Potential of the Scotia Sea Region for Determining the Onset and Development of the Antarctic Circumpolar Current

Peter Barker[1] · **Ellen Thomas**[2]

[1] Threshers Barn, Whitcott Keysett, Clun, Shropshire SY7 8QE, UK, <pfbarker@tiscali.co.uk>

[2] Center for the Study of Global Change, Dept. of Geology and Geophysics, Yale University, New Haven CT 06520-1809, USA

Abstract. The strength of interaction between tectonics, ocean circulation and climate is a major concern of palaeoclimate research. To evaluate the strength, we must assess the time of onset and development of the Antarctic Circumpolar Current (ACC) and its likely effects on climate, particularly Antarctic glaciation. Developments in numerical climate modelling, marine geology, tectonics and physical oceanography have cast doubt on widely held assumptions of a causal relationship between the ACC and glacial onset, in the Eocene-Oligocene boundary interval. Here we argue that our best chance to determine ACC onset and development is in the Scotia Sea region ("Drake Passage"), south of South America. There lies the greatest tectonic uncertainty, concerning when a complete deep-water circumpolar pathway was created, and (thus) when the ACC developed as we know it today. There also, the ACC is topographically constrained, and key factors (water mass and sediment distributions, sea-floor spreading history) are sufficiently well known. Determination of the time of onset would enable solution of other questions, such as the nature of Southern Ocean circulation and primary productivity in any period (possibly Oligocene and early Miocene) when Antarctica was glaciated but before a complete circumpolar deep-water pathway existed, and the extent to which ocean circulation changes affected palaeoclimate, particularly Antarctic glaciation. We assess the parameters that might be capable of determining ACC onset, and show that suitable sedimentary records are available in the Scotia Sea region.

Introduction

The Antarctic Circumpolar Current (ACC) is highly influential in the modern climate system. The largest ocean current in the world, it averages about 130 Sv ($10^6\,m^3\,s^{-1}$) volume transport through Drake Passage. It is mainly or entirely wind-driven, but extends to the seabed in most places. It is closely associated with one or more deep-reaching oceanic fronts, and its mean "axial" position is approximated by the locus of the Polar Front (PF in Fig. 8.4-1). The sea surface expression of most of the fronts associated with it (PF, Sub-Antarctic Front SAF, Southern ACC Front SACCF – Fig. 8.4-1) is a sharp southward temperature drop. This association of the ACC with changes in sea surface temperature and thus planktonic biotic assemblage, and its extension to the seabed, have led to its past identification and location using proxies within the geologic record, and to speculation about its effects on palaeoclimate. The ACC developed at some time during the Cenozoic, as deep-water gaps opened around Antarctica, and has been widely viewed as having reduced meridional heat transport, isolating the continent within an annulus of cold water and thus being at least partly responsible for Antarctic glaciation (e.g., Kennett 1977). It is today the major means of exchange of water between oceans, and its onset may have significantly modified Northern Hemisphere climate (Toggweiler and Bjornsson 1999; Sijp and England 2004). Some consider the atmospheric concentration of greenhouse gases (principally CO_2) to have been the prime influence on Antarctic palaeoclimate (e.g., De Conto and Pollard 2003), but the relative contributions of ocean circulation and greenhouse gases to global climate change are not yet understood. In this paper, we assess the potential of the geological record in the Scotia Sea region to reveal the time of onset and subsequent development, and thence probably the climatic influence, of the ACC.

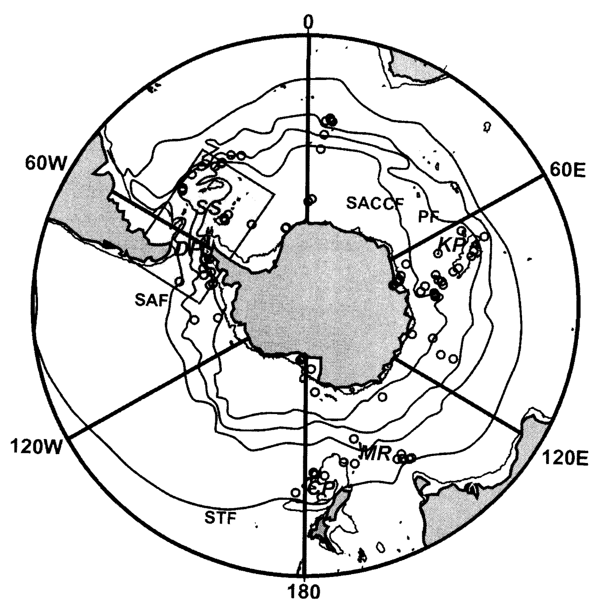

Fig. 8.4-1. ACC fronts (*SAF:* Sub-Antarctic Front; *PF:* Polar Front; *SACCF:* southern ACC front), and Subtropical Front (*STF*) which is not continuous, located by Orsi et al. (1995) based on ca. 100 ship transects. Also existing Southern Ocean DSDP and ODP sites (*open circles*). Figure 8.4-3 shows detail in Scotia Sea region (outline of Fig. 8.4-3 is *lightly shaded box*)

From: Fütterer DK, Damaske D, Kleinschmidt G, Miller H, Tessensohn F (eds) (2006) Antarctica: Contributions to global earth sciences. Springer-Verlag, Berlin Heidelberg New York, pp 433–440

Nature and History of the ACC

The time of onset of the ACC is uncertain, and abundant speculation exists about its onset and effects, despite improvements in our understanding of the geological record and an expanded palaeoceanographic data base. The traditional view is that the ACC began coevally with substantial Antarctic glaciation, in the Eocene-Oligocene boundary interval (the isotope peak Oi-1 is actually shortly after the boundary, e.g., Zachos et al. 2001), and probably caused this glaciation by isolating the continent in a cold-water annulus. In the traditional view also, ACC signature is a southern biosiliceous facies, indicating cold surface waters, with a coeval biocalcareous facies north of an ACC axis, the two separated by a broad zone of non-deposition or erosion corresponding to rapid bottom-water flow at the axis itself.

Recent ODP drilling on Leg 189 (Exon et al. 2001) confirmed that a deep-water gap opened south of Tasmania close to the Eocene-Oligocene boundary, supporting the view of a link between glacial onset and ocean circulation. However, the final barrier in an otherwise-continuous deep-water pathway, essential for continuous, deep-reaching current jets similar to the modern ACC, is generally accepted as lying south of South America, at Drake Passage and other obstructions around the developing Scotia Sea. Estimates of the removal time of this final barrier, based on regional and local tectonics, range from 16–22 Ma to 31–34 Ma (Barker and Burrell 1977, 1982; Barker 2001; Lawver et al. 1992; Lawver and Gahagan 1998, 2003; Livermore et al. 2004. See also Fig. 8.4-2).

Three developments have thrown doubt on the validity of past palaeoceanographic conclusions. First, modern physical oceanography (e.g., Nowlin and Klinck 1986; Gille 1994; Heywood and King 2002) recognises that virtually all ACC transport occurs in narrow jets within deep-reaching fronts that are continuous around Antarctica (the SAF, PF and a less energetic SACCF, Fig. 8.4-1). Second,

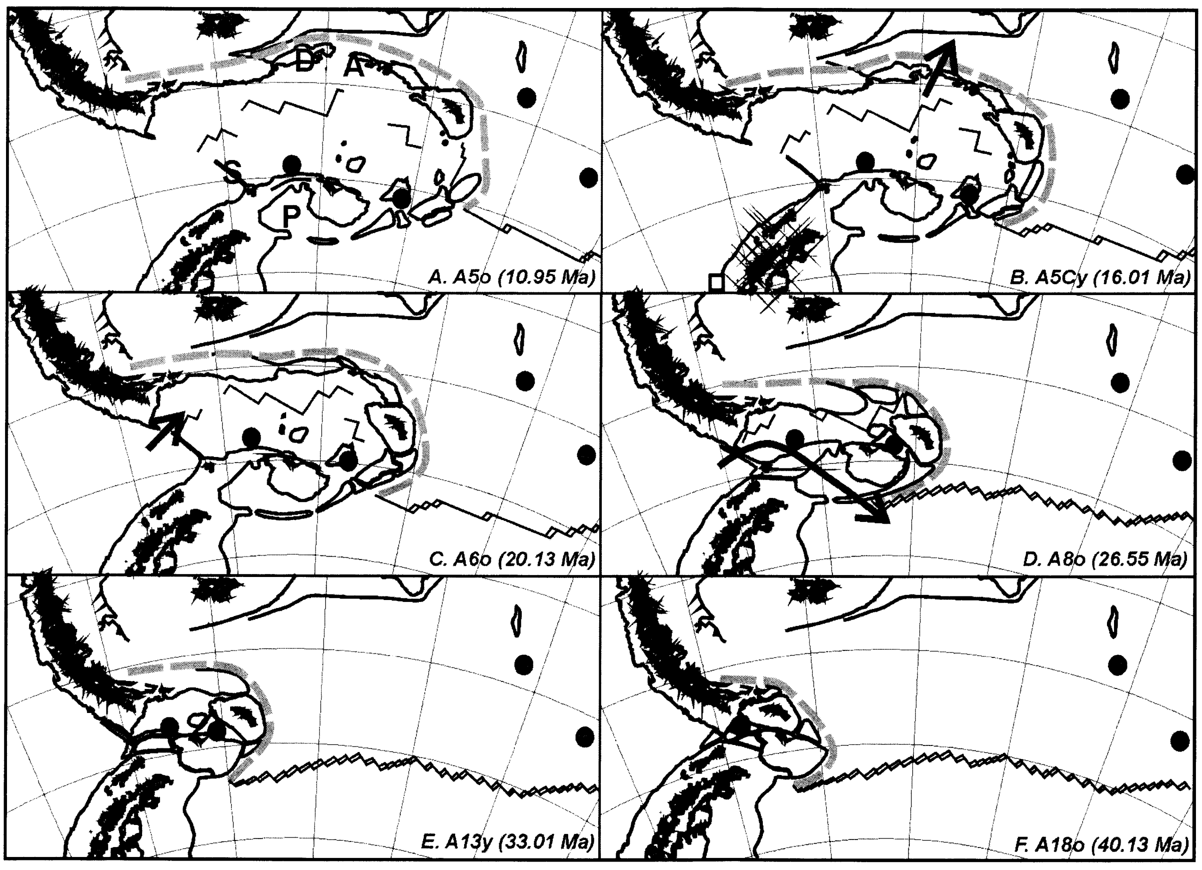

Fig. 8.4-2. Six stages in Scotia Sea evolution from Barker (2001), showing present 2000 m contour, with locations of possible sample sites (Fig. 8.4-3 and 8.4-4) to show that sites may be found on basement sufficiently old to test all existing models of ACC onset and development. In speculating on the time of ACC onset, there is little dispute concerning ocean floor ages, more concerning palaeo-elevations of parts of the Scotia Ridge and Shackleton Fracture Zone (*top left: S:* Shackleton Fracture Zone; *A:* Aurora Bank; *D:* Davis Bank; and *P:* Powell Basin respectively, are such parts; *arrows* show pathways suggested by Barker (2001) and Lawver and Gahagan (2003), at approximate times of opening)

numerical modelling (DeConto and Pollard 2003) suggests that substantial Antarctic glaciation could have developed rapidly as a result of gradual reduction of global atmospheric pCO_2, with or without an ACC. Third, recent results from ODP Leg 189 (e.g., Stickley et al. in press), together with additional numerical modelling (Huber et al. in press), suggest that creation of a deep-water gap south of Tasmania did not significantly change the level of thermal isolation of Antarctica, because of a pre-existing clockwise South Pacific oceanic circulation. In passing, the numerical model underlines the importance of a future focus on the region south of South America, which opened last. It suggests (e.g., Fig. 8.4-3 of Huber et al.) that, with a similar pre-existing ocean circulation, creation of a gap in that region could have resulted in a dramatic change in thermal isolation.

The first two of the above developments gave rise to the following conclusions and possibilities (Barker and Thomas 2004):

1. Existing DSDP and ODP drill sites are too sparse to allow the firm conclusion that sediment biofacies reflect the past existence of large areas of near-constant sea-surface temperature separated by fronts. Fronts are a relatively common feature of the modern ocean, but the conditions that develop and sustain them are not understood, so their past existence as interpreted is in question.
2. If such fronts did exist, it cannot be concluded that they were deep-reaching, or the loci of strong, along-front current jets, or (particularly) that they were continuous. Very few modern frontal zones show these features.
3. The observed sea-surface cooling, with or without intervening fronts, may be a simple effect of continental glaciation (and associated sea-ice formation) rather than an indicator of its cause. Independently of the ACC, much of the Southern Ocean has sea-ice cover for part of the year at present, and at parts of the Antarctic continental margin sea-ice formation is sufficiently persistent and systematic for it to be involved also in the production of cold, salty bottom water. In the past, similar cooling processes may have acted, even with water much warmer than today's arriving at a glaciated Antarctic margin. Cold surface water off Antarctica need not indicate an ACC.
4. Enhanced biogenic production, often taken as a proxy for invigorated circulation, may not have been caused by the ACC. Upwelling, carrying nutrients into the photic zone, is a feature of the present-day Southern Ocean south of the Polar Front but, since cold water sinks at parts of the glaciated Antarctic margin as well as at the fronts, the compensatory upwelling cannot be taken as a certain indicator of an ACC.

Useful Sedimentary Parameters

Future studies in physical oceanography and palaeoclimate modelling may remove some of the uncertainty described above. Given that tectonics cannot easily provide precise and unambiguous answers, direct sampling of sediments may be the only way of determining the onset of the ACC. However, much of the evidence of ACC existence and location adduced in the past from the sedimentary record may not be diagnostic. What parameters remain valid?

1. Grain-size studies of bottom current strength. Modern ACC transport occurs within narrow jets extending to the seabed, rather than within a broad zone, but the jets meander and in places generate detached current rings. Thus, the seabed is swept at intervals by strong bottom currents within a zone much broader than the jet width, but experiences much lower bottom current speeds otherwise (e.g., data in Pudsey and Howe 2002). The ACC, unlike the far steadier and better-known western boundary currents common within the world's oceans, is a high eddy-kinetic-energy (K_e) regime. Grain-size studies cannot distinguish between different bottom current regimes, nor provide useful estimates of mean current flow (mean kinetic energy K_m) in high K_e regimes (McCave et al. 1995). Sedimentation may reflect quieter periods, in between times of more rapid flow, and a greater energy is required for resuspension than to prevent original deposition. Nevertheless, the geological record will reflect in some way the existence of faster currents over an area broader than the jet width, because the periodicity of variation remains shorter than the time resolution of most sediment sections. In summary, grain-size studies on properly-sited samples *will* be capable of indicating an onset and subsequent development of the ACC. Care must be taken, of course, to choose sites beneath the ACC, rather than beneath a bottom current, such as Weddell Sea-produced bottom water, that is clearly related to continental climate, and to choose hemipelagic rather than turbiditic sediments so as to determine local conditions.
2. Studies of current flow direction. Estimates of flow direction from magnetic susceptibility anisotropy of the deposited sediments may be useful, but could be degraded by uncertain directions of fast flow within eddies and rings. Geochemistry and mineralogy, on both clays and ice-rafted detritus (IRD), may provide information on provenance and thus the continuity or otherwise of deep and shallow pathways. Clays would have been transported mainly by deep pathways. The age uncertainties considered here lie entirely within the period of known Antarctic glaciation, so IRD would be available also, to provide information on shallow-

water pathways and the places of origin of icebergs, its coarser-grained component being incapable of bottom-current transport. In addition, studies on radiogenic isotopes (e.g., Nd isotopes in fish teeth) may help establish the overall directions of deep-ocean circulation (e.g., Frank 2002).

Very few measurements of current strength and direction have been made in the past, and the unfavourable distribution of drill sites provides little hope that measurements on existing samples will solve the problem of onset. However, such measurements on new, optimally-sited samples could be complemented by detailed work on biofacies, with the aims of fruitful reinterpretation of the comparatively large number of biofacies studies that already exist, and the separate determination of deep- and shallow-water conditions. The sea-surface palaeotemperature determinations from biofacies studies remain valid and of palaeoceanographic significance, with or without an ACC. For example, the PF probably migrated north of the mid-ocean ridge south of Australia, and of the Kerguelen Plateau, as recently as the latest Miocene or early Pliocene (Kemp et al. 1975; Wei and Wise 1992). Also, recent benthic oxygen isotopic curves (e.g., Zachos et al. 2001) show major changes (in water temperature or ice volume) at several times since glacial onset, that are not satisfactorily explained. A choice of continuous sections for future sampling would ensure that ACC variation since onset could also be examined.

Potential of the Scotia Sea Region

As a region where ACC onset may be determined, the Scotia Sea has several distinct advantages. First, it is generally acknowledged as the region where the final barrier in an otherwise-complete deep-water circumpolar path was removed, this proximity reducing the chance of confusion of an ACC onset-related signal with any other. Second, the confining western North Scotia Ridge prevents northward migration of ACC fronts in response to (for example) externally-induced climate change, making its investigation there potentially less time-consuming. Third, the region is relatively well-known in several respects (see below), so that selection of ACC-related sedimentary sections there may be made more confidently.

In the Scotia Sea region, the SAF and PF cross northern Drake Passage and pass northward through deep gaps in the North Scotia Ridge, to cross the Falkland Plateau. The less prominent SACCF crosses southern Drake Passage and stays within the Central Scotia Sea until east of South Georgia (Fig. 8.4-1 and 8.4-3). To ensure the preservation of a continuous geological record, target sedimentary sections that recorded ACC onset and development should be located away from both the mean frontal positions, which are erosional or non-depositional, and the inner flanks, close to mean positions, where eddies are so common as to induce sediment reworking and hiatuses (see unsuitable sections in, e.g., Fig. 7 of Barker and

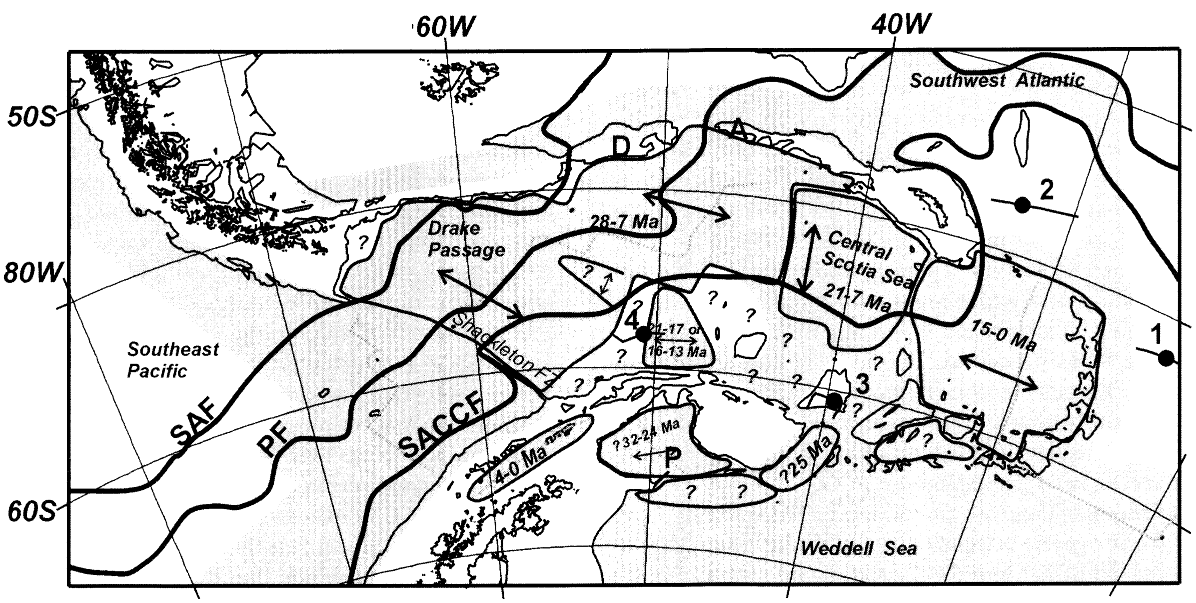

Fig. 8.4-3. Area in Scotia Sea region *shaded*, where sediment sampling would be unwise because of glacial (including glacial turbiditic) sedimentation, Weddell Sea-origin bottom water flow, too-young basement, deformed sediments. Scotia Sea basement ages and bottom-water pathways from Tectonic Map (1985) and Barker (2001). Suitable sections (ship tracks and arrowed sites from Fig. 8.4-4 marked and numbered) avoid these areas. Modern mean loci of component oceanic fronts of the ACC (*SAF*, *PF* and *SACCF*) and key Scotia Ridge components (*A, D, P:* Aurora Bank, Davis Bank and Powell Basin respectively) are marked, but areas of strong ACC-related bottom currents (along mean loci and inner flanks of meander zones) are not. Continuous but ACC-influenced sedimentation occurs on outer flanks

Burrell 1977 and Fig. 8.4-6 of Howe and Pudsey 1999). The outer flanks are ideal. In general around Antarctica, sections are better selected in the south (closest to the present SACCF, for example) than in the north, because a wide range of proxies that might be associated with an ACC migrated northward with time (the biocalcareous/biosiliceous transition, zones of restricted biological diversity and of non-deposition or erosion, e.g., Kemp et al. 1975; Wei and Wise 1992). Further, sedimentary sections are better located on minor structural elevations, to avoid possible glacial-origin bottom water and unwanted thickening of sections by nepheloid-transported clays.

There are two other main constraints. First, the sediment sections must extend back far enough in time (i.e. latest Eocene) to include the oldest alternative age of ACC onset: most of the floor of the Scotia Sea (and of other nearby areas) is too young. Older basement occurs outside the Scotia Sea, but also inside in a few places (e.g., Toker et al. 1991). The exact age of this older basement is uncertain, but it is generally acknowledged as older than that in dated regions (e.g., Barker 2001; Lawver and Gahagan 2003, and Fig. 8.4-2). Second, ACC onset must be recognisable. Towards this, the best sampling sites would before onset have been quiet – well away from a gyre edge or large anomalous elevation – and after onset would have been within the zone of ACC influence (best defined as the farthest reach of eddies and rings away from the frontal zones that spawned them). Other sections to avoid are deformed sediments (fore-arc accretionary prisms of Pacific South America, the North Scotia Ridge, South

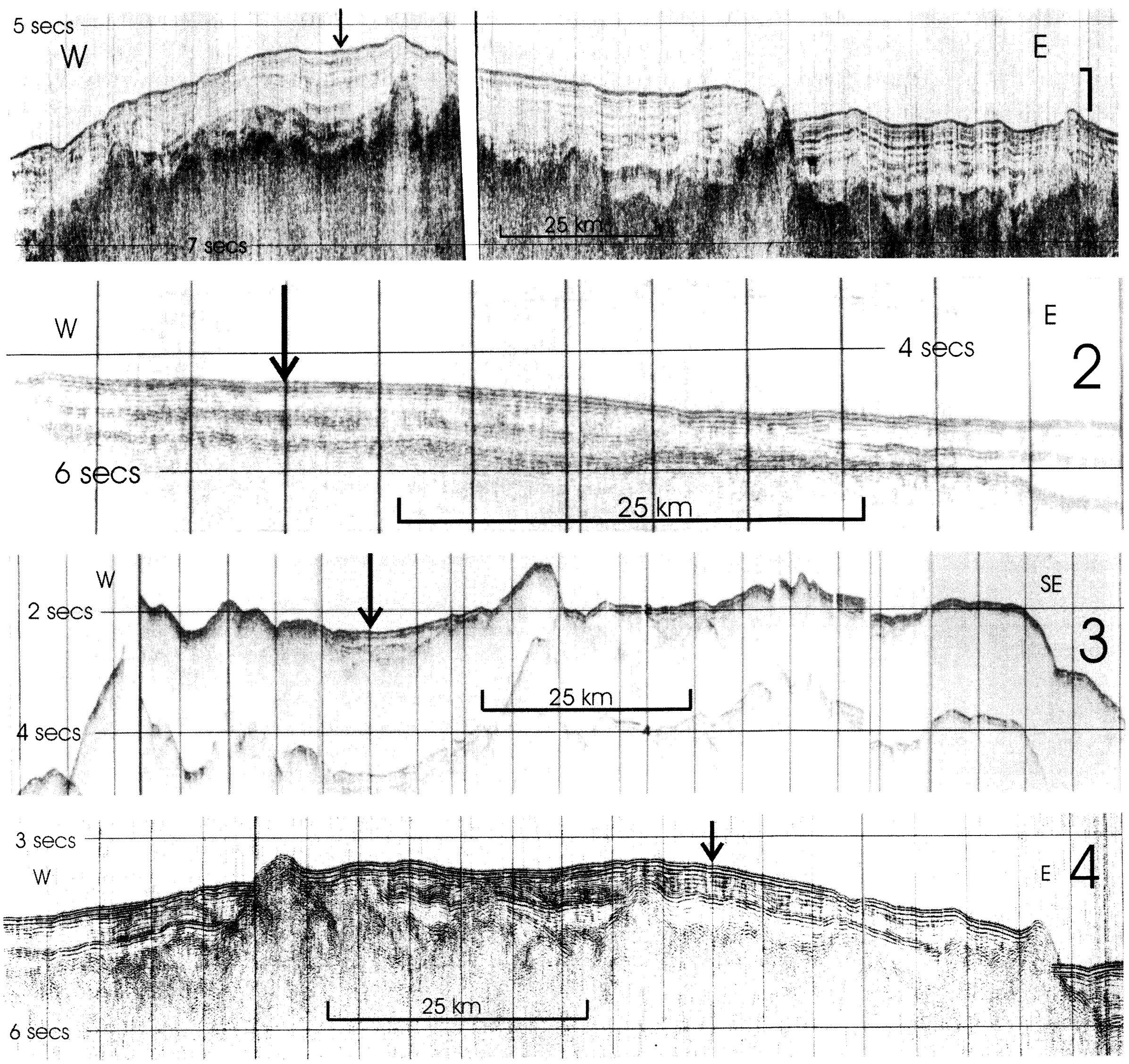

Fig. 8.4-4. Selected seismic profiles showing suitable sedimentary sections (arrowed sections located in Fig. 8.4-2 and 8.4-3), from University of Birmingham data

Sandwich and South Shetland Islands), and glacial and other sediments related primarily to Antarctic climate, such as those deposited beneath glacial-origin bottom water (Weddell Sea, southernmost and eastern Scotia Sea, South Sandwich Trench, western boundaries and Antarctic Peninsula margin), and glacially-initiated turbidites (as off the Antarctic Peninsula: Hollister and Craddock 1976). In the Scotia Sea region, all these provinces are very well-defined. A composite of "where NOT to sample" forms Fig. 8.4-3, which also shows four suggested sections (seismic profiles crossing those sites form Fig. 8.4-4) and the mean loci of the three circum-Antarctic fronts that comprise the ACC. Two suitable areas (sections 1 and 2) lie outside the Scotia Sea, on oceanic basement ca. 70 Ma old now on the outer rise of the South Sandwich Trench (Barker and Lawver 1988) but previously more remote from the growing Scotia Sea, and on ca. 100 Ma old basement on the SE flank of the NE Georgia Rise (Kristoffersen and LaBrecque 1991) respectively. The other two lie on a likely stretched and subsided continental fragment (3) and on old ocean floor (4) in the southern west/central part of the Scotia Sea, generally considered to have been formed during the earliest stages of Scotia Sea development (see Fig. 8.4-2). All show sections that lack unconformities and are parallel-bedded, compatible with mainly pelagic/hemipelagic sedimentation and relatively minor current control. We have not included the more elevated continental regions around the Scotia Sea, which may have risen above sea level (suffering erosion) during break-up, or large parts of the SE Pacific where terrigenous turbidites dominated deposition (Hollister and Craddock 1976), and pelagic/hemipelagic interbeds, representative of local conditions, may or may not exist. The preferred strategy, in view of the importance of determining ACC onset, would be to examine several sections for essentially simultaneous effects.

Conclusions

Re-assessment of ACC onset and development is important for the understanding of global palaeoclimate, despite (or even because of) uncertainties over its role, but should be undertaken with care because some previously-accepted indicators of ACC existence may have other origins. Changes in bottom current strength and deep-water pathways remain valid indicators.

We suggest that the Scotia Sea region is an appropriate location for obtaining sediments that would make such a reassessment possible. It is generally acknowledged as the location of removal of the final barrier in a complete circumpolar deep-water path (this proximity reducing the chance of confusion of an ACC onset signal with others), confines the ACC topographically (reducing the range and complexity of any variation in path) and is relatively well-known (permitting a more discriminating choice of sediments). We identify four suitable sedimentary environments, and show a typical seismic profile from each (Fig. 8.4-4):

- ocean floor of Mesozoic age east of the South Sandwich island arc and trench;
- the southeast flank of the Northeast Georgia Rise (also Mesozoic);
- two areas within the Scotia Sea, as old as possible; one probably on ocean floor, the other probably on a subsided continental fragment.

Acknowledgments

We are grateful for the comments of Dieter Fütterer and anonymous reviewers. PFB thanks the Trans-Antarctic Association for funding his attendance at 9th ISAES. ET thanks NSF for partial funding for her research by Grant EAR-0120727.

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