiuridae; Long 1991, 1992b, 1992c. Cione and Re-guero 1994, Cione *et al.* 1994, Kriwet 2005). The porbeagle shark *Lamna* occurs both cold and warm temperate waters (Compagno *et al.* 2005) but is rare in the unit. Consequently, ichthyological evidence suggests that sea temperatures would have been similar to those of the recent marine Argentinian Province especially those of the Sudbrazilian District (e.g., Cione 1978, Long 1992 b, Cione and Reguero 1994. Cione *et al.* 1994, Fig. 2).

On the basis of oxygen isotope ratios on Late Eocene shells in Seymour Island areas, mean temperatures appear to have been above 8°C in winter and above 15°C in summer (Kennett and Barker 1990).

On the continent, plant (Gandolfo *et al.* 1998), geological and palynological (Askin 1997, Dingle *et al.* 1998) evidence suggest that the climate in Seymour Island would have been similar to that of the recent Subantarctic Province (the Valdivian forest) of southern Chile and Argentina (see also Case 1988, Reguero *et al.* 2002, Poole and Cantrill 2006, Fig. 2). Moreover, microbiotheriid mammals still live in this province. The Subantarctic Province has a cold temperate and wet climate, with annual mean temperatures between 11°C and 13°C and the coldest month mean between -3°C and 2°C (Gandolfo *et al.* 1998). Certainly, temperatures could be colder in higher altitudes and in the southernmost area.

The northern part of the Subantarctic Province scarcely overlaps the latitude of the southern part of the Argentine Province (Fig. 2).

Palynological and geological continental evidence agree with a dramatic shift to colder conditions both in the marine and continental environments at the top of the La Meseta Alloformation (Dingle *et al.* 1998, Poole and Cantrill 2006). Invertebrate diversity is low in the basal part but steadily increases to a peak in the abundant shell lenses of *Cucullaea* I Allomember (Stilwell and Zinsmeister 1992). However, a sharp decrease in diversity occurs near the boundary *Cucullaea* II and Submeseta allomembers. In agreement, in the Submeseta Allomember, the largest diversity of penguins occurs (Tambussi *et al.* 2006), there is a dramatic diminution of diversity of those selachians that dominated below, there are no teleost taxa characteristic of warm water (e.g., Labridae, Oplegnathidae, Xiphiorhynchidae), sharks dramatically decreases in diversity and quantity (a few *Pristiophorus* and odontaspidid teeth) and begin to predominate some sharks (*Lamna*) and teleosts with species characteristic of colder waters (e.g., gadiforms of the informal genus "*Mesetaichthys*") are recorded.

Marine temperatures depend on latitude, but also on the current pattern. Presently, the two branches of the Antarctic Circumpolar Current that run along the eastern and western coasts of South America are different in strength (Fig. 4). This difference cause that temperatures are very different on both sides of the continent and that biogeographic pattern is different.

During the Eocene, notwithstanding that some circulation could exist in Drake area (Wrenn and Hart 1992), there was not a well developed Antarctic Circumpolar Current and consequently no author proposed the existence of the equivalent to Humboldt and Malvinas currents. Smith and Briden (1977 fide Manceñido and Griffin 1988; see also Parrish and Curtis 1982) suggest a model of circulation for the Paleogene that involves a warm current running southward along the eastern coast of South America at least to the present Drake Passage latitude (Fig. 6). Both the terrestrial fauna of southern South America and Seymour Island suggest that a terrestrial connection existed at least until de early Eocene. Mammal taxa in the Vacan Subage (early Eocene) permit to propose a terrestrial communication for the sparnotheriodontids in Antarctica near the Vacan Subage (early Eocene) or Riochican Age (late Paleocene; Bond *et al.* 2006).

In the Weddell area, a counter current that flowed northward along the eastern coast of the Antarctic Peninsula exists today (Sverdrup *et al.* 1942). There is no evidence of its presence in the Eocene and the southward current could have extended into the southernmost regions. Actually, the Weddell area could have some similarity to the present northeastern Atlantic area, where the North Atlantic Current warms higher latitude areas (Sverdrup *et al.* 1942).

In summary, we suggest that, at least during the deposition of the *Cucullaea* I Allomember of the La Meseta Alloformation in the Seymour Island area, a cold temperate terrestrial environment coexisted with relatively warmer temperatures in the adjacent shallow shelf sea. This could have been due to the presence of waters of a warm current reaching the region. The temperature drop proposed for the time of deposition of the uppermost part of the La Meseta Formation (Submeseta Allomember) appears to correspond to the global drop of the end of the Eocene and beginning of Oligocene and not to the establishment of the Antarctic Circumpolar Current.

THE WEDDELLIAN PROVINCE

The Weddellian Province was proposed as a shallow water and temperate marine shelf region that encompassed New Zealand, Tasmania, Australia, Antarctica and southern South America during the late Cretaceous through Eocene (Zinsmeister 1979, 1982, Woodburne and Zinsmeister 1984, Zinsmeister and Feldmann 1984). At this time, these continents were proximate and shared many marine taxa.

This biogeographic hypothesis was expanded to include the terrestrial fauna and flora (Case 1988). The province was based on the predominance of species of the Southern Beech *Nothofagus* and caenolestid marsupials.

However, marine and continental biogeographic (both large and small) units do not necessarily have the boundaries at the same latitude. In South America, continental units (see Cabrera and Willink 1973) hardly have something to do with shelf units (see López 1964). Actually, in southern South America there is an approximate coincidence in the northern boundary of the marine Magallanian Province with the continental Subantarctic forest in the western side of South America. However, the northern boundary of the marine Magallanian Province does not agree with a continental biogeographic boundary on the eastern side of South America (López 1964, Ringuelet 1961, Cabrera and Willink 1973, see Fig. 2). In this case, as in many others, the marine organism distribution is greatly affected by marine currents, the western and stronger Humboldt Current and the eastern Malvinas Current. On the other hand, the continental topography and climate greatly determine the continental organism distribution (Ringuelet 1961, Cabrera and Willink 1973).

We found that the marine fauna appears to correspond to warmer environments that the continental in the Eocene of Seymour Island (see above). Moreover, plant taxa present in the La Meseta Formation do not appear to differ much from those of the recent Subantarctic Province of southern Chile and Argentina (i.e., a flora dominated by species of genus *Nothofagus*; Cabrera and Willink 1973). A typical inhabitant is also a small marsupial, the microbiotherid *Dromyciops gliroides*.

Consequently, it appears more appropriate to restrict the term Weddellian Province for the marine realm and perhaps to propose a different one for the continent.

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