Utrecht University

A more comprehensive understanding of the Antarctic Circumpolar Current

The emergence and development of the ACC described with the help of knowledge obtained by studies using several scientific techniques

Bachelor thesis Very Compen

Studentnumber: 5509351

First supervisor: Dr. Peter Bijl

Second supervisor: Dr. Francesca Sangiorgi

Department of Earth Sciences

Faculty of Geosciences

Utrecht University

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Abstract

The Antarctic Circumpolar Current is nowadays an important ocean current with the highest volume transport of all ocean currents and relatively many of its characteristics are known. However, the estimates on the onset time of the ACC vary widely. The aim of this thesis is therefore to establish a more comprehensive understanding of the onset and development of the ACC. A scientific literature search on the ACC was performed to research if the difference in the defined ages of the ACC is due to a difference in the definition of the ACC within earth scientific subdisciplines, due to a fundamental difference in definitions and descriptions used for the ACC per individual research or due to the fact that the ACC had multiple onsets. Interpretations of the results were later addressed in the discussion section and new hypotheses were established. The outcome of this thesis is that the difference in the estimated age of the ACC is due to a fundamental difference in definitions and descriptions that are used for it. The development of oceanic gateways that led to the current ACC has become generally clear. First, a westbound Antarctic Counter Current was in place at approximately 50-49 Ma. This current did not completely encircle Antarctica, as the Drake Passage was still closed. Between 49 and 41 Ma, but probably after 45 Ma, the first shallow eastward current encircled Antarctica. The first analogue of the modern ACC was established between 37 and 30 Ma. This current was of intermediate to deep depth and it had gained strength since the appearance of the first eastward current. The state of the ACC between 30 and 15 Ma is uncertain, although it is hypothesized that it weakened between 30 and 22 Ma, after which its strength remained approximately the same until about 15 Ma. The ACC gained strength in the period between 15 and 10 Ma, in which a full developed, strong and coherent ACC is reported. Lastly, the modern ACC exists of jet streams that each correspond to fronts which are predominantly steered by bathymetry.

Keywords: Antarctic Circumpolar Current; Drake Passage; Tasmanian Gateway; Southern Ocean

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Introduction

At present, the Antarctic Circumpolar Current (ACC) is the largest and strongest ocean current and it connects the Atlantic, Indian and Pacific Ocean basins. Therefore, it is nowadays an important current nowadays that serves as a conduit of all active and passive oceanic tracers that affect Earth's climate, notably heat and salt which strongly influence the oceanic mass stratification, circulation and consequently the ocean heat transport and the greenhouse gas carbon dioxide (Olbers et al., 2004). However, it is not clear how the early ACC is exactly defined and estimates of its onset time vary widely. For instance, scientists agree upon the fact that the ACC is originated in the Cenozoic (66 Ma to recent) and estimate its age between 50 Ma and 11 Ma (e.g. Dalziel et al., 2013; Sijp et al., 2016), but consensus on a specific time of onset has not been reached yet. The geological dating of this time is nevertheless important, because any variability in the state of the ACC had consequences for oceanography and climate. However, the uncertainty of the onset time might not lie within the dating of the ACC, but either in a fundamental difference in definitions and descriptions of the ACC within different studies or earth scientific disciplines or in the possibility that the ACC occurred multiple times. For example, dinoflagellate biogeography and sea surface temperature paleothermometry studies reveal that the earliest throughflow of a westbound Antarctic Counter Current began approximately 49-50 Ma through a southern opening of the Tasmanian Gateway (TG), while ^{40}AR/^{39}Ar dating experiments together with multibeam mapping and dredging of the seafloor suggest that the upper age limit of the onset of a deep ACC is ca. 11.6 Ma (Bijl et al., 2013; Dalziel et al., 2013). In addition, other studies present results on the onset of the ACC, without clearly indicating how this onset is interpreted (i.e. Olbers et al., 2004). It is difficult to study and understand several research papers with regard to the ACC, as long as it is not clear how the ACC is defined within several earth scientific subdisciplines and periods. This thesis therefore aims to establish a more comprehensive understanding of the onset and development of the ACC that is fitting for all earth scientific subdisciplines.

To accomplish the aim of this thesis, it is first researched if the difference in the estimated onset times of the ACC varies mostly per earth scientific subdiscipline. Next, results of a small research regarding the characteristics of the modern Antarctic Circumpolar Current are given in order to form a better understanding of the definition and development of the ACC in earlier times. Next, the onset and development of the ACC is researched with the help of five broad stages in which the (precursor of the) ACC clearly differs from other stages. These stages consist, in sequence, of an Antarctic Counter Current (not to be confused with the ACC) at approximately 50-49 Ma, the first routes for easterly waterflows around Antarctica between 50 and 41 Ma, the first onset of an early analogue of the modern ACC between 37 and 30 Ma, a period of uncertainty that can be divided into two stages, the first one being from 30 until 22 Ma and the second one from 24 until 15 Ma and lastly a stage in which the ACC is described as a full developed, strong, coherent and deep ACC between 15 and 10 Ma.

1. Methods

To establish a more comprehensive understanding of the onset and development of the ACC, three hypotheses were formulated:

1. The difference in the estimated time of onset of the ACC varies mostly per earth scientific subdiscipline, in which each of them has its own reasons to ascribe a certain age to the ACC.

2. The difference in the estimated time of onset of the ACC is due to a fundamental difference in definitions and descriptions that are used for it.

3. The difference in the estimated time of onset of the ACC is due to the fact that the ACC did not occur once, but multiple times.

As a first step to being able to research the hypotheses, two tables of the descriptions, definitions and defined onset times of the ACC together with the used methods per study were made. One table (Appendix 1) was ordered per researched earth scientific subdiscipline. These subdisciplines are: atmospheric sciences, biogeography, biomarine sciences, climatological sciences, environmental sciences, geography, geology, geophysics, paleoceanography and physical oceanography. In the other table (Appendix 2), the findings were ordered per age of the ACC. With the help of these tables and additional earth scientific literature that was needed to fill gaps in the thus far obtained knowledge, it was investigated whether the difference in the defined ages of the ACC is either due to a difference in the definition of the ACC within the earth scientific subdisciplines, due to a fundamental difference in definitions and descriptions used for the ACC per research or due to the fact that the ACC had multiple onsets.

2. Results

2.1 Similar earth scientific subdisciplines ascribe significant different ages to the ACC

A table (Appendix 1) that was created to research hypothesis 1: "*The difference in the estimated time of onset of the ACC varies mostly per earth scientific subdiscipline, in which each of them has its own reasons to ascribe a certain age to the ACC.*" shows descriptions, definitions and defined onset times of the (precursor of the) ACC ordered per researched earth scientific subdiscipline. This table shows that similar subdisciplines ascribe significant different times of onset to the ACC. There is thus no clear connection found between the estimated onset times of the ACC and the earth scientific subdisciplines.

2.2 Characteristics of the modern ACC

The modern ACC (fig. 1) is the largest ocean current and has a volume transport of approximately 130-140 Sv over a length of roughly 24000 km around Antarctica (Olbers et al., 2004). It is an ongoing current which exists of more or less intense jet streams that are in place because of a high variability in surface water temperature gradients (Olbers et al., 2004). These jet-like currents each correspond to fronts, namely the sub-Antarctic Front at the lowest latitudes of the ACC, the Antarctic Front in the middle and the Southern ACC Front at the highest latitudes (fig. 1) (Gille et al., 2016). These fronts limit meridional exchange and it is often hypothesized that they isolate the uttermost southern Oceanic basins from heat and substance sources in the rest of the world's oceans (Gille et al., 2016; Olbers et al., 2004). The fronts are mainly steered by bathymetry and they separate waters with substantially different densities and correspondingly different temperature and salinity properties (Gille et al., 2016). As a result of these jet streams, the ACC serves as a conduit of all active and passive oceanic tracers which affect Earth's climate, notably heat and salt which strongly influence the oceanic mass stratification, circulation and consequently the ocean heat transport and the greenhouse gas carbon dioxide (Olbers et al., 2004). In addition, it shapes the appearance of deep-sea populations and biogeographical patterns that can be found in the southern parts of the oceans (Dueñas et al., 2016). It also most likely separates and structures deep-sea octocoral populations (Dueñas et al., 2016).

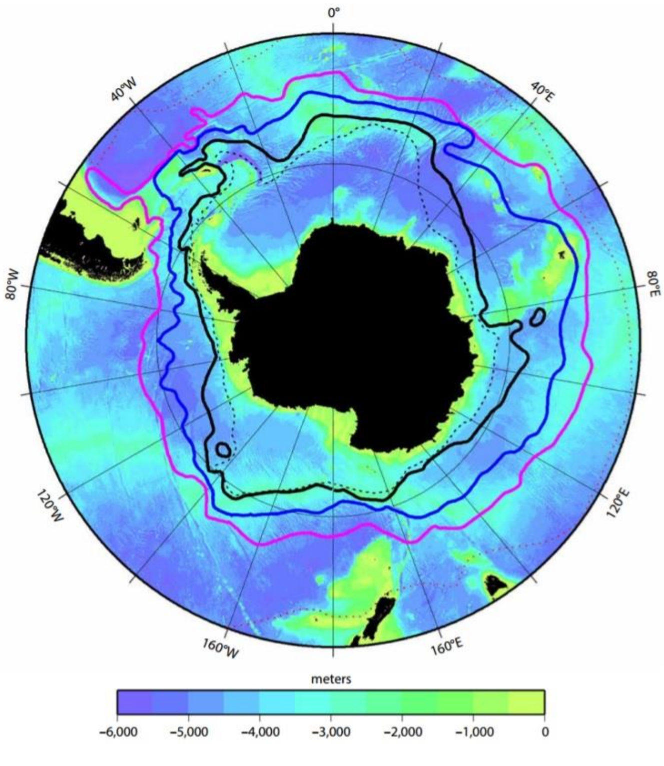

Figure 1: Major frontal features that define the modern ACC: the sub-Antarctic Front (magenta), the Antarctic Front (dark blue), and the Southern ACC Front (black)
Source: Gille et al. (2016)

2.3 Onset and development of the ACC

2.3.1 Opening of the Tasmanian Gateway, leading to an Antarctic Counter Current : ~ 50-49 Ma

Signs of the earliest current along Antarctica appear in two researched studies with regard to the ACC. First, a study using dinoflagellate biogeography and sea surface temperature paleothermometry reveals that the earliest throughflow of a westbound Antarctic Counter Current began approximately 50-49 Ma through a southern opening of the Tasmanian Gateway (TG) (Appendix 3, fig. 14) (Bijl et al., 2013). In this study, differences in endemic dinocyst taxa between 52 and 49 Ma, in biogeographic age sediment patterns from ~55-42 Ma of both sides of the TG, are inferred to be best explained by an opening in the southern part of the TG at approximately 50-49 Ma (fig. 2). The absence of low-latitude taxa from the southwest Pacific Ocean (Fig. 2) implies that the northern continental blocks in the TG and/or the westward throughflow of the Antarctic Counter Current effectively blocked the eastward flow of the Proto-Leeuwin Current (PLC) (Appendix 3, fig. 13) surface waters to the Pacific side of the TG during the middle Eocene (Fig. 3) (Bijl et al., 2013). In addition, Global Climate Model (GCM) simulations of the Eocene climate show that the Tasman Current (TC) (Appendix 3, fig. 13) is primarily wind-driven, which means that the southern region of the TG would have been under the influence of an atmospheric circulation dominated by easterlies, which favoured a westward throughflow in the southern TG (Bijl et al., 2013; Huber et al., 2004; Huber, 2001).

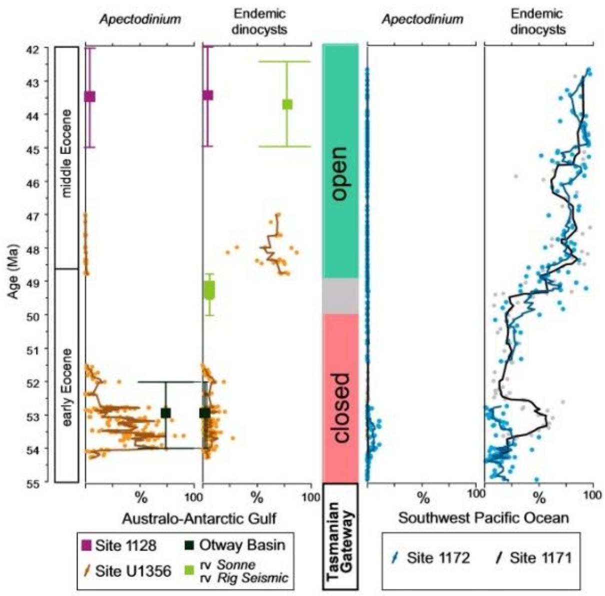

Figure 2: Differences in dinocyst assemblages on both sides of the Tasmanian Gateway across the early-to-middle Eocene transition Source: Bijl et al. (2013)

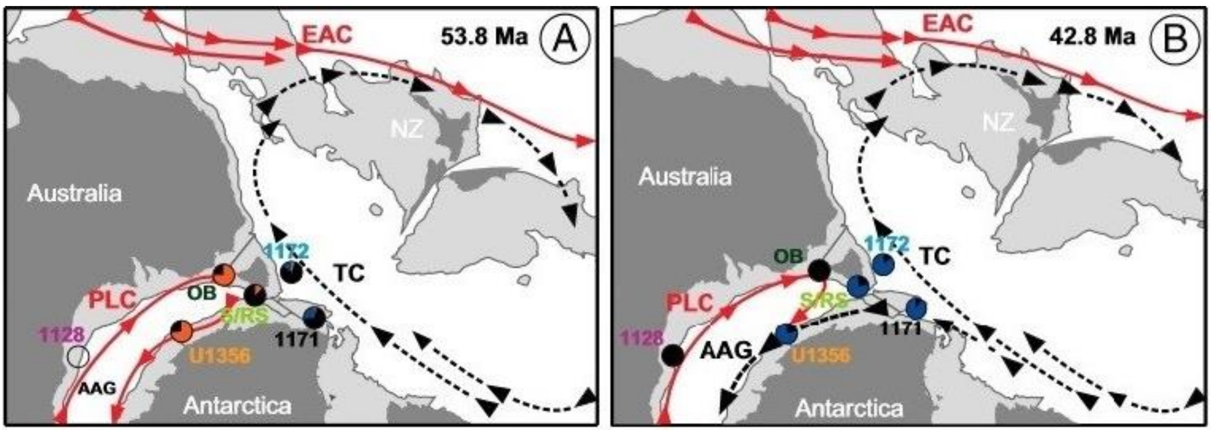

Figure 3: Tectonic evolution of the Tasmanian Gateway. Eocene continental configurations of the Australian sector of the Southern Ocean for the (A) early Eocene and (B) middle Eocene. Source: Bijl et al. (2013)

Second, simulations with a modified version of the coupled climate model of intermediate complexity (the so-called UVic model, as described in detail by Weaver et al. (2001)) show that an open southern TG and a closed Drake Passage (DP) (Appendix 3, fig. 12) during the early Eocene leads to a westward flow throughout the water column near Antarctica and a shallower eastward flow to the north (Fig. 4) (Sijp et al., 2016). With the DP closed, the simulation shows that the circulation of the Southern Ocean is split into two subpolar gyres, namely the Ross Sea gyre (Appendix 3, fig. 13) to the east of Australia and the Weddell gyre (Appendix 3, fig 15) spanning the (south) Indian and Atlantic oceans to the east of the DP (Sijp et al., 2016). In this case, a full encircling current around Antarctica did not yet exist in the early Eocene.

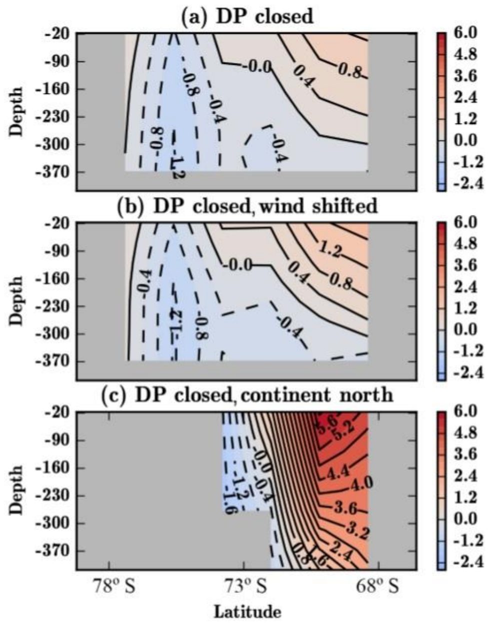

figure 4: Meridional section of zonal velocity u (cm s−1) inside the Tasman Gateway with the Drake Passage closed for three different simulations (as fully described by Sijp et al. (2016). Positive values indicate eastward flow; negative values indicate westward flow. Source: Sijp et al. (2016)

Besides, simulations with an open DP yield to the conclusion that an eastward 'proto-ACC' already would have existed in the early Eocene (Sijp et al., 2016). This proto-ACC would have been as strong as 35 Sv through the DP and 8 Sv through the TG, with the remaining 27 Sv passing north of Australia. However, decadal timescale simulations were performed to examine links between Eocene ocean circulation and dinoflagellate biogeography. These simulations result in dinoflagellate distributions that are not consistent with dispersion patterns found by Bijl et al. (2013), which indicates that either the DP was closed during this period or sufficient obstructions downstream of the DP existed to prevent an eastward flow through the TG (Sijp et al., 2016).

2.3.2 Routes for easterly waterflows across the Atlantic, Indian and Pacific Ocean basins: ~ 50-41 Ma

Results of researched studies show that there has been eastward water exchange across the Atlantic, Indian and Pacific Ocean basins, at least in surface waters at approximately 50-41 Ma. First, results from a set of paleoclimate model simulations derived by the UK Met Office fully coupled Atmosphere-Ocean General Circulation Model (HadCM3L, as described by Cox et al., 2001) show that as soon as the Drake Passage opened, significant easterly flows could be established (Table 1) (Hill et al., 2013). This is in agreement with simulations performed with the UVic model (Sijp et al., 2016). In addition, the HadCM3l study suggests that there may have been routes for water exchange through the DP, at least in surface waters, from as early as the middle Eocene (45 Ma) (Hill et al., 2013). On the other hand, the timing of the opening of the DP is still uncertain. For example, some scientists suggest that the DP opened through crustal stretching of the upper crust soon after approximately 50 Ma (i.e. Eagles and Jokat, 2014; Livermore et al., 2005). These conclusions are based on detailed reconstructions of the DP region, using a combination of major and minor plate motions derived from marine geophysical studies in the Scotia Sea (Appendix 3, fig. 12), South Atlantic and the Weddell Sea (Appendix 3, fig. 12) and a minimum-complexity tectonic reconstruction based on basin opening models. Other scientists however found evidence for an early shallow opening of the DP around 41 Ma, using secular variations of neodymium (Nd) isotope ratios at Agulhas Ridge (Appendix 3, fig. 11) (Scher and Martin, 2006). In addition, identification of anomalies suggest that the Drake Passage region was a zone of slow-spreading from approximately 80 to 43 Ma, until rapid seafloor spreading started around 43 Ma, which could have been the period that the DP opened enough to allow waterflows between the South Pacific and the South Atlantic Ocean basins (Brown et al., 2006; Cande and Mutter, 1982).

Table 1: Simulated flows through the Southern Ocean gateways and Pacific sector by the HadCM3L model Source: Hill et al. (2013)

Simulation Name	Drake Passage Total Zonal Flow (Sv)	Tasman Seaway Total Zonal Flow (Sv)	Southernmost High Surface Flow (> 50 mm/s) in Pacific (°S)
Rupelian^{closedDrake}	0	25.81	48.75
Rupelian^{noAIS}	44.66	74.46	51.25
Rupelian^{Control}	42.75	64.68	53.75
Chattian	91.32	93.65	56.25
Preindustrial	124.1	146.8	66.25

2.3.3 First onset of an early analogue of the modern ACC: ~ 37-30 Ma

A wide range of studies found evidence for the first onset of an early analogue of the modern ACC in the period between 37-30 Ma. First, interpretation of calcareous and siliceous plankton and dinocysts of Ocean Drilling Program (ODP) Leg 189 sites (Tasmanian Gateway Region, Appendix 3, fig 14) (drilling project explained in detail by Roberta et al., 2001) show that a developing ACC with both shallow and deep circulation has been in place from the early Oligocene (~33.5 Ma) onwards (Exon et al, 2002). Second, Nd isotope ratios at Agulhas Ridge suggest that a deeper Drake Passage was established in the late Eocene (Scher and Martin, 2006). This age of a deeper Pacific-Atlantic connection is in agreement with studies concerning tectonic reconstructions that take marine magnetic anomalies in consideration (fig 5) (i.e. Lawver and Gahan, 2003). A phase of rapid deepening of seaways in the West Scotia Sea and the Dove Basin (Appendix 3, fig. 12) between 37-34 Ma is furthermore endorsed by reconstructions of tectonic plates around the West Scotia Sea (Lagabrielle et al., 2009). Moreover, a continuous, intermediate to deep pathway through the proto-Scotia Sea at 34-30 Ma is shown by a combination of major and minor plate motion in the Drake Passage and Scotia Sea regions, which also would have led to a stronger oceanographic throughflow at this time (Livermore et al., 2007). In addition, Lagabrielle et al. (2009) state that a proto-ACC flowed over Patagonia and Tierra del Fuego at 32 Ma, because of continental micro-blocks that formed an N-S barrier in the DP. A study on the marine benthic limpet 'Nacella' also found evidence for an intermediate to deep Drake Passage from approximately 32 Ma onward, because the limpet was found on both sides of the DP from approximately that time on (González-Wevar et al., 2017).

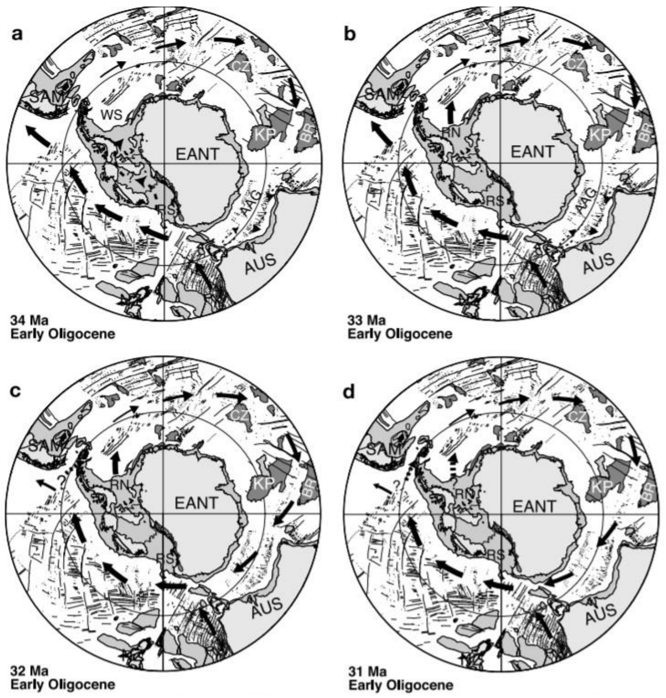

Figure 5: Tectonic polar reconstructions of the period between 34 Ma to 31 Ma.
Source: Lawver and Gahan (2003)

Furthermore, a mixed-resolution general circulation model (GCM) Fast Ocean Atmosphere Model (FOAM) was used to research the effect of ice sheet growth on Antarctica on the waterways along the continent (Ladant et al., 2014). Several simulations were performed in correspondence to the atmospheric CO_2 level, to the amount of Antarctic ice and to the presumable tectonic evolution from the Eocene to the Miocene. The acquired simulations show that increasing ice sheets on Antarctica trigger the formation of a proto-Ross Gyre as well as a proto-Weddell Gyre during the Eocene-Oligocene (EO) transition, which probably would have led to a reorganization of oceanic currents around Antarctica. According to Ladant et al. (2014), these reorganizations would also have led to the development of a rather strong so-called 'proto-ACC' during the EO transition.

Lastly, an integration of micropaleontological, sedimentological, geochemical and paleomagnetic data from Site 1172 (Appendix 3, fig 14) has been used by Stickley et al. (2004) to identify four phases in the deepening of the Tasmanian Gateway during the EO transition. The first three phases occur within the 37-30 Ma period and will be described here. The first phase revealed by Stickley et al. (2004) is a phase prior to ~35.5 Ma. In this period, the TG mostly deepened and the gateway region consisted of a shallow marine environment. The second phase described by them is between 35.5-33.5 Ma and is characterized as a more open-oceanic and nutrient-rich environment in which the TG deepened and in which energetic bottom-water currents occurred from approximately 35 Ma onward. They also mention that there was probably a connection of surface waters between the eastern and western areas of the TG at approximately 34.5 Ma. The period between 33.5-30.2 Ma is the third period and is described as a period in which the TG deepening intensified and in which the energetic bottom-water currents increased. It is also noted that the settings became more oligotrophic and that erosion in the TG occurred for approximately 3 million years.

2.3.4 Period of uncertainty, divided into two stages: ~30-15 Ma

Stage one: ~30-22 Ma

The period between approximately 30 Ma and 22 Ma is a period of which scientists do not widely agree upon. Here, several descriptions of the ACC between ~30-22 Ma will be formulated as described by various scientists. First, reconstructions of the tectonic opening of the Tasmanian Gateway together with the zonal gradient of Nd isotopes obtained from ODP Sites 1124, 1168 and 1172 (fig. 6) indicate that the Pacific Ocean basin came under the influence of an eastward ocean current at approximately 30 Ma (Scher et al., 2015). The results of these reconstructions show that the zonal gradient of Nd isotopes collapsed around 30 Ma (fig. 7), which indicates a major reorganization of intermediate to deep ocean pathways between 30 and 29 Ma. This reorganization includes a deep-water flow reverse (westward → eastward) at 30 Ma, which would, according to Scher et al. (2015), be strong evidence for the onset of a modern like ACC between 30 and 29 Ma.

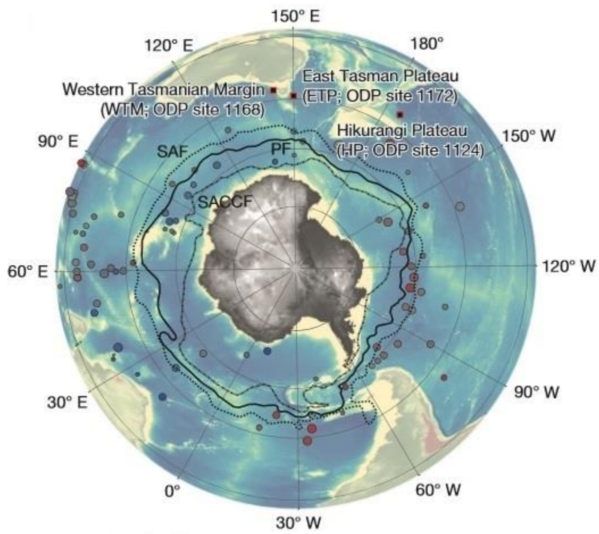

Figure 6: Present day Southern Ocean; Map showing ODP Sites 1124, 1168 and 1172
Source: Scher et al. (2015)

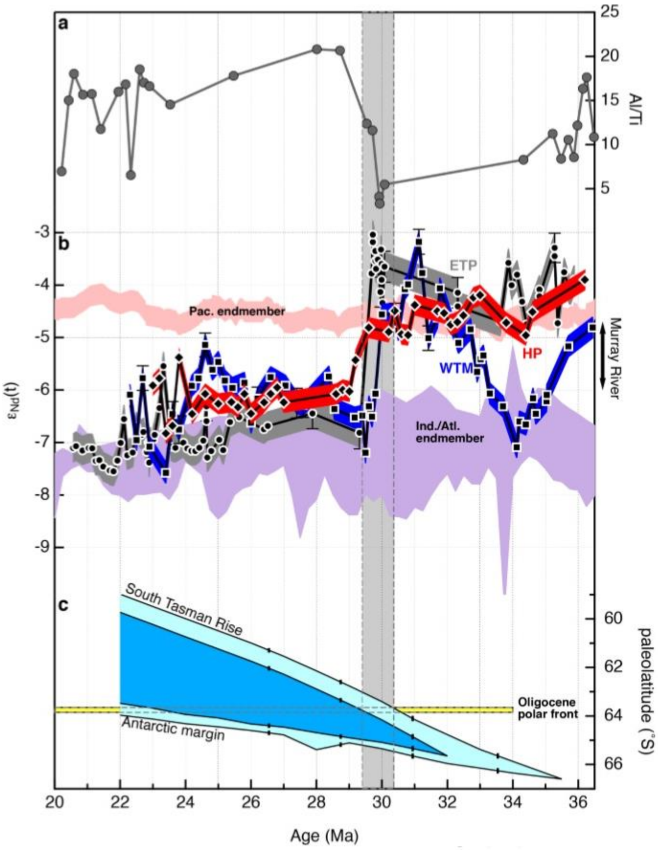

Figure 7: Subsidence curves, Nd isotope records, and conjugate margin palaeogeography (as further explained by Scher et al. (2015); zonal gradient of Nd isotopes collapsed around 30 Ma
Source: Scher et al. (2015)

Furthermore, results from the HadCM3L model indicate that changes in paleogeography between the Rupelian (33.9-28.1 Ma) and the Chattian (28.1-23.03) provide a significant step towards an analogue of the modern ACC and also suggest that a strong, coherent ACC was only established sometime after approximately 26 Ma (Hill et al., 2013). In addition and in contrast to Ladant et al. (2014) and Scher et al. (2015), Hill et al. (2013) suggest that the increasing icecaps on Antarctica have had little to no impact on the development of the ACC, but that it did cause a reorganization of the waterways around the continent. According to them, Australian Paleogeography would have retained oceanic currents from developing a modern style ACC during the Rupelian and they moreover state that neither solely the opening of the DP and the TG nor an increase in Antarctic glaciation is sufficient to initiate the establishment of a modern like ACC (fig. 8).

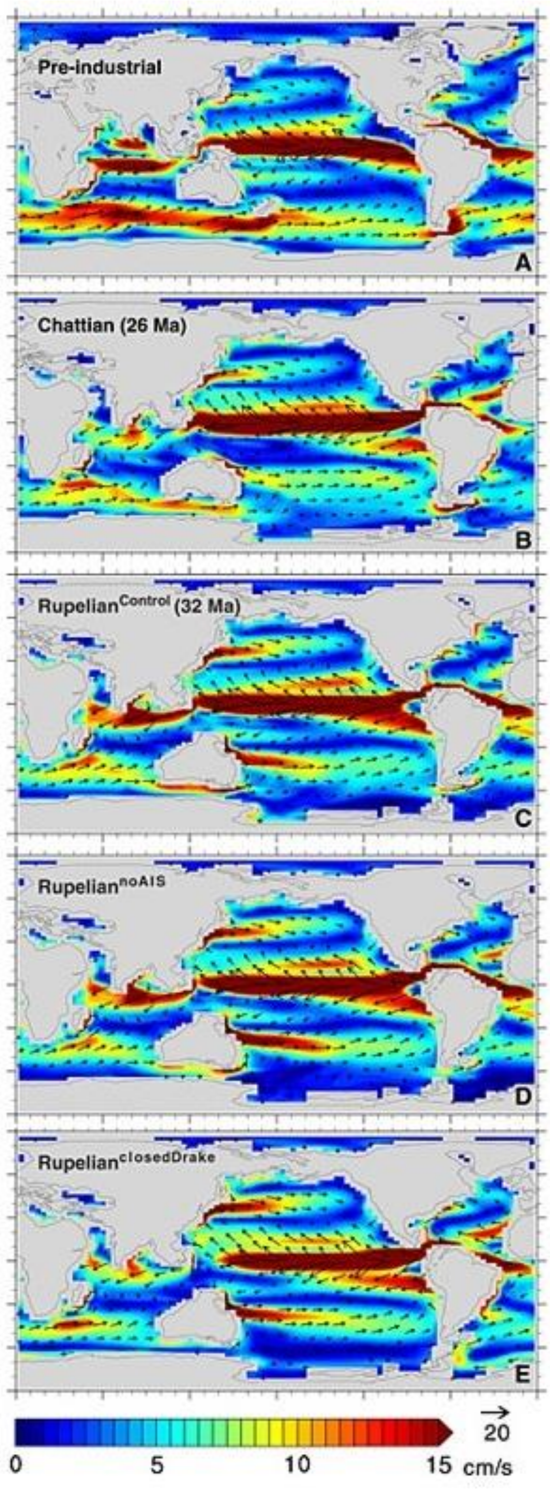

Figure 8: Simulations obtained from the HadCM3 model; Global ocean surface currents in the (a) Preindustrial, (b) Chattian, (c) Rupelian with Antarctic glaciation and an open DP (Rupelian-control), (d) Rupelian without Antarctic glaciation and an open DP (Rupelian-noAIS), and (e) Rupelian without Antarctic glaciation and a closed DP (Rupelian-closedDrake)
Source: Hill et al. (2013)

Paleobathymetric reconstructions of the Drake Passage moreover show that between 26 and 20 Ma a broad unbroken gateway into the Scotia Sea opened over the deep seafloor between Terror Rise (Appendix 3, fig. 12) and Tierra del Fuego, which would have led to a moderately wide deep water gateway between Bruce Bank and Shag Rocks (Appendix 3, fig. 12) (Eagles and Jokat, 2014). Eagles and Jokat (2014) nevertheless state that the possibility of deep water transport out of the Scotia Sea would still have depended on the shape and state of the South Sandwich Arc (Appendix 3, fig. 12). Similarly, benthic marine molluscan genus-group taxa from several sites on land (more fully described by Beu et al., 1997) together with records from the newer ODP and Deep Sea Drilling Project (DSDP) sites, show that there could have been a complete opening of the DP, a deepening of the TG and an ACC that followed a late Oligocene opening of these gateways (Beu et al., 1997; Lagabrielle et al., 2009; Pfuhl and McCave, 2005; Rack, 1993).

However, according to a stratigraphic study with relevance to the geography of the Drake Passage, the geographic conditions in the Drake Passage, especially near Tierre del Fuego, extremely change towards much shallower environments between 29 and 24 Ma (Malumián and Olivero, 2005, cited by Lagabrielle et al., 2009). Additionally, Lagabrielle et al. (2009) state that continuous spreading and subsequent strike-slip movement along the North Scotia Ridge boundary occurred from ~27 Ma to 22 Ma, which would have led to a tectonic phase that closed Tierra del Fuego seaways and deep ocean basins near the DP (Appendix 3, fig. 12). The amount of uplift and convergence during this period is difficult to estimate, but according to Brown et al. (2006) and Lagabrielle et al. (2009) it would have been large enough to lead to a reduced volume transport to a complete shutdown of the Fuegian Seaways and a decreased ACC flow. In addition, Bijl et al., (in prep) found that dinocysts did not bear a real analogy with present-day dinocysts at the same location during the late Oligocene. They suggest that the obtained values mean that, if the TG in the late Oligocene had opened already to an extent that allows for the development of an ACC, the ACC was much weaker than today (Bijl et al., in prep).

Stage two: ~24-15 Ma

Several studies suggest that an ACC was definitely in place from as soon as 24 Ma, but that, if an ACC was also in place before 24 Ma, it developed to a stronger ACC from the early to mid-Miocene. First, magnetic data and anomalies show that the Drake Passage experienced a widening along the East Scotia Ridge since approximately 20.13 Ma (Eagles et al., 2005). Eagles et al. (2005) therefore suggest that the ACC strengthened from that moment on. Furthermore, grain size and stable isotope ($\delta^{13}C$ and $\delta^{18}O$) analysis from sediment records from ODP Leg 189 (Appendix 3, fig. 14) suggest that there was an intensification of current strength and a deepening of the Drake Passage after about 23.95 Ma (Pfuhl and McCave, 2005).

On the contrary, Lagabrielle et al. (2009) suggest that the Drake Passage was constricted until approximately 14 Ma, which would mean that the strength of the ACC would have been reduced until 14 Ma. This is in accordance with a suggestion that Bijl et al. (in prep) make on the basis of dinocyst assemblages. They namely suggest that it is very unlikely that the ACC increased in strength during the Oligocene-Miocene, because this would mean that this strengthening had no influence on the dinocyst assemblages that were studied (Bijl et al., in prep.). They furthermore show that there is no trend towards a more thermal or oceanographic isolation of the Wilkes Land margin throughout the Oligocene to mid-Miocene, which causes them to conclude that the ACC did not obtain its full present-day strength yet. The fact that there is no trend towards a more thermal or oceanographic isolation of the Wilkes Land margin may also mean that the ACC did not increase in strength until the mid-Miocene.

2.3.5 Full developed, strong, coherent and deep ACC: ~15-10 Ma

Several studied research papers indicate that a significant strong and deep ACC occurred between 15 and 10 Ma. For example, statistical analysis and ecological grouping of dinocysts, that were obtained by samples from the Integrated Ocean Drilling Program (IODP) Expedition 318 Hole U1356A (fig. 9) show that the dinocyst assemblages offshore Wilkes Land only started to bear some analogy to those of the present-day at the same location at the mid-Miocene transition (14-12 Ma) (Bijl et al., in prep). They moreover suggest that this means that a strong coherent ACC was not installed until approximately 14 Ma, but likely later. In addition, a combination of geophysical data, multibeam mapping of the ocean floor and $^{40}Ar/^{39}Ar$ dating indicates that a significant deep ACC was only established between 11.2 and 12.0 Ma, because the South Sandwich Arc most likely acted as a barrier to deep-water flow (Barker et al., 1982 as cited by Dalziel et al., 2013; Dalziel et al., 2013). Furthermore, according to a reconstruction of paleobathymetry in the DP region, Eagles and Jokat (2014) draw the conclusion that a modern like ACC could only have been established after a full opening of both the North Scotia Ridge (approximately 17 Ma) and the northern end of the East Scotia Sea (approximately 10 Ma). Similarly, plate kinematics of the West Scotia Sea together with geological records from the North Scotia Ridge, $\delta^{18}O$ records of benthic foraminifera and pCO_2 records indicate that an increase in the strength of the ACC occurred around 15-14 Ma (Lagabrielle et al., 2009; Pagani et al., 2005; Pearson and Palmer, 2000; Zachos et al., 2001; Zachos et al., 2008).

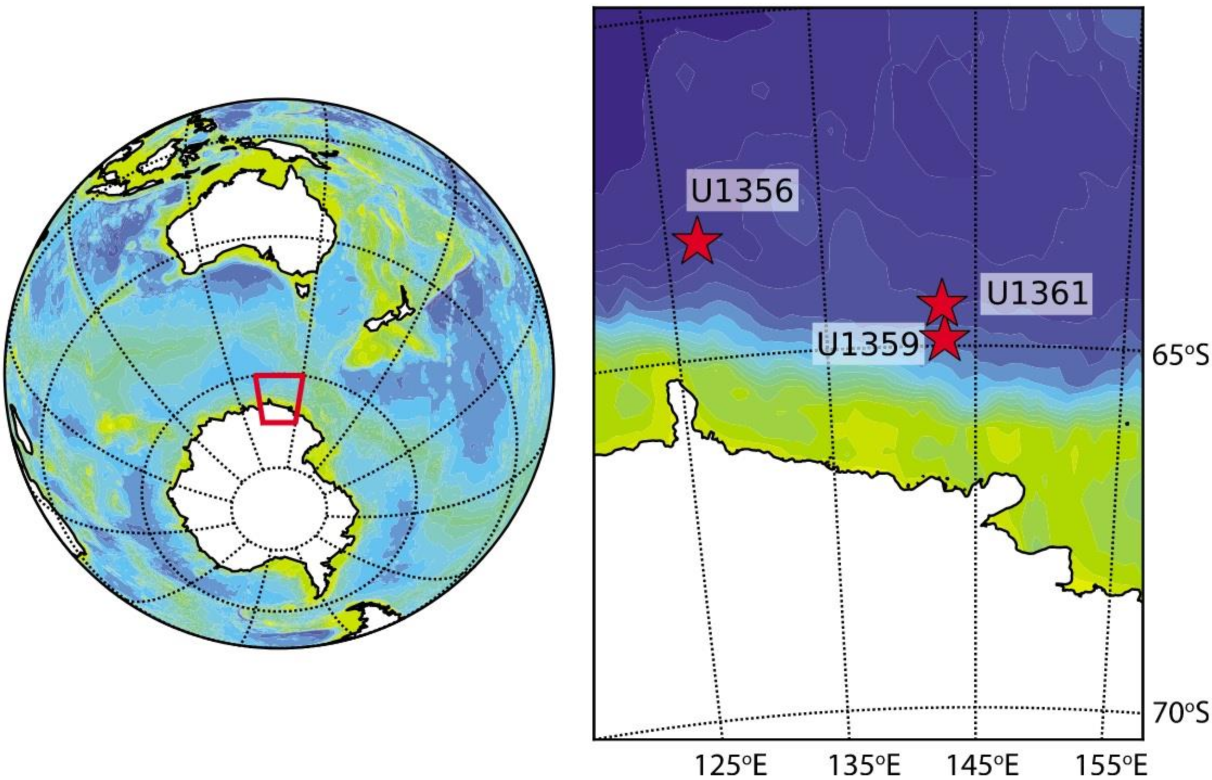

Figure 9: Map of three IODP expedition 318 sites. Hole U1356: 64.5452°S, 143.5768°E, 3020 meters below rig floor (mbrf), Hole U1356A being 949-1000 mbrf
Source: Tauxe et al. (2012)

3. Discussion

3.1 Comparing the different descriptions of the ACC during equivalent periods

There are many different estimates for the onset and development of the ACC. These differences do not depend on the earth scientific subdiscipline, because the descriptions and definitions of it vary even per subdiscipline. The results of this thesis show that a wide range of estimates for the onset of the ACC often depend on the definitions and descriptions used for it. A specific onset time of the ACC will not be given, because this clearly depends on how the ACC is described. The development of the ACC has nevertheless become comprehensible and a description for the ACC during most periods has become clear. An overview of these periods will be given (see also fig. 10) and important uncertainties with regard to the timing of stages of the ACC will be discussed here.

First, the timing of the opening and development of the Drake Passage is still very uncertain and a topic of debate under scientists. The results show that a westbound Antarctic Counter Current was in place from as early as 50-49 Ma, until the DP had opened to a large enough extent to allow for water exchange across the Pacific and Atlantic Ocean basins. When this extent was reached, a large reorganization of ocean currents took place and the first eastward flow along Antarctica occurred. Because the early opening of the DP is still uncertain, the timing of this reversal is also uncertain. The researched studies however show that the earliest small opening of the DP appeared between 50 and 41 Ma. It is therefore likely that the first eastward waterflow along Antarctica, at least in surface waters, would have been in place by then. Again, the earliest large ocean current was probably a westbound Antarctic Counter Current that started around 50-49 Ma and so it is unlikely that the eastward flow was in place already at or soon after 49 Ma. In addition, most researched studies suggest that the Drake Passage opened after 45 Ma. It is therefore hypothesized that the first complete eastward current around Antarctica initiated between 45 and 41 Ma.

The first onset of an early analogue of the modern ACC has been dated between 37 and 30 Ma. This circumpolar current would have been a shallow to intermediate or deep waterflow along Antarctica, with the high probability that geological features (i.e. micro-blocks; South Sandwich Arc) blocked parts of the Drake Passage. The eastward current along Antarctica probably deepened from approximately 37 to 30 Ma. This is evidenced by several studies that estimate this state of the ACC between 37 and 30 Ma. Furthermore, Stickley et al. (2004) describe three stages of deepening and strengthening of the ocean current between 35 and 30.2 Ma.

Next, there is one large period of uncertainty about the state of the ACC between approximately 30 and 15 Ma, which can be divided into two subcategories, the first one lasting from approximately 30 to 22 Ma and the second one from about 24 to 15 Ma. According to Ladant et al. (2014) and Scher et al. (2015), there was a major reorganization of intermediate to deep ocean waterways around Antarctica at approximately 30-29 Ma, which would have led to a reversal from a westward to an eastward deep water flow. Hill et al. (2013) state on the contrary that there was indeed a reorganization of waterways around the continent, but that this had little to no impact on the development of a modern like ACC. Moreover, there are large differences in the believed development of the depth of the Drake Passage and consequently of the strength of the ACC, during the Oligocene. For instance, Malumián and Olivero (2005) and Lagabrielle et al. (2009) suggest that the geographic conditions of the DP changed extremely to much shallower environments and a closure of basins near the DP between 29 and 24 Ma, while Beu et al. (1997) and Pfuhl and McCave (2005) suggest that there was probably a moderately wide, deep DP in place during the Oligocene. Eagles and Jokat (2014) furthermore state that a moderately wide and deep DP could have been in place between 26 and 20

Ma, but only if the shape and state of the South Sandwich Arc would have allowed this. Moreover, Bijl et al. (in prep) state that the ACC could have been developed in the late Oligocene if the Tasmanian Gateway had opened to a large enough extent, but in that case, it still would have been a much weaker ACC than at present. This statement is in accordance with the researched studies mentioned in the last paragraph of the results section, in which a full developed, strong and coherent ACC between 15 and 10 Ma is described. In addition, it is important to mention that the Panama Seaway was open until it started restricting around 14 Ma (Yang et al., 2014). The closure of this seaway would have had a major influence on the ocean circulation around the Drake Passage, due to its impact on the Pacific-Atlantic exchange of fresh water and the impact on the southward transport of salty subtropical waters (Yang et al., 2014). The constriction of the Panama Seaway around 14 Ma could therefore have led to a stronger ACC after 14 Ma. This, together with the information obtained in sections 2.2.4 and 2.2.5 suggest that there was indeed an ACC in place between 30 and 15 Ma and that this current strengthened after 15 Ma. In this thesis it is therefore hypothesized that the Drake Passage progressively narrowed from approximately 30 Ma until the end of the Oligocene, leading to a decreased ACC flow until a combined set of conditions favoured the restrengthening of the ACC during the mid-Miocene. The ACC would probably have strengthened from 15 Ma onwards, which led to a strong, coherent and deep ACC from the mid- to late Eocene onwards.

In addition, the modern ACC has an approximate volume transport of 130-140 Sv and it exists of more or less intense jet streams which probably isolate the uttermost southern oceanic basins from heat and substance sources in the rest of the modern oceans. These jets each correspond to fronts that are mainly steered by bathymetry, which was also a major influence on the state of past ocean circulation patterns around Antarctica.

3.2 Implications for science

It has become clear that the opening and development of the Drake Passage is relatively poorly understood, while the development of the ACC largely depends on the depth and width of the DP region. A better understanding of the development of the ACC, most importantly between 30 and 15 Ma, can therefore be obtained when more details on the geologic and geographic features of the Drake Passage region through time become clear. This information can firstly be derived if the important and currently available information on the DP will be organized to obtain a clear overview of the similarities and differences with regard to the geology and geography of the DP. Afterwards, more specific studies can be performed to research what causes these differences, so that more structured studies can be carried out to gain knowledge on the development of the Drake Passage region. This also implicates that new studies on the uncertain periods of the development of the ACC can thereafter be performed.

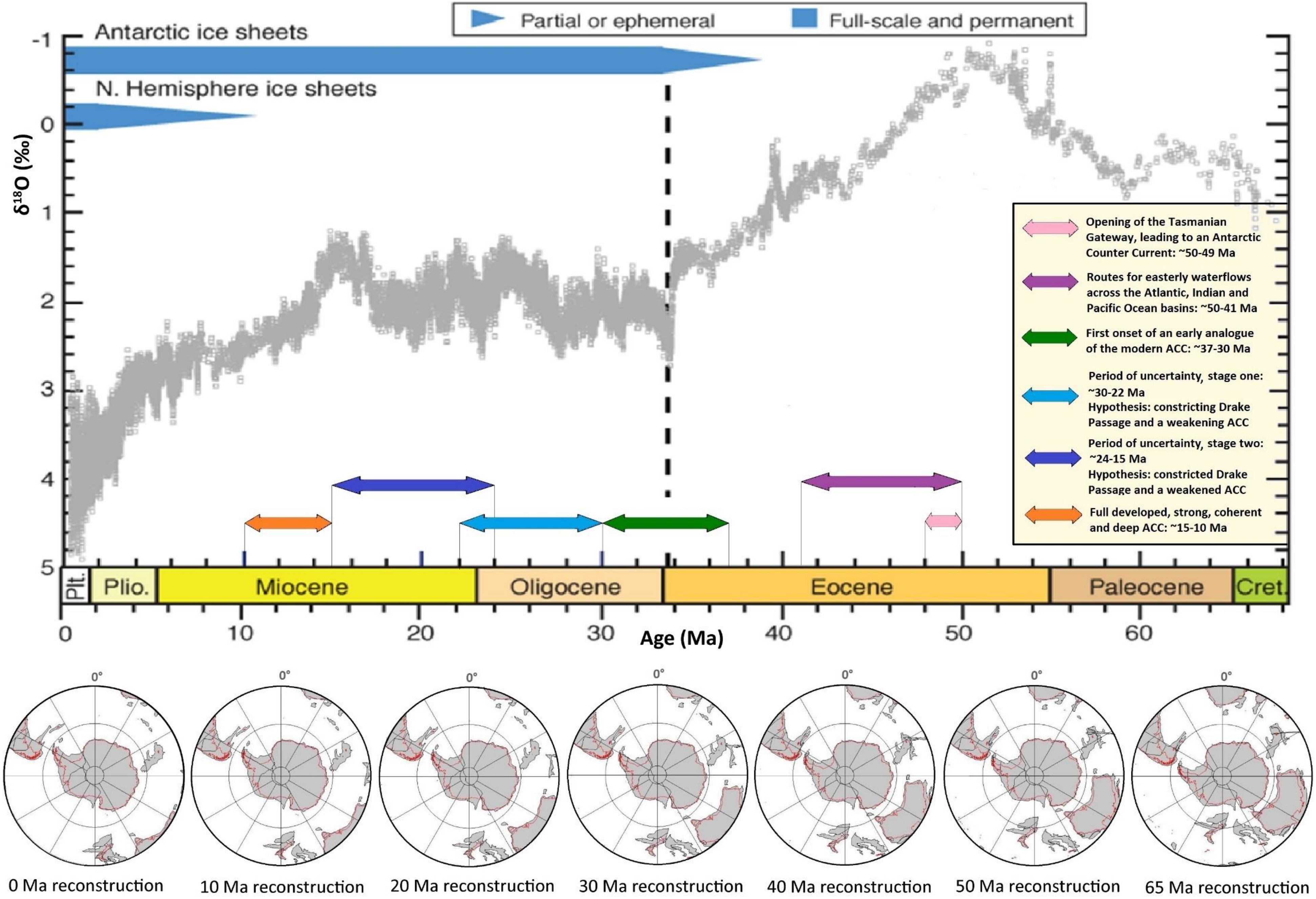

Figure 10: Overview of the acquired stages of the ACC
Edited from: Zachos et al. (2008) and Powerpoint slides from Dr. P.K. Bijl

Conclusion

Three hypothesis were researched in this thesis. The first hypothesis: “*The difference in the estimated time of onset of the ACC varies mostly per earth scientific subdiscipline, in which each of them has its own reasons to ascribe a certain age to the ACC.”* is disproved. However, hypothesis two: “*The difference in the estimated time of onset of the ACC is due to a fundamental difference in definitions and descriptions that are used for it*.” has been confirmed. Hypothesis three: “*The difference in the estimated time of onset of the ACC is due to the fact that the ACC did not occur once, but multiple times*.” is up for debate, as it is hypothesized in this thesis that the ACC has probably weakened between 30 and 15 Ma and strengthened again after 15 Ma. It thus depends on the preferred definition of the ACC to determine whether the ACC did or did not occur at least twice.

The opening and development of the Drake Passage region is poorly understood while the development of the ACC largely depends on the geography and bathymetry in this region. However, most periods with regard to several states of the ACC have become clear, even though the former state of the DP region is uncertain. First, a westbound Antarctic Counter Current was in place at approximately 50-49 Ma. This current did not completely encircle Antarctica, as the Drake Passage was still closed. Between 49 and 41 Ma, but probably after 45 Ma, the first shallow eastward current encircled Antarctica. The first analogue of the modern ACC was established between 37 and 30 Ma. This current was of intermediate to deep depth and it had gained strength since the appearance of the first eastward current. The uncertainty in the state of the DP between 30 and 15 Ma causes large differences in the supposed states of the ACC in this period, although it is hypothesized in this thesis that the ACC weakened between 30 and 22 Ma, after which its strength remained approximately the same until about 15 Ma. The ACC gained strength in the period between 15 and 10 Ma, in which a full developed, strong and coherent ACC is reported. Lastly, the modern ACC exists of jet streams that each correspond to fronts which are predominantly steered by bathymetry.

A more comprehensive understanding of the onset and development of the ACC is established in this thesis, but more research on the DP has to be performed to understand the entire development of this current, mostly between 30 and 15 Ma.

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Appendix 1 – Table of the gathered information ordered per subdiscipline that was used to start writing results

Earth Scientific Subdiscipline	Brief description of the ACC	Estimated onset of the (precursor of the) ACC	Authors
Biogeography	The earliest throughflow of a westbound Antarctic Counter Current began approximately 49-50 Ma through a southern opening of the Tasmanian Gateway	~ 49-50 Ma	Bijl et al., 2013
Biogeography/ Biomarine sciences	A contiguous, eastward flowing circumpolar current that also flows through a deepened Tasmanian Gateway	much later than 35.5 Ma	Bijl et al., 2011
Biogeography/ Biomarine sciences	A circumpolar pathway along Antarctica, with a wide and deep Drake Passage	~ 34-36 Ma	Scher and Martin, 2006
Biomarine sciences	A wind driven eastward geostrophic that extends to the seafloor and has the modern four-layer ocean structure	30-29 Ma	Scher et al., 2015
Biogeography/ Atmospheric sciences	A Proto-ACC was established when there was an influx of relatively cool surface waters though the Australo-Antarctic Gulf (AAG) into the south-west Pacific	Proto-ACC: ~ 34-36 Ma	Huber et al., 2004
Geography/ Geology	The dominant circulation feature of the Southern Ocean, extending from the surface to the ocean floor and connecting the Atlantic, Pacific and Indian Ocean basins So, only a deep water or only a surface water throughflow is not enough to name a circumpolar current the ACC Note: there may have been routes for water exchange, at least in surface waters, from as early as ~ 45 Ma However, a continuous intermediate to deep water channel through the Drake Passage was probably not open until sometime between 34 Ma and 30 Ma	~ 26 Ma Stronger ACC ~ 23 Ma However, a continuous intermediate to deep water channel was probably open as of ~34 to 30 Ma	Hill et al., 2013

Earth Scientific Subdiscipline	Brief description of the ACC	Estimated onset of the (precursor of the) ACC	Authors
Geophysics/ Geography	A significant deep current flowing around Antarctica The ancestral South Sandwich arc likely acted as a barrier to deep-water flow A significant deep ACC could not have been initiated until sizable gaps developed in the ancestral arc, the North Scotia Ridge, or both. Gap formation and deep ACCC initiation likely followed cessation of CSS arc activity and dismemberment and submergence of the Andean cordillera along the North Scotia Ridge and South Georgia-Northeast Georgia Rise collision at ca. 12 Ma.	~11.6 Ma	Dalziel et al., 2013
Climatological and environmental sciences	Ladant et al. propose that the combined variations of the atmospheric CO_2 level, of the Antarctic ice sheet size and of the tectonic evolution of the Southern Ocean from the Eocene to the Miocene may have modulated the intensity of the circumpolar current, making the issue of a unique onset of the ACC more complex and probably obsolete. There were probably 2 onsets of the ACC	1st onset: ~ 31-34 Ma 2nd onset: ~ 22-24 Ma	Ladant et al., 2014
Climatological sciences	The ACC circulates through the Tasmania-Antarctic Gateway and the Drake Passage and is the only current to flow around the globe without encountering any continental barrier. It connects the Atlantic, Pacific and Indian Ocean basins and is the principal pathway of exchange between these basins. It is a wind-driven current, 24,000 km long, composed of a number of fronts and is strongly constrained by landform and bathymetric features (Orsi et al, 1995).	Proto ACC: 43 Ma Strong ACC: 32 Ma Partial collapse of ACC and a decreased flow: 29-22 Ma Increased ACC flow: 14-15 Ma	Lagabrielle et al., 2009

Earth Scientific Subdiscipline	Brief description of the ACC	Estimated onset of the (precursor of the) ACC	Authors
Climatological sciences/ paleoceanography	Onset: a westward throughflow of surface waters from the SW pacific into the Australo-Antarctic Gulf through a southern shallow opening of the Tasman Gateway (closed Drake Passage) An open Drake Passage, up to 517 m deep, leads to an eastward flow, even when the Tasman Gateway and the Australo-Antarctic Gulf are entirely constrained within the latitudes of easterly wind.	49-50 Ma	Sijp et al., 2016
Physical Oceanography	ACC is a fragmented system of more or less intense jet streams, that serves as a conduit of all active and passive oceanic tracers which affect Earth's climate, notably heat and salt which strongly influence the oceanic mass stratification, circulation and consequently the ocean heat transport, and the greenhouse gas carbon dioxide	30 Ma	Olbers et al., 2004

Appendix 2 – Table of the gathered information ordered per estimated age of the ACC that was used to start writing results

Brief desciption of ACC	**Estimated age ACC**	**Scientific field**	**Methods/ description research**	**Authors**
Throughflow of a westbound ACC (opening of TG)	49-50 Ma	Biogeography/ Biomarine sciences	- GCM experiments (that simulate the effects of Tasmanian Gateway opening) - Analysis of circum-Antarctic biogeographical patterns of marine phytoplankton an microfossils - Organic biomarker paleothermometry - Benthic foraminiferal oxygen isotope evaluation	Bijl et al., 2013
Westward throughflow of surface waters (opening of TG, closed DP)	49-50 Ma	Climatological sciences/ paleoceanography	- the UVic (University of Victoria model), a modified version of the intermediate-complexity coupled model. It consists of an ocean general circulation model coupled to a simplified one-layer energy-moisture balance model for the atmosphere and a dynamic-thermodynamic sea-ice model.	Sijp et al., 2016
routes for water exchange, at least in surface waters	~45 Ma	Geography/ Geology	- Paleoclimate models (UK Met Office fully coupled Atmosphere-Ocean General Circulation Model, HadCM3L)	Hill et al., 2013
Proto-ACC	43 Ma	Climatological sciences	- Integrated review of plate kinematic constraints and geological records from Southern South America and from the Scotia Sea region during the Cenozoic - review of plate tectonic models of the evolution of the Antarctic-Patagonia connection. - Drawing of a temporal framework for the sedimentary and tectonic events of the North Scotia Ridge and Tierra del Fuego with additional data compiled from entire Patagonia and the Austral Basin - Provision of robust correlations of seaways and tectonic events across the Drake Passage region between 29-22 Ma and 14 Ma	Lagabrielle et al., 2009
A continuous intermediate to deep water channel through the Drake Passage	~34-30 Ma	Geography/ Geology	- Paleoclimate models (UK Met Office fully coupled Atmosphere-Ocean General Circulation Model, HadCM3L)	Hill et al., 2013
Proto-ACC	34-36 Ma	Biogeography/ Atmospheric sciences	- Biogeographical distributions of phytoplankton - Fully coupled climate model simulations	Huber et al., 2004

Brief desciption of ACC	Estimated age ACC	Scientific field	Methods/ description research	Authors
Initiation of ACC	25-42 Ma (approx.. 32 Ma)	Biogeography	- Collection of Nacella species across the Southern Ocean - Multi-locus time-calibrated phylogeny of Nacella at the scale of the whole Southern Ocean to elucidate the underlying processes involved in the origin and diversification of the genus	González-Wevar et al., 2017
First onset of ACC (formation of Proto-Ross Gyre and a Proto-Weddell Gyre makes the case for a reorganization of oceanic currents)	31-35 Ma	Climatological and environmental sciences	- mixed-resolution general circulation model - fast ocean atmosphere model (GCM, FOAM) without icecaps and with fixed amounts of ice cap sizes and fixed CO_2 levels	Ladant et al., 2014
Strong ACC	32 Ma	Climatological sciences	- Integrated review of plate kinematic constraints and geological records from Southern South America and from the Scotia Sea region during the Cenozoic - review of plate tectonic models of the evolution of the Antarctic-Patagonia connection. - Drawing of a temporal framework for the sedimentary and tectonic events of the North Scotia Ridge and Tierra del Fuego with additional data compiled from entire Patagonia and the Austral Basin - Provision of robust correlations of seaways and tectonic events across the Drake Passage region between 29-22 Ma and 14 Ma	Lagabrielle et al., 2009
Separation of South America from Antarctica and the subsequent formation of the Drake Passage enabled the development of the ACC	34-36 Ma	Biogeography/ Biomarine sciences	- Nd isotope ratios ($^{143}Nd/^{144}Nd$ expressed as ε_{Nd} values)	Scher and Martin, 2006
Northward movement of Australia from Antarctica deepened the Tasman Gateway and much later allowed for the ACC to establish	Much later than 35.5 Ma	Biogeography/ Biomarine sciences	- Generation of data from Southern Ocean Sites - Southern Ocean Surface-Current Configurations - Palynological Processing and Taxonomy - Use of Dinocysts: endemic versus nonendemic taxa - Canonical Correspondence Analyses	Bijl et al., 2011

Brief desciption of ACC	Estimated age ACC	Scientific field	Methods/ description research	Authors
Partial collapse of the ACC and a decreased flow	29-22 Ma	Climatological sciences	- Integrated review of plate kinematic constraints and geological records from Southern South America and from the Scotia Sea region during the Cenozoic - review of plate tectonic models of the evolution of the Antarctic-Patagonia connection. - Drawing of a temporal framework for the sedimentary and tectonic events of the North Scotia Ridge and Tierra del Fuego with additional data compiled from entire Patagonia and the Austral Basin - Provision of robust correlations of seaways and tectonic events across the Drake Passage region between 29-22 Ma and 14 Ma	Lagabrielle et al., 2009
ACC is a fragmented system of more or less intense jet streams, opening of Drake Passage established the ACC	30 Ma	Physical Oceanography	- Physical/mathematical equations used to calculate characteristics of the ACC - Several models	Olbers et al., 2004
- A wind driven, eastward geostrophic flow that extends to the seafloor, shift toward the modern four-layer ocean structure - Northward migration of the Tasmanian Gateway into the influence of the westerly winds established the conditions for geostrophic balance in the Southern Ocean that drive the modern ACC - Deep-water flow reverse at 30Ma (westward → eastward)	30-29 Ma	Biomarine sciences	- Reconstruction of the absolute paleolatitudes of the Tasmanian Gateway through time, the position of the polar front during the Oligocene epoch and the evolution of the zonal gradient of neodymium (Nd) isotopes in the Southern Ocean - Reconstruction of the tectonic opening of the Tasmanian Gateway in a moving hotspot reference frame, using geophysically determined continent-ocean boundaries from the South Tasman Rise and Antarctica	Scher et al., 2015

Brief desciption of ACC	Estimated age ACC	Scientific field	Methods/ description research	Authors
- The dominant circulation feature of the Southern Ocean, extending from the surface to the ocean floor and connecting the Atlantic, Pacific and Indian Ocean basins. So, only a deep water or only a surface water throughflow is not enough to term a circumpolar current the ACC	~26 Ma Stronger ACC around ~23 Ma	Geography/ Geology	- Paleoclimate models (UK Met Office fully coupled Atmosphere-Ocean General Circulation Model, HadCM3L)	Hill et al., 2013
Partial collapse of ACC and a decreased flow	29-22 Ma	Climatological sciences	- Integrated review of plate kinematic constraints and geological records from Southern South America and from the Scotia Sea region during the Cenozoic - review of plate tectonic models of the evolution of the Antarctic-Patagonia connection. - Drawing of a temporal framework for the sedimentary and tectonic events of the North Scotia Ridge and Tierra del Fuego with additional data compiled from entire Patagonia and the Austral Basin - Provision of robust correlations of seaways and tectonic events across the Drake Passage region between 29-22 Ma and 14 Ma	Lagabrielle et al., 2009
- Second onset of the ACC - Initiation of the ACC at the Oligocene-Miocene boundary might just be a reappearance or a restrengthening of a prior proto-ACC	Between 25-23 Ma	Climatological and environmental sciences	- mixed-resolution general circulation model - fast ocean atmosphere model (GCM, FOAM) without icecaps and with fixed amounts of ice cap sizes and fixed CO_2 levels	Ladant et al., 2014
Strong coherent ACC	14 Ma but probably later	Biomarine sciences	- Palynological sample processing - Taxonomy and nomenclature -Statistical analysis for defining reworked versus *in situ* dinocysts - Ecological grouping of dinocyst species	Bijl et al., in prep.

Brief desciption of ACC	Estimated age ACC	Scientific field	Methods/ description research	Authors
Significant deep current	~11.6 Ma	Geophysics/ Geography	- Combination of geophysical data and vessels of the British Antarctic Survey - Multibeam mapping and dredging of the seafloor - $^{40}Ar/^{39}Ar$ dating	Dalziel et al., 2013
Full development of a deep ACC	~12 Ma	Biogeography	- Collection of Nacella species across the Southern Ocean - Multi-locus time-calibrated phylogeny of Nacella at the scale of the whole Southern Ocean to elucidate the underlying processes involved in the origin and diversification of the genus	González-Wevar et al., 2017
Increased ACC flow	14-15 Ma	Climatological sciences	- Integrated review of plate kinematic constraints and geological records from Southern South America and from the Scotia Sea region during the Cenozoic - review of plate tectonic models of the evolution of the Antarctic-Patagonia connection. - Drawing of a temporal framework for the sedimentary and tectonic events of the North Scotia Ridge and Tierra del Fuego with additional data compiled from entire Patagonia and the Austral Basin - Provision of robust correlations of seaways and tectonic events across the Drake Passage region between 29-22 Ma and 14 Ma	Lagabrielle et al., 2009

Appendix 3 – Relevant (paleo)geographic concepts

To give context to the results section, relevant (paleo)geographic concepts with regard to the onset and development of the ACC are shown and briefly explained alphabetically.

- *Agulhas Ridge* (fig. 11): topographic feature in the Atlantic sector of the Southern Ocean that parallels the Agulhas-Falkland Fracture Zone.

- *Bruce Bank* (fig. 12): Separates the Dove Basin to the west from the Scan Basin to the East and presents elevations of less than 2000m in water depths (Cevile et al., 2012).

- *Dove Basin* (fig. 12): The basin between the elevated Pirie Bank and *Bruce Bank*; on the northside it opens to the abyssal part of the *Scotia Sea.*

- *Drake Passage* (fig. 12): Ocean gateway between the Cape Horn (Southern South-America) and Antarctica, which connects the Southern Atlantic and Pacific ocean basins.

- *North Scotia Ridge* (fig. 2): An elevated region in the North of the Southern Ocean; it is the northern boundary of the *Scotia Sea;* located on the South America Plate-Scotia Plate boundary.

- *Proto-Leeuwin Current* (PLC) (fig. 13): An eastward flow of relatively warm surface waters from the Australo-Antarctic Gulf (Southern Indian Ocean) into the Southwest Pacific Ocean along the southern margin of Australia before the complete opening of the Tasmanian Gateway.

- *Proto-Ross (Sea) Gyre* (PRG) (fig. 13): A primarily wind driven, clockwise subpolar gyre, that existed before the opening of the Tasmanian Gateway, in the Southern Pacific Ocean and which produces the Tasman Current (Huber et al., 2004).

- *proto-Weddell gyre* (fig. 15): A subpolar gyre to the east of either a closed or an earliest Drake Passage.

- *Scotia Sea* (fig. 12): The northernmost part of the Southern Ocean; located between the *Drake Passage*, the *North Scotia Ridge*, the *Sandwich Arc* and the South Scotia Ridge.

- Shag Rocks (fig. 12): Shelves to the North West of South Georgia, part of the fracture zone in the *Scotia Sea* area

- *South Sandwich Arc* (fig. 12): The southern part of the western boundary of the Scotia Sea; an elevated region in the South Atlantic.

- *Tasman Current* (TC) (fig. 13): A relatively cool, northward flowing current that flowed along the eastern margin of Australia before the opening of the Tasmanian Gateway, which influenced surface waters in the Pacific sector of the Tasmanian region (Bijl et al., 2013; Huber et al., 2004).

- *Tasmanian Gateway* (TG) (fig. 14): Tectonic changes produced the Tasmanian Gateway when Australia drifted away from Antarctica.

- *Terror Rise* (fig. 12): An elevated region in the *Scotia Sea*; before the opening of the Drake Passage it was a conjugate margin of the Tierra del Fuego (Cevile et al., 2012).

- *Tierra del Fuego* (fig. 12): Southernmost tip of South America; Disruption of Tierra del Fuego and Antarctica probably led to the formation and migration of *continental micro-blocks*, the *Bruce Bank* and the *Terror Rise* and was separated by active opening of the *Dove Basin* (Eagles et al., 2006).

- *Weddell gyre* (fig. 14): A subpolar gyre to the east of the *Drake Passage*, spanning the south Indian and Atlantic ocean basins.

- *Weddell Sea (fig. 12)*: Located to the Southeast of the *Scotia Sea* on the Antarctic Plate.

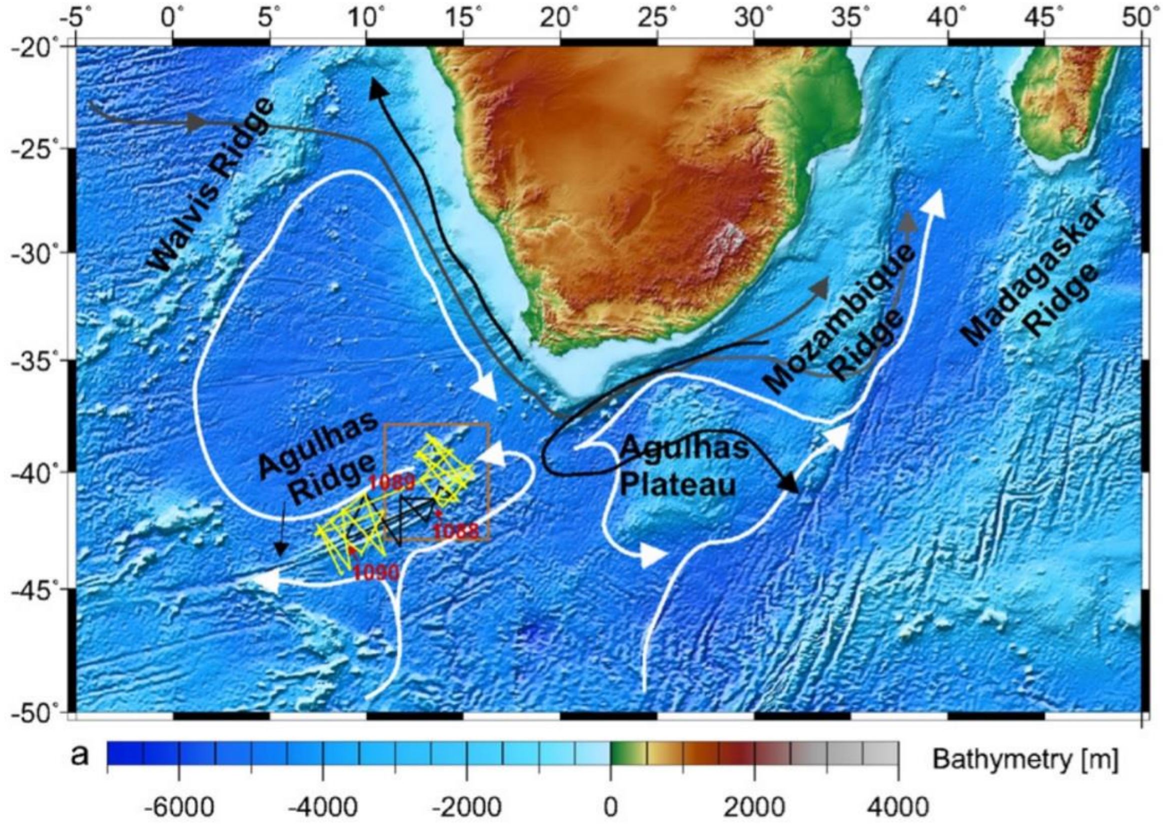

Figure 11: Bathymetric map of the eastern South Atlantic Ocean
Source: Gruetzner and Uenzelmann-Neben (2016)

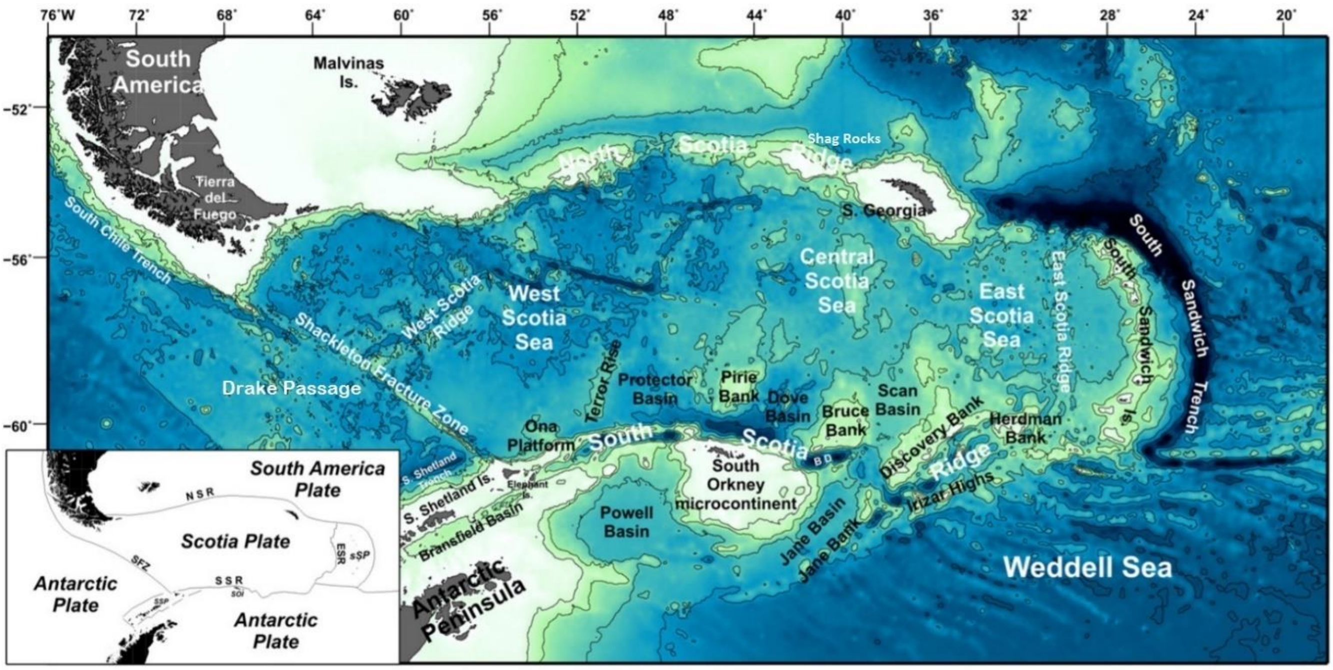

Figure 12: Physiographic map of the Scotia Arc, with some of the features discussed in the introduction
Source: Ceville et al. (2012)

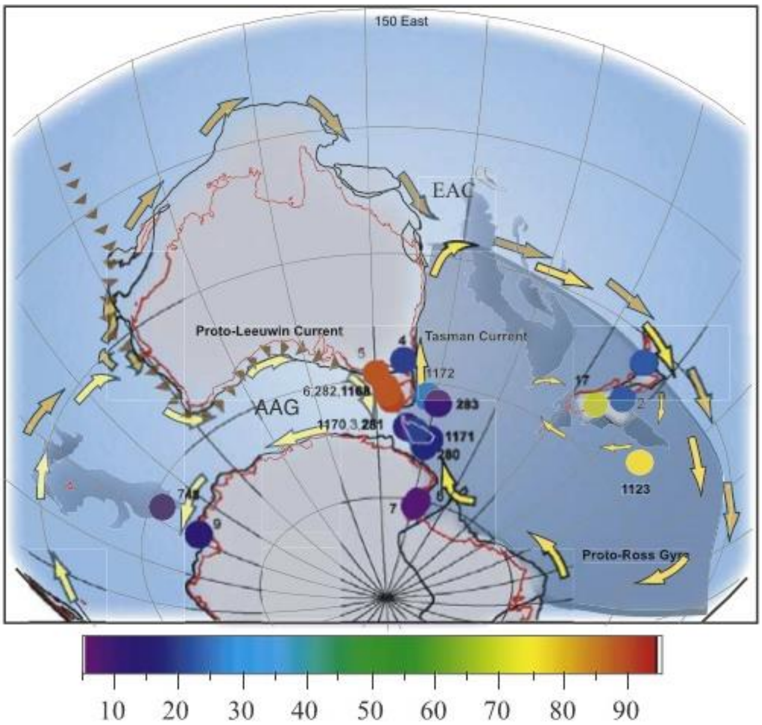

Figure 13: Middle Eocene biogeography and oceanic circulation, Tasmanian region
Source: Huber et al. (2004)

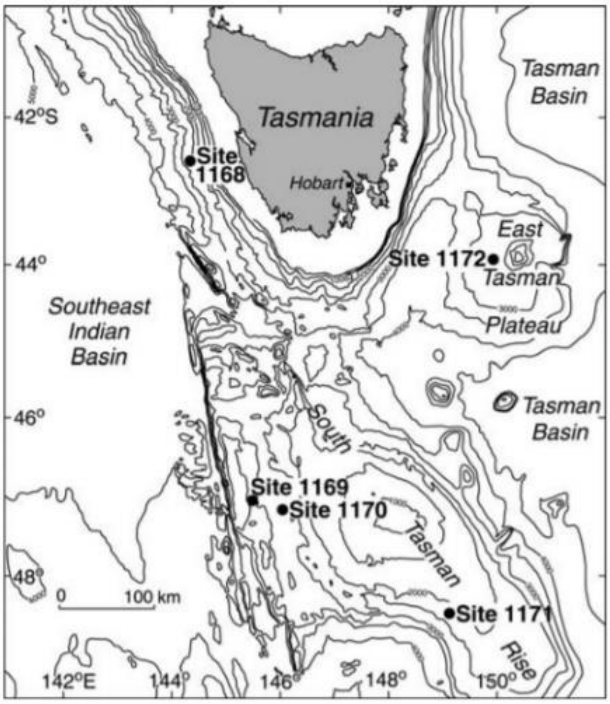

Figure 14: Bathymetric map of the Tasmanian Seaway and ODP Leg 189 drill sites
Source: Stickley et al. (2004)

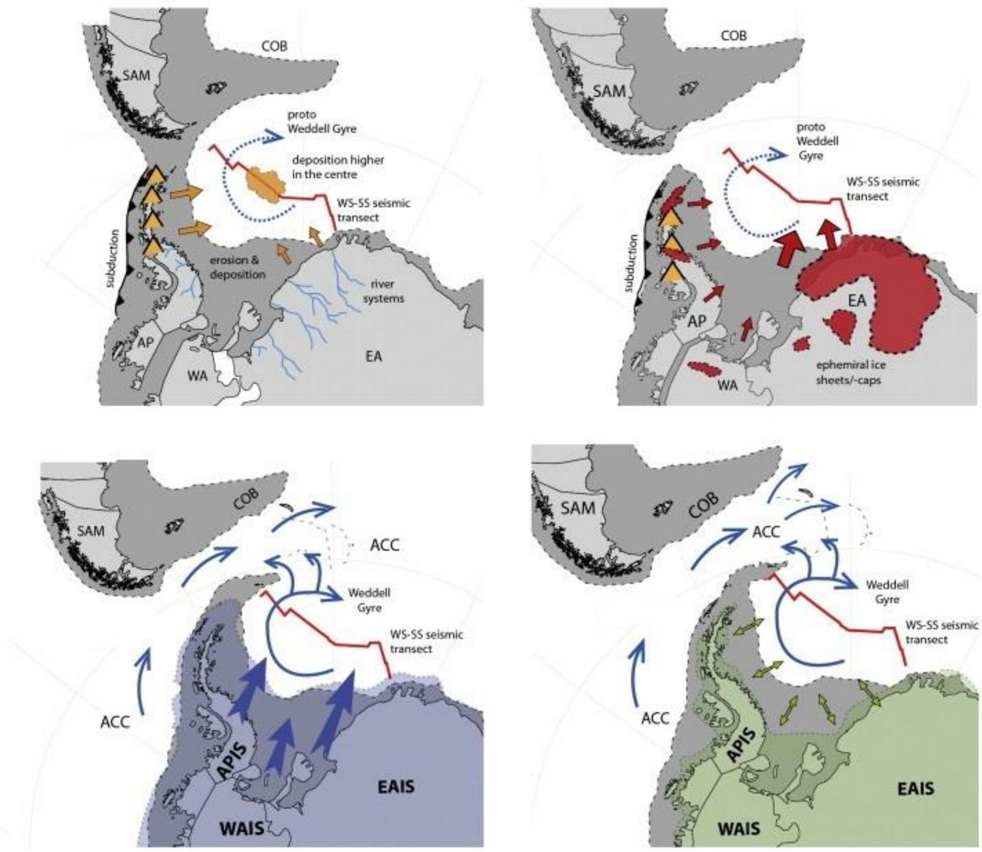

Figure 15: Ocean circulation in the Weddell Sea region with regard to several stages of the Drake Passage region
Source: Lindeque et al. (2013)