Onset and Role of the Antarctic Circumpolar Current.

[1]Peter F Barker, [2]Gabriel M Filippelli, [3]Fabio Florindo, [4]Ellen E Martin, [5]Howard D Scher.

[1]25 Church St., Great Gransden, SG19 3AF, UK
[2]Dept of Geology, Indiana Univ.-Purdue Univ. Indianapolis (IUPUI), Indianopolis, IN 46202-5132 USA
[3]Istituto Nazionale di Geofisica e Vulcanologia. Via di Vigna Murata 605, 00143 Rome, Italy
[4]Dept of Geological Sciences, Univ. of Florida, Gainesville, FL 32611-2120, USA
[5]Dept of Earth & Environmental Sciences, Univ. of Rochester, Rochester NY 14611, USA

Abstract

The major role for the ACC, as inferred in the past, is to have caused or stabilised full Antarctic glaciation. This role has since been questioned, and other hypothesised roles are relatively minor. Using a "smoking gun" assumption, determination of the time of onset of an ACC will resolve uncertainties in its role, and constrain the importance of ocean circulation to climate. To this end, we summarise all published estimates of ACC onset. The time of onset, of shallow circulation or deep, is extremely uncertain, whether based on tectonic studies or the interpretation of changes in the sediment record. Two potential final barriers to circumpolar flow have been identified; south of Tasmania and south of South America. The former is well-constrained by tectonics and marine geology to before 32 Ma for a deep gap, with a shallow gap in place by 35.5 Ma at the latest. These ages fit nicely with the onset of full Antarctic glaciation at 33-34 Ma, although some workers deny the causality. Estimates of the time of opening of the latter range very widely, whether based on tectonics or sedimentary geology, from as recently as 6 Ma to as early as 41 Ma, with the gap depth uncertain also. Resolution of the tectonics-based uncertainties by additional survey being most probably both time-consuming and inconclusive, and the geological estimates being open to alternative interpretations, we define an optimal strategy for additional sampling and measurement, designed to resolve the time of onset much more certainly, possibly also resolving between deep and shallow opening, and thereby constraining the ACC role. Sample sites would have to be close to likely final barriers, to avoid extraneous influence, and within modern zones of ACC influence, ideally would form a depth transect, and would have continuous, mixed terrigenous and biogenic sections. A wide range of carefully-selected parameters would be measured at each.

Introduction

The Antarctic Circumpolar Current (ACC) is today the largest ocean current, and the major means of exchange of water between oceans; its onset may have significantly modified global climate. It was commonly considered that the ACC started in the Eocene-Oligocene boundary (E/O) interval and caused the full development of Antarctic continental glaciation by reducing meridional heat transport across the Southern Ocean (eg Kennett, 1977). Contrasting views suggested that changes in ocean circulation elsewhere (eg Lawver & Gahagan 2003), tectonic uplift (eg Raymo & Ruddiman 1992), or the concentration of greenhouse gases in the atmosphere (principally CO_2) had been the prime forcing factor of Cenozoic global cooling and Antarctic glaciation (eg De Conto & Pollard, 2003; Coxall et al., 2005; Tripati et al., 2005), and that ocean circulation played at most a minor part. Such debate over causality, with developments in other fields, resulted in a reassessment of available data (Barker & Thomas, 2004): published estimates of ACC onset time range widely.

The modern ACC is mainly or entirely wind-driven, but extends to the sea bed, where its path is considered to be influenced by seabed topography (eg Lazarus & Caulet, 1993). The sea surface expression of most of the fronts associated with the ACC (Polar Front, PF; Sub-Antarctic Front, SAF; Southern ACC Front, SACCF: Fig. 1) is a sharp, southward sea surface temperature (SST) drop. The association of the ACC with SST (and thus planktonic biotic assemblages), and its extension to the seabed, led to its identification as a broad current, using proxies in the geological record. Geological signature of the ACC was thought to be a co-existing cold-water biosiliceous facies south of the ACC "axis" and biocalcareous facies to its north, separated by a broad zone of non-deposition or erosion corresponding to rapid bottom-water flow at the axis. Modern physical oceanography, both ship-based (eg Nowlin & Klinck, 1986; Orsi et al, 1995; Heywood & King, 2002) and satellite-based (Gille, 1994), shows that the bulk of ACC transport (around 130 Sv) takes place within deep-reaching jets at the three associated fronts (Fig. 1), which meander and may form isolated current rings. The reality of intermittent rapid currents at the ocean floor in places remote from the mean loci of the fronts, and their influence on sedimentation, are evident from current meter moorings and seismic reflection profiling (eg Barker & Burrell, 1977; Pudsey & Howe, 2002). In thinking about some of the effects of the ACC therefore, we should consider "zones of influence" rather than "paths", although the difference in the geological record may be minor. It is important to appreciate, however, that the numerical models of ocean circulation and heat transport that have been used to estimate the change in oceanic heat transport that accompanied ACC onset, have not modelled deep-reaching, meandering fronts, so that the validity of existing models is uncertain

All published studies have been concerned principally or entirely with only one aspect of the ACC - its onset. This is entirely reasonable: the possibility of migration of ACC fronts with time suggests that time variation of ACC transport, although it could be equally important in its effect on climate, will be more difficult to describe from a small number of drill sites than the more dramatic ACC onset, making the latter a more realistic initial target.

The timing of ACC onset and its likely climatic impact have been closely related in the past: geoscience commonly uses a "smoking gun" assumption, in which events found to be contemporaneous are attributed a causal relationship. The attribution to ACC onset of the relatively sudden development of large-volume Antarctic glaciation within the E/O interval, under this assumption, implied the same age for both events. The age for full glaciation, an ice sheet extending regularly or continuously to sea level, is now well-defined (for a review, see Barker et al, this volume), but estimates of ACC onset age vary widely. It is important to recognise that no preference should be given to estimates falling within this E/O interval. Not only have De Conto & Pollard (2003) shown that a fall in atmospheric pCO_2 could cause glaciation, without any involvement of a change in ocean circulation, but their and earlier studies (eg Huybrechts 1993; Barker et al, 1999) suggest that Antarctic glacial development is non-linear: a steady change in an external variable (such as SST or CO_2) can cause a large, discontinuous change in ice volume because of positive feedback mechanisms such as albedo or surface elevation. An oceanic "event", though not ruled out, is unnecessary.

Two kinds of geological evidence of onset are available, essentially the tectonic and the palaeo-environmental. Tectonic evidence is concerned with the development of gaps that permit continuous pathways around Antarctica, and is least ambiguous when concerned with gaps at oceanic depths, associated with sea-floor spreading, since ocean floor so formed is usually capable of precise dating. However, there is much uncertainty over the palaeo-elevation of non-oceanic bodies, such as subsiding microcontinental blocks, and virtually no possibility of demonstrating by tectonics the existence of a gap at continental shelf depth. In fact, the existence of a land bridge, demonstrated by the free movement of land fauna and flora between adjacent continents, is the only clear demonstration possible of the absence of a shallow seaway, and even here it is difficult to establish the time duration of such a bridge. No evidence of this kind is available in the cases of South America-Antarctica and Australia-Antarctica for the early and middle Cenozoic.

Palaeo-environmental data such as sedimentation pattern, sediment composition and grain size, micropaleontological assemblages, tracers for productivity and ocean circulation, interpreted to show the development of an inter-ocean or circumpolar connection, are vulnerable to misinterpretation (Barker & Thomas, 2004). It is necessary to question data that could reflect climate change, for example, since a link between Antarctic glaciation and the ACC is unproven. This concern affects most of the older interpretations. In addition, interpretations of meridional changes confined to shallow water, such as form the basis of many microfossil assemblage studies, are vulnerable because there were most probably pre-ACC fronts, with contrasting SSTs (and consequently, contrasting planktonic microfossil assemblages) across them. Of major modern, non-ACC frontal jets, the Subtropical Front (Fig. 1) is shallow-reaching (eg Orsi et al, 1995). The Kuroshio and Gulf Stream jets are shallow also, with lower transport, in their extensions away from western boundaries where a deeper current might be expected to occur (eg. Hall, 1989; Krauss et al., 1987); the bottom boundary current off North America actually flows southwest, opposing the surface expression of the Gulf Stream. Pre-ACC fronts were probably shallow also, and would not have controlled deep-sea sedimentation. The locations and mechanisms of heat transport at meandering oceanic fronts are poorly understood, so the nature of circulation change that could contribute to Antarctic glaciation by reducing oceanic heat transport is unknown. For this reason we do not confine our interest to dating the onset of a deep-reaching ACC similar to today's. The palaeoenvironmental data interpretations, like those based on tectonics, vary over a wide age range, which may partly be explained by the most likely scenario of a continuous deep-water pathway being preceded by one that includes barriers to shallow depth. Some workers have used the term "proto-ACC" to signify a continuous circumpolar circulation much shallower than at present, while others have applied the term without regard to depth, to imply a circulation that is only partly circumpolar because of the continued existence of a complete barrier. We use the term here in the former sense, to mean a shallow but continuous current jet or jets, as may have preceded creation of a continuous deep-water path.

The history of atmospheric circulation is unknown, including that of the band of westerly winds, now lying between 35^{o}S and 55^{o}S, that drive the ACC. However, we may assume that westerly winds and a wind-driven ocean circulation were features of the Southern Hemisphere mid-latitudes for much of the Cenozoic, given an Equator-to-Pole surface temperature gradient and a rotating earth, although the temperature gradient would have been lower before Antarctic glaciation. Numerical modelling using coupled ocean-atmosphere models supports this assumption (eg Huber et al, 2003). There would have been no delay between creation of a gap, to whatever depth, and its exploitation by a wind-driven circulation.

Possible roles for an ACC other than that of enabling or stabilising Antarctic glaciation are barely investigated. Since the Pliocene closure of the Pacific-Atlantic connection in the Pliocene it has been the only significant means of exchanging oceanic water masses. Some numerical models (eg Toggweiler & Bjornsson 2000) have suggested that an open Drake Passage contributes to an inter-hemispheric climatic asymmetry, causing a warming in the north at the expense of the south.

Estimates from Tectonics

The two contenders for site of the final barrier in an otherwise-complete deep-water circumpolar pathway are the regions south of Tasmania and south of South America. Other regions of the Southern Ocean are older (the youngest regions being those of the Macquarie Ridge, and north of the Kerguelen Plateau), even allowing for plausible changes in ACC paths. For an ACC to develop, both gaps must be open. The history of the region south of Tasmania is comparatively well-known, and indicates the creation of a deep gap within or close to the E/O interval. The opening history of the second is much disputed, with gap creation ranging from earlier than this to much later.

Opening of the Tasman Seaway, south of the South Tasman Rise, was addressed by DSDP Leg 29 (Kennett & Houtz, 1975; Kennett, 1977) and, more recently, by ODP Leg 189 (Exon et al, 2001, 2004). A detailed description of South Tasman Rise evolution, by Stickley et al (2004) based on Leg 189 data (Sites 1168-1172), reported subsidence at the drill sites over 5 myr, straddling the E/O interval and beginning (ca. 35.5 Ma) 1.8 myr before the Oi-1 isotopic peak taken as the high point of Antarctic glaciation. Over this same period also, of course, the gap was widening at oceanic depths by horizontal separation of the Antarctic and Australian continents. From an analysis of plate motions, Lawver & Gahagan (2003) proposed “unrestricted opening deeper than 2000 m dating from about 32 Ma”.

Scotia Sea evolution has been complicated, but there is little or no dispute about the age of ocean floor in the region south of South America. The range of ages proposed for opening (particularly deep opening) results from disputed views on the palaeo-elevation of key parts of the Scotia Arc and Shackleton Fracture Zone (Fig. 2). The Shackleton Fracture Zone, forming the western boundary of the Scotia Sea in Drake Passage, includes ridges extending ca. 75 km from the South American continent and ca. 300 km from the Antarctic Peninsula. Based on a comparison of sedimentation in the lee of the long southern ridge with that beneath the ACC at present, Barker & Burrell (1977) concluded that the ridges had existed from initial opening, and that ACC onset could have occurred, at the earliest (because of a possible barrier to the east, within the North Scotia Ridge), at about 23 Ma when the ridge ends cleared. Livermore et al (2004), based on dredged rocks from the southern ridge, attributed ridge elevation to post-spreading transpression (comparing it with the Vema Fracture Zone) and adduced an opening age greater than 29 Ma. Barker (2001) endorsed Barker & Burrell’s (1977) interpretation, and drew attention to a potential barrier to the east, that would only disappear when Davis Bank and Aurora Bank (Fig. 2) cleared at between 22 and 17 Ma, depending on their tectonic evolution, as the North Scotia Ridge extended. Lawver et al (1992) noted an east-west separation of the Antarctic and South American plates by 40 Ma, before the onset of recognisable spreading in Drake Passage at ca. 30 Ma, but acknowledged that continental fragments to the east may have delayed ACC onset until the Miocene. A similar analysis by Livermore et al (2005) concluded that a change in South American-Antarctic plate motion at about 50 Ma could have produced crustal thinning and a shallow (>1000 m) connection in the middle Eocene, with a deep-water connection developing between 34 and 30 Ma. Eagles et al (2005), citing De Wit (1977), suggested an earlier deep opening of Drake Passage by claiming a greater age for the Central Scotia Sea. Lawver & Gahagan (1998) suggested ACC flow through an opening Powell Basin (South Scotia Ridge: Fig. 2) by 32 Ma, but Eagles & Livermore (2002) proposed a later time of Powell Basin opening and (with Barker, 2001) concluded that continental parts of the South Scotia Ridge would have barred an early deep connection between Powell Basin and the Pacific, as they do today. Lawver & Gahagan (2003) concluded that major plate motions require that an unrestricted deep passageway for the ACC existed at Drake Passage by 28 Ma, and that, probably via Powell Basin, likely ACC onset was at 31 (±2) Ma.

Lawver & Gahagan (1998) also proposed a shallow early Cenozoic (pre-glacial) pathway between unglaciated East and West Antarctic land areas, using modern subglacial topography and taking into account isostatic rebound. This is a favoured pathway to explain a host of similarities between Ross Sea and Seymour Island Paleogene faunas, following Webb (1979), but has been questioned by Barker & Thomas (2004) on the grounds of the erosional nature of the ice base, crustal structure where known, and absence of Cenozoic relative plate motion and seismic reflection evidence of current flow.

Estimates from Marine Geology/Palaeoceanography

Along with their description of Tasman Seaway opening, Stickley et al (2004) also reported warmer surface-water conditions and invigorated deep-water circulation, as a result of creation of the gap. The absence of any indication of cooling from sedimentology and micropaleontology is compatible with independent, coupled atmosphere/ocean modelling results (Huber et al, 2004), which showed a clockwise (equatorward, *from* Antarctica) Tasman Current before gap creation and implied, if anything, a warming as a result of eastward flow (a "proto-Leeuwin Current") through the gap. The "classical" model, of Antarctic continental cooling and glaciation as a result of reduced meridional oceanic heat transport, was not supported. The existence of a shallow Seaway before 35.5 Ma was not contradicted by the drilling, but no evidence was seen of Eocene current flow. The limitations of these studies (the ocean modelling did not treat of frontal jets, and the drill sites were not at the shoalest or deepest points of the developing Seaway) did not necessarily invalidate their basic conclusions. Elsewhere, Kennett and Exon (2004: see also Exon et al., 2005) argued that an ACC flowed through the newly-created gap, and thermally isolated Antarctica. This view appears to contest the interpretation of Stickley et al (2004) and Huber et al (2004) but may be partly compatible under certain circumstances. For example, if a deep ACC were to have developed later, rather than immediately (perhaps as proposed by Pfuhl & McCave, 2003), then it may have had the isolating effect suggested (though it could not have caused Antarctic glaciation, whose major onset is now well-dated - see Barker et al, this volume). Alternatively, an ACC might have lain largely to the south of the Leg 189 sites, leaving them warm, or might itself have involved warm water masses in its early stages. It seems difficult to reconcile the complete set of Leg 189 views and interpretations, beyond the clear establishment of a time of opening of a deep-water gap south of Tasmania.

Pfuhl and McCave (2003) reported an increase in sediment grain size (sortable silt mean diameter) at 23.9 Ma at ODP Site 1170 of Leg 189, on the South Tasman Rise, suggesting increased bottom-current strength associated with the "deep opening of Drake Passage". As noted above, they suggested ACC onset significantly later than the time of opening of the

Tasman Seaway. Site palaeodepth is difficult to determine, but could have exceeded 2000 m. It should perhaps be noted, however, that sedimentary hiatuses occurred at that site in the late Oligocene and late Miocene (Exon et al, 2004). Roberts et al (2003), and Roberts and Florindo (2005) have used magnetostratigraphy to determine precisely the time limits of hiatuses within sedimentary sections at, respectively, Sites 744 and 748 on the Kerguelen Plateau and Site 690 on Maud Rise. From these determinations, they proposed ACC onset in the mid-Oligocene (ca. 30-31 Ma). Work on nannofossils from the Kerguelen Plateau (Sites 744 and 748 in particular) led Wei & Wise (1992) to propose a late Miocene-early Pliocene age for the onset of the Polar Front, now known to be linked to the ACC.

Sites on Maud Rise and in other regions more distant from the present ACC path have been examined by Diester-Haass & Zahn (1996, 2001). In the earlier paper, they used a change in the relationship between productivity and temperature at Maud Rise (ODP Site 689) to infer Drake Passage opening (“at least for surface- and intermediate water circulation”), allowing the development of a “proto-ACC” at around 37 Ma.

Two studies are based on ODP Site 1090, on the Agulhas Ridge in the South Atlantic slightly north of the present SAF. Latimer & Filippelli (2002) inferred a change in source area (from Al/Ti ratios in terrigenous sediments) and in circulation (ie in planktonic biogenic productivity, from Ba concentrations), implying a deep ACC onset at 32.8 Ma. Diekmann et al (2004) documented a (planktonic) biosiliceous productivity pulse that ended at 33.4 Ma, the inferred result of a southward frontal shift associated with ACC onset.

Maud Rise (Site 689) and the Agulhas Ridge (Site 1090) have also been the focus of paleocirculation investigations using Nd isotopes to detect the presence of Pacific seawater in the Atlantic sector (Scher & Martin 2004). A rapid shift in radiogenic values at both sites around 41 Ma is best explained by the influx of Pacific seawater to the Atlantic, in the middle Eocene. Subsequent shifts at both sites around 37 Ma is believed to reflect increased throughput of Pacific seawater with continued deepening of Drake Passage.

Several studies have used data from remote sites. Diester-Haass & Zahn (2001) attributed palaeoproductivity changes at ODP Site 763 (NW of Australia) and DSDP Site 592 (Tasman Sea) to Tasman Seaway opening at about 34 Ma, assuming that their earlier estimate of 37 Ma for an initial (shallow?) opening at Drake Passage was valid. Gamboa et al (1983) explained enhanced deposition in the southern Brazil Basin (DSDP Site 515) as the disruption of Antarctic Bottom Water flow by the ACC, following onset close to the Oligocene/Miocene boundary. Pagani et al (2000) attributed a ca. 20 Ma decrease in C_{37} alkenone γ_p at the neighbouring DSDP Site 516 on the Rio Grande Rise to an increase in upper water nutrient concentrations resulting from the onset or strengthening of the ACC.

A small number of relevant modern studies are based on regional comparisons. Beu et al (1995) concluded that a late Oligocene connection between the Pacific and Atlantic was required to explain dispersals of molluscs between New Zealand and South America. Kennett & Barker (1990) noted Oligocene biogeographic similarities between Maud Rise (Sites 689 and 690) and the Falkland Plateau (DSDP Legs 36 and 71, particularly Sites 511 and 512) and hiatuses in both regions around the Oligocene-Miocene boundary, to constrain the time of ACC onset.

The published marine geological estimates for the time of onset of the ACC (or Polar Front, which is closely related) are given in Table 1, and those derived from Southern Ocean data are shown in Figure 3. Our main conclusion is that, as for the estimates based on tectonics, the spread of ages is considerable. In the next section we consider the possibilities for alternative causes for the variations observed, and how the situation might be resolved.

Discussion

There is a wide range of estimates of onset age, from observations in both tectonics and marine geology, which it is necessary to try to reconcile and explain. Not all can be correct, and even those which posit the correct age could have had other origins, but all observations are likely to have been correct, and cannot be dismissed. With such a wide range of techniques having been used to produce these estimates, we focus here on alternative explanations that concern palaeocirculation and palaeoclimate, rather than considering particularities of the data sets, analytical techniques etc., on the assumption that the authors themselves would have considered such alternatives in far greater detail than we can here.

The reason for differences in the tectonics-based estimates is clear: different assumptions have been made concerning palaeo-elevation and tectonic evolution of features such as microcontinental fragments, arc volcanoes, fore-arcs or remnant arcs. For the marine geological/palaeoceanographic estimates, some resolution is afforded by considering the depth of pathway inferred. We may assume that a shallow gap would precede rather than follow a deep gap and (in the absence of evidence to the contrary) that a shallow gap precludes the existence of a deep current jet elsewhere along its path, but at present there is no consensus on the effect on meridional oceanic heat transport of a frontal jet confined above a particular depth. Under these assumptions, those estimates based on changes in deep sea-floor conditions in the likely zone of influence of an ACC (eg Pfuhl & McCave, 2003; Latimer & Filippelli, 2002), probably reflect a deep-reaching jet. This conclusion may also apply to some variations in areas now displaced from the modern ACC, such as Maud Rise and the southern Kerguelen Plateau (eg Roberts et al, 2003; Florindo & Roberts, 2005), which may have lain under previous zones of influence. Alternatively, large elevations such as these may have been susceptible to hiatuses through the acceleration of otherwise quite slow currents around their obstructive bulk (Barker & Thomas, 2004). Other implied connections and effects (eg Diekmann et al, 2004; Beu et al, 1995; many of the older estimates) require only a shallow gap, being based on assemblages of fauna and flora that occupy shallow water for all or part of their life-cycle. The implications for gap depth of changes in sea-water composition (eg Latimer & Filippelli, 2002; Scher & Martin, 2004) are uncertain, since it is possible for shallow inputs to be transported to the deep ocean during deep water formation.

The concern with estimates that could be climate-related, *via* evidence of a change in either temperature or biogenic productivity (or a proxy thereof) that might be independent of ocean circulation (Barker & Thomas, 2004), extends from the older estimates, not mentioned here, to some of the more recent ones (eg Wei & Wise, 1992; Diester-Haass & Zahn, 1996; 2001; Latimer & Filippelli, 2002). Although temperature and productivity co-vary in the modern ocean, caution has to be applied when making interpretations about past ocean conditions, as the concentration of preformed nutrients, hence nutrient fluxes, can change over time in an otherwise unchanging circulation. In more general terms, estimates based on measurements at remote sites (eg Gamboa et al, 1983; Pagani et al, 2000; Diester-Haass & Zahn, 2001) are similarly vulnerable, their remoteness increasing the opportunity for variability in other parameters, particularly climatic, to intervene, even though remoteness does not affect the mechanism originally invoked. This applies also to parameter determinations that are within the present ACC pathway but remote from the site of the inferred final gap (eg Pfuhl & McCave 2003; Diekmann et al, 2004).

With virtually all estimates of the onset times of both deep and shallow ACC vulnerable to alternative explanations, the most useful action is to look for ways of resolving the question with minimal doubt. Resolution by marine geophysical means is likely to be difficult, time-consuming and inconclusive: the uncertainties lie in palaeo-elevations of such features as microcontinental fragments, accretionary wedges and subduction-related volcanoes, and inferred subsidence models might be disputed. Also, it could be necessary to examine most or all potential barriers in order to determine which was crucial.

A marine geological study of the sediment record seems advisable, and it would be necessary within it to treat the onset of a deep-reaching and a shallow ACC as separate events. From our examination of existing estimates, it seems that measurable parameters are divisible into those that can only change as a result of deep onset, and those that can also change as a result of shallow onset. It seems most likely that shallow onset would precede deep onset, but this need not be assumed.

Again from our analysis of existing estimates, a study can be designed in greater detail.

1. Location.

Within the zone of influence of the present ACC, but not close to mean paths, where erosion is likely

Close to the likely site of the final barrier, to minimise external influences.

Ideally, to either side of the final barrier.

Away from a "western boundary", where a strong gyral current would be expected even without an ACC.

In deep water, to measure both deep- and shallow-water changes. Site depths should vary, facilitating a transect approach.

2. Section Characteristics.

Continuous, avoiding hiatuses if possible (ie use seismic reflection data, avoid major elevations and possible subaerial erosion).

Mixed biogenic and terrigenous lithology (planktonic record, palaeomagnetic and biogenic dating, many studies on terrigenous fraction).

Autochthonous (avoid turbidites).

Avoid climate-influenced sites (eg bottom water)

3. Parameters to measure.

Terrigenous grain size to examine bottom current onset

Terrigenous sediment mineralogy/geochemistry (hemipelagics and IRD) to look for deep and shallow pathways

Fossil assemblages - zonal changes reflect (mainly shallow?) pathways

4. Built-in redundancy.

Many sites, to resolve issues beyond doubt.

Such a study would be capable also of informing the wide range of observations and interpretations we have described: the observations are undoubtedly valid, whatever their interpretation.

It is important that the time of ACC onset is resolved. However, the role of an ACC in palaeoclimate cannot be resolved, beyond the "smoking gun" of synchroneity, except by advances in understanding of oceanic heat transport, possibly by numerical modelling. These are matters outside the scope of marine geological study, but it is essential that any such work in allied fields is informed, and perhaps steered, by palaeoceanographic observation and analysis.

Conclusions

The ACC has been cited as the cause of onset or stabilisation of Antarctic glaciation. Although physical oceanographic understanding of the nature of the ACC has developed, invalidating much earlier work, and although other potential causes of Antarctic glaciation have been proposed, it remains important to try to determine its time of onset.

! there are two candidates for the final barrier in an otherwise-continuous circum-Antarctic pathway that would be utilised by an ACC, south of Tasmania and south of South America

! the barrier south of Tasmania (the Tasman Seaway) was open to shallow depth by 35.5 Ma at the latest, and to deep water (>2000m) by 32 Ma at the latest. These determinations straddle the known age (33-34 Ma) of establishment of full, stable Antarctic glaciation.

! the time and depth of opening of seaways south of South America is uncertain: estimates based on tectonics range from pre-34 Ma to 16 Ma, and those based on sediment parameters from 6 Ma to pre-41 Ma.

! additional survey to resolve tectonic uncertainties would be time-consuming and ultimately ambiguous

! an optimal strategy for determining ACC onset would involve additional sampling of several continuous ACC-influenced sections proximal to likely final barriers (to avoid external influences where possible), ideally forming a depth transect, and measurement of an extensive range of carefully-chosen parameters.

Acknowledgments

Much of the research on which this synthesis is based used samples and data provided by the Ocean Drilling Program (ODP). The ODP is sponsored by the U.S. National Science Foundation (NSF) and participating countries under management of Joint Oceanographic Institutions (JOI), Inc. GMF acknowledges research support from JOI/USSSP, NSF (OCE 9711957 and 045248), and the donors of the American Chemical Society through the Petroleum Research Fund.

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Figure Captions

Figure 1. ACC fronts (Sub-Antarctic Front SAF, Polar Front PF, southern ACC front SACCF), located by Orsi et al (1995) based on ca. 100 ship transects. Also shown are the Subtropical Front (STF) which is not continuous (and is shallow), and existing Southern Ocean DSDP and ODP sites (open circles), filled and labelled if referred to in the text. MR is Maud Rise, KP is Kerguelen Plateau, STR is South Tasman Rise, SS is Scotia Sea, DP is Drake Passage. Inset shows location of Figure 2.

Figure 2. Locations in the Scotia Sea region, referred to in the text. SFZ is Shackleton Fracture Zone, DB is Davis Bank, AB is Aurora Bank, PB is Powell Basin. ACC fronts, as determined by Orsi et al (1995) are labelled SACCF (southern ACC Front), PF (Polar Front), SAF (Subantarctic Front). Contour line is 2000 m.

Figure 3. Ages of Southern Ocean, geology-based estimates of ACC onset. See also Table 1

Table 1. Estimates of ACC onset (Polar Front development, Drake Passage opening) time from sedimentary parameters

AUTHOR/DATE	SITE	TECHNIQUE/ BASIS	ONSET (MA)	FEATURE
Diester-Haass & Zahn 1996; 2001	689, 763, 592	benthic biomass increase; Si productivity	37	PF,ACC
Kennett & Barker 1990	689/690, Falkland Pl.	similar biogeography	post-Oligocene	ACC
Florindo & Roberts 2005; Roberts et al 2003	690; 744, 748	magnetobiochron (hiatus)	31-30	ACC
Scher & Martin 2004	689	Nd isotopes	41-37	ACC/DP
Gamboa et al 1983	515	increased sedimentation	early Miocene	ACC
Pagani et al 2000	516	alkenone ^{13}C	early Miocene	ACC
Wei & Wise 1992	737,744,747/8, 751	planktonic biofacies	latest Miocene	PF
Latimer & Filippelli 2002	1090	terrigenous geochemistry	32.8	ACC

Diekmann et al 2004	1090	opal pulse, reduced sedimentation	33-30	ACC
Pfuhl & McCave 2003	1170	grain size	23.9	ACC
Exon & Kennett 2004	1168-1172	summary	33-34	proto-ACC
Beu et al 1997	continental outcrop	molluscan dispersal	23	ACC