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# Small basins in the Scotia Sea: The Eocene Drake Passage gateway

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**Abstract**

After isostatic correction for their sedimentary fill, the depths of two small oceanic basins in the southern Scotia Sea suggest that both started to open in mid to late Eocene times. Models of the short magnetic anomaly profiles across the basins provide support for these determinations. The location of the basins, adjacent to the present-day Drake Passage marine gateway, and the timing of continental stretching leading up to their opening, during the Ypresian (early Eocene) onset of global cooling, mean that their importance is potentially far greater than their small size implies. Extension in the region of the two basins would have opened Drake Passage to shallow or intermediate depth oceanic circulation between the Pacific and Atlantic oceans for the first time. This coincided with a reorganisation of vertical mixing patterns in the global ocean, a shift in the site of carbon sequestration from coal swamps and peatlands to ocean sediments, and the onset of a long decline in atmospheric carbon dioxide concentrations. Cenozoic global cooling may therefore have begun as a result of the shallow opening of Drake Passage.


*Keywords:* Antarctic circumpolar current; Antarctic glaciation; Drake Passage; Eocene; Gateways; Scotia sea

## 1. Introduction

The opening of the Drake Passage gateway (Fig. 1) is thought to have been an important event in the history of global oceanic and atmospheric circulation, because it allowed the free transfer of water masses between the Pacific and Atlantic oceans at mid to high southerly latitudes for the first time since the breakup of Gondwana. This circulation may have led to the onset of the Antarctic Circumpolar Current (Fig. 1), the world's largest current, whose development has been implicated in the formation of permanent ice sheets on Antarctica near the Eocene–Oligocene transition (~34 Ma; [4]).

Gateway opening was not a straightforward affair, and would have involved a period of extension preceding the onset of seafloor spreading at the West Scotia Ridge prior to 27 Ma [5] after a major change in South America–Antarctica plate motion at about 50 Ma [6]. So, the formation of a marine connection would have depended on the subsidence of shallow banks and the configuration of small basins in the embryonic Scotia Sea. In this paper, we present evidence for extension in the opening of small basins in the southern part of Drake Passage starting during the Early Eocene Climatic Optimum (~54–50 Ma; [7]), its possible role in circulation change, and its wider implications.

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## 2. Small basins and intervening highs

The southern Scotia Sea hosts two small, deep (3500–4000 m), basins, the Protector Basin and Dove Basin, (Fig. 2) that lie between three shallow topographic highs. The westernmost of these highs, Terror Rise, is presently a swell where the seafloor shoals to about 3000 m from surrounding depths of > 3500 m. The approximately 200 km wide Protector Basin separates Terror Rise from the shallow (<2000 m) Pirie Bank. Dove Basin, which is also about 200 km wide, lies to the east of Pirie Bank and separates it from the shallow (<2000 m) Bruce Bank.

The crustal natures of the Terror Rise, Pirie Bank, and Bruce Bank are not known with certainty, but available evidence suggests they are fragments of continental crust. Seismic reflection profiles over all three highs show a basement reflector that lacks the numerous diffractions characteristic of the basaltic surface of oceanic crust. Dredge hauls have returned rocks of continental affinity from Pirie Bank [9], although it is not clear whether or not these all represent glacial dropstones, while a piston core taken from the southern edge of Bruce Bank (Fig. 2) yielded evidence of shallower paleodepths and a nearby terrestrial source in Paleogene and Cretaceous times [10,11]. Each of the three highs exhibits a high amplitude (c. 1000 nT) positive magnetic anomaly, which gridded magnetic data (Fig. 2; [5]) shows in each case to have a north–south width of ~100 km. A fourth magnetic anomaly of this type occurs over the broad southwestern plateau of Discovery Bank, which lies east of Bruce Bank across the small (150 km wide) Discovery Basin (Fig. 2). These anomalies would have formed a continuous belt before the opening of the intervening basins. A reconstruction of the west Scotia Sea [5] juxtaposes this belt with a magnetic anomaly of similar amplitude and width in and offshore of Tierra del Fuego, which formed over a Cretaceous igneous batholith [12]. Terror Rise, Pirie Bank, Bruce Bank, and possibly southwestern Discovery Bank, are therefore likely to be extensions of continental Tierra del Fuego that have been distributed across the southern Scotia Sea during its opening.

## 3. Scotia Sea tectonics and paleocirculation

Recent advances in knowledge of the west Scotia Sea, Antarctic–Phoenix, and South America–Antarctica

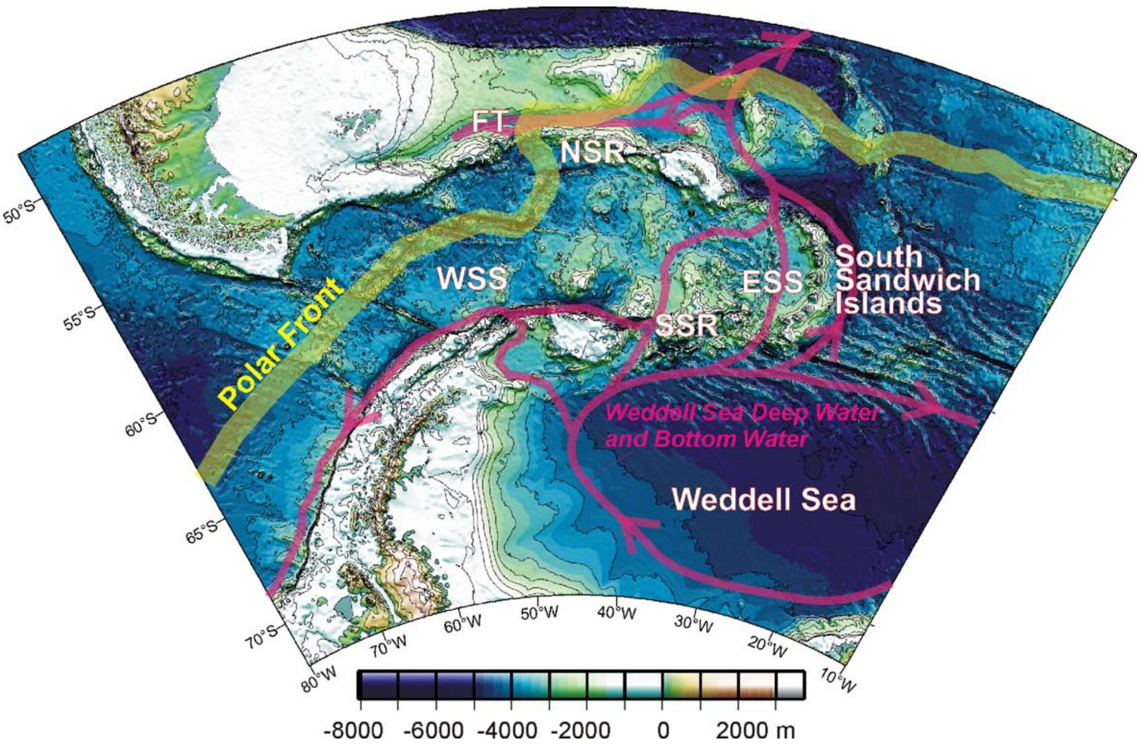


Fig. 1. Drake Passage bathymetry [1] with present-day currents. The Polar front is an averaged path from sea surface temperature data after [2]. Weddell Sea deep water flows are schematic, after [3]. ESS, East Scotia Sea; FT, Falkland Trough; NSR, North Scotia Ridge; SSR, South Scotia Ridge; WSS, west Scotia Sea.

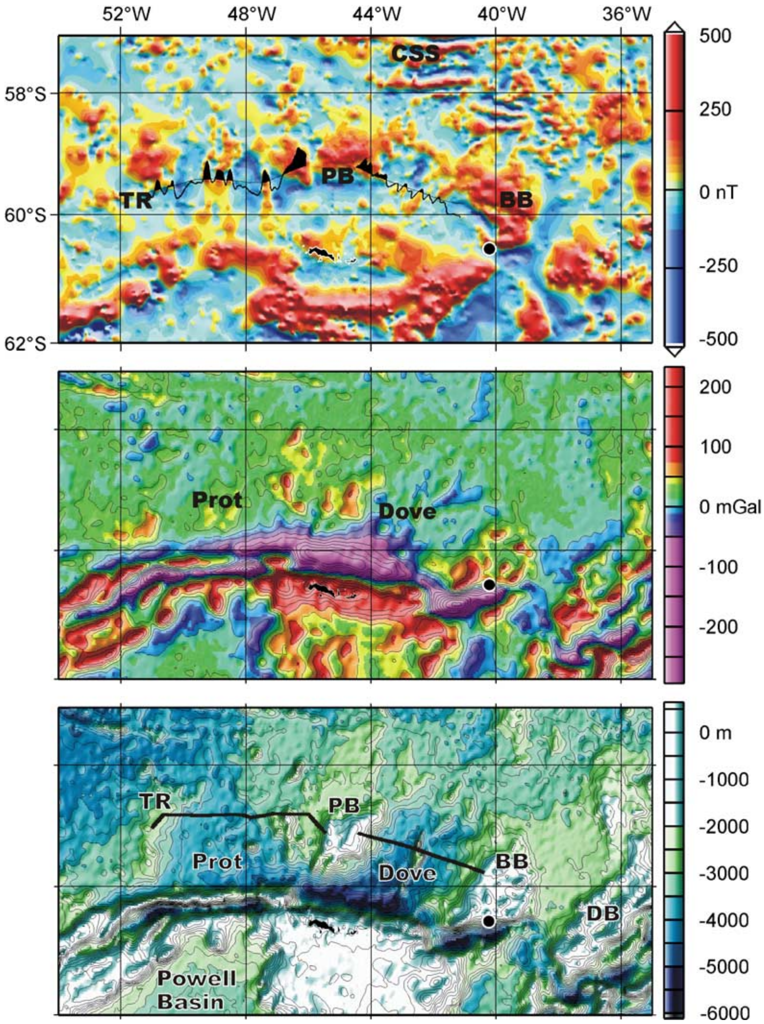


Fig. 2. The southern parts of the Scotia Sea, as shown by magnetic (top; grid from a compilation of marine track line data [5]), free-air gravity (middle; [8]), and bathymetric (bottom; [1]) data. Bruce Bank core location is shown by a black disc. Abbreviations as in Fig. 1 and also BB: Bruce Bank; DB, Discovery Bank; PB Pirie Bank; Prot, Protector Basin; TR, Terror Rise. Magnetic anomaly profiles from Figs. 5 and 7 are shown in the top panel. The seismic reflection profiles from Figs. 4 and 6 are located by bold lines in the bottom panel.

seafloor spreading systems (Fig. 1; [5,6,13]) have tightened the bounds on possible plate movements during the opening of Drake Passage. As well as this, recent studies [5,14] dealt with doubts (e.g. [3]) about blockages to deep current flow at the Shackleton Fracture Zone and North Scotia Ridge by showing that these features are likely to have been uplifted to their present shallow depths during a period of convergent movements at the west Scotia Sea margins that started around 17 Ma, after the onset of seafloor spreading in the East Scotia Sea back-arc basin. However, the roles of the central Scotia Sea, Protector and Dove basins remain poorly understood.

Knowledge of the tectonic history of the central Scotia Sea is complicated by ambiguous data that will not be addressed in detail here. Two main interpretations, both with inconsistencies, can be found in the literature. In the first, the central Scotia Sea contains an Oligocene or Miocene back-arc basin [15] and in the second it is an Early Cretaceous extension of Tierra del Fuego's Rocas Verdes Basin [16,17]. In the former view, the South Georgia microcontinent would have moved northwards as the northern margin to the back-arc basin, whose opening left a set of east-striking magnetic anomalies in the central Scotia Sea (Fig. 2). Undoing this motion places South Georgia immediately to the north of the Bruce and Pirie banks, where the southernmost anomalies occur. In the latter view, South Georgia is confined to the northern edge of the Scotia Sea during its opening.

Presently available literature [3,18] shows late Eocene and early Oligocene reconstructions in which the Dove and Protector basins are closed, suggesting that they opened in Oligocene–Miocene times. These reconstructions are based on a short sequence of magnetic anomalies in Protector Basin that has been identified and modelled as C5C-C5 [15,19]. Alternatively, the basins may have opened during a period of east–west extension in the Drake Passage region that is predicted by both direct and indirect determinations of motions between the South America and Antarctica plates between around chron C21 (49 Ma) and the opening of the west Scotia Sea [5,6,20,21]. In a recent study [6], based on joint inversion of magnetic anomaly and fracture zone data from the Weddell Sea and flanks of the South American-Antarctic Ridge, the onset of this period of extension is estimated to have occurred in the period 50 ± 3 Ma.

The importance of the Dove and Protector Basins to the opening of Drake Passage is demonstrated in Fig. 3, which shows two possible reconstructions of the Scotia Sea at chron C8 (~26.5 Ma). The reconstructions show present-day bathymetry [1] with respect to a fixed Antarctica, and no attempt has been made to undo uplift of the accretionary prism at the North Scotia Ridge associated with collision there since 17 Ma [5]. In both reconstructions, Protector and Dove basins are shown to be open, as discussed above, having been moved towards Tierra del Fuego according to published reconstruction

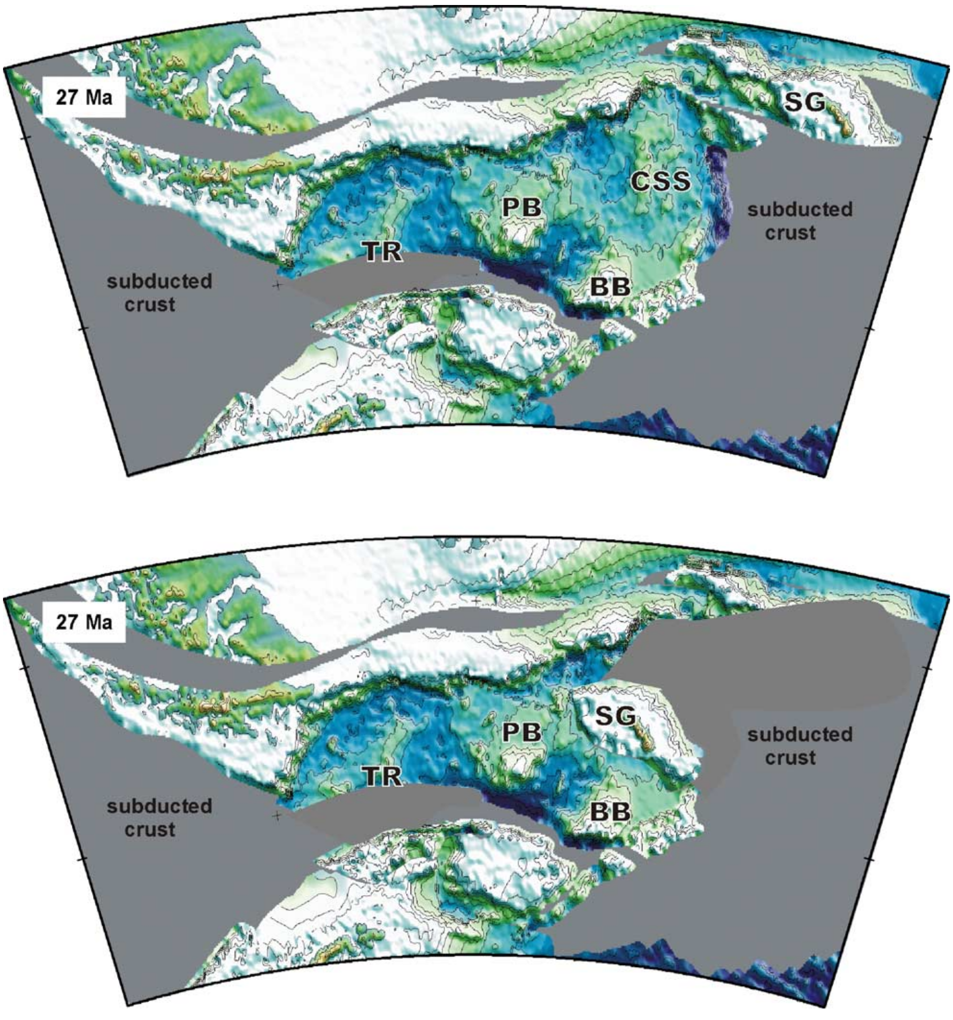


Fig. 3. 27 Ma/anomaly C8 reconstructions. Top: assuming an 'old' central Scotia Sea. Bottom: reconstruction with a post-C8 central Scotia Sea closed. The North Scotia Ridge would have been deeper than shown, due to post-17 Ma uplift [5] and the seafloor of the small basins, west Scotia Sea, and northern Weddell Sea would have been slightly shallower than shown, due to post-C8 thermal subsidence. Colour scale as in Fig. 1. Abbreviations as in Figs. 1 and 2, and also SG: South Georgia.

parameters for the west Scotia Sea [5]. In one of them, the central Scotia Sea is in existence at chron C8 (e.g. [17]) and, in the other, the central Scotia Sea is shown closed as if it had opened as a back-arc basin after C8 [15]. The principal difference between the two reconstructions is, consequently, the position of South Georgia; in the reconstruction with a 'young' central Scotia Sea, South Georgia occupies a position in the centre of the Scotia Sea as a northward continuation of Bruce Bank. However, it is Terror Rise that is critically placed with respect to potential current flow into Drake Passage. If the Protector Basin were closed in these reconstructions, then the combined Terror Rise-Pirie Bank block would occupy the gateway, presumably not having undergone stretching and subsidence related to basin opening, and therefore possibly even emergent. In such a state, the Terror Rise-Pirie Bank block would have presented a significant, perhaps total, barrier to current flow. A subsided Terror Rise, on the other hand, as shown, would permit shallow or intermediate depth circulation through the gateway. In the next sections, we examine some of the geophysical data from this region to address the likely age of the basins, and hence of subsidence of their margins.

## 4. Age of Protector Basin

Although heat flow measurements have been made in Protector Basin [22] they have not been published. A symmetrical set of north–south lineated magnetic anomalies (Fig. 2)—one positive axial anomaly and two positive anomalies on each flank—suggest that the basin opened by seafloor spreading with an east–west azimuth. This azimuth permits a reconstruction that reunites the wide linear magnetic anomalies on the Terror Rise and Pirie Bank as a possible extension of the Tierra del Fuego batholith anomaly. Satellite-derived gravity anomalies (Fig. 2) over the basin reveal no obvious fracture zones or other flowlines that might support this determination of the spreading direction. The basin floor is mostly smooth (Fig. 2), due to the presence of sediments, which seismic profiles reveal to be around 1 s thick in two-way travel time (Fig. 4). The basement surface shown by these data is rough and the profile shows a buried median valley at the axis, both indicating a slow spreading rate [23], as in the neighbouring west Scotia Sea and Powell Basin [5]. Recently acquired multichannel seismic reflection profiles over the southern part of the basin [19] show a clear increase in basement depth towards the margins, consistent with an interpretation based on symmetrical seafloor spreading.

The basement depth in the basin can be used a guide to the basin's age, by correcting the observed seafloor depth for the presence of, and subsidence due to, the sediments deposited there. An empirically derived correction [24], of 600 m for each second (two-way travel time) of sediments in seismic data, is appropriate for modest sediment loads like those in the Protector and

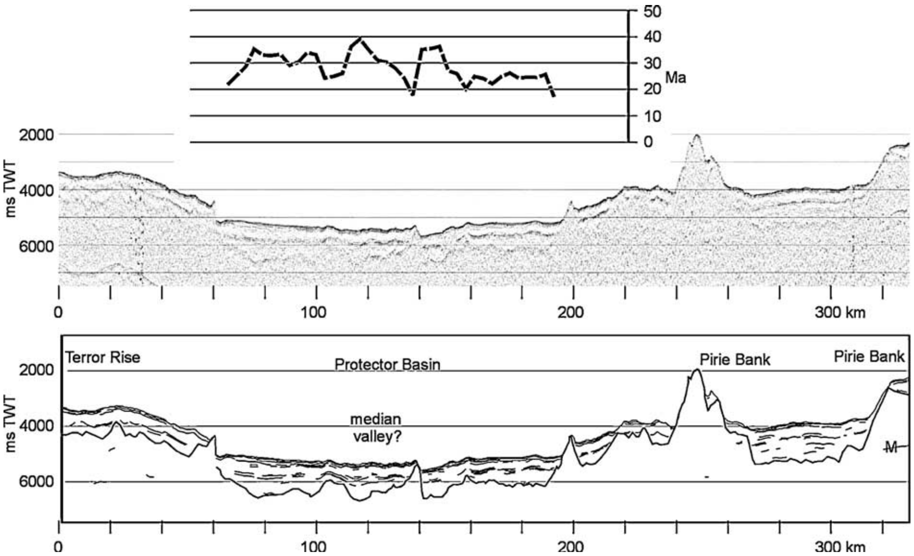


Fig. 4. Protector basin: single channel seismic data (acquired by the British Antarctic Survey in 1975). The top panel shows model ages determined from the depth of the basin floor in those parts where linear magnetic anomalies, formed in seafloor spreading, occur, after an isostatic correction for the imaged sediment layer is applied to the bathymetry. M: multiple.

Dove basins [25], and has been used successfully in a large-scale study of the North Atlantic [26] as well as in nearby Powell Basin [18,27]. Age determinations along the single channel seismic line in Fig. 4, that crosses the basin's magnetically lineated floor in the north, suggest ages scattered between 40 and 20 Ma (late Eocene to Oligocene).

Using the subsidence age range as a guide, we can look for possible matches between the magnetic anomalies in the basin and the magnetic reversal timescale [28]. In view of the rough basement surface and presence of a median valley, we confine the modelling process to the use of slow (<25 km/m.y. half rate) spreading rates. The magnetic anomaly profiles are characterised by a long stretch of reversed polarity, which, at slow spreading rates, can only have been produced during one of two periods since early Eocene times (Fig. 5). These periods are chron C21-chron C19 (~48.5–41 Ma; mid Eocene) and chron C13-chron C11 (~34–30 Ma; earliest Oligocene), the latter of which is more consistent with the isostatically corrected bathymetry. It is, of course, possible to model the short sequence of anomalies using other parts of the timescale with faster and more variable spreading rates. For example, two studies have presented models for the period C5C-C5AC [15,19]. The more recent of these studies used a recent timescale and fast half-rates of 35 km/m.y., without large changes, but it predicts a non-existent normal polarity anomaly (C5B) within the long reversed anomaly. A model that does not feature this reversal would require even faster initial spreading half-rates of ~55 km/m.y. that drop abruptly to ~30 km/m.y. just before chron C5B. Neither of these faster spreading, younger, models is consistent with the roughness of the basement reflector or with the basin's isostatically corrected depth.

Measurements of variations in seafloor age with depth in small basins are often subject to greater scatter than in larger oceans [29]. The oceanic lithosphere in such settings may be anomalously shallow, due to the presence of proportionally more buoyant lithologies of 'transitional' crust, thermal uplift related to edge-effect convection in the asthenosphere, or tectonic inversion, biasing determinations to younger ages. A thin and anomalously deep lithosphere is also conceivable, due to conductive cooling at the thick continental lithospheric margins, which would yield dates that are too old. Recent multichannel seismic data and gravity modelling in Protector Basin [19], however, often show a typical thermal subsidence trend in the basement surface, and a 7 km thick crust above sparse Moho reflections, suggesting that the oceanic crust at least is not anomalous. In addition to this, the fact that the Protector Basin magnetic anomalies can only be modelled at times that are consistent with the observed, or slightly deeper, depths, speaks in favour of the assumption of normal thermal subsidence.

## 5. Age of Dove Basin

Although heat flow measurements have been made in Dove Basin [22], none have been published. A set of lineated magnetic anomalies strikes NNE–SSW on the basin floor, suggesting that the basin opened by seafloor spreading with an ESE–WNW azimuth. The magnetic reversals on individual profiles are often subdued, and

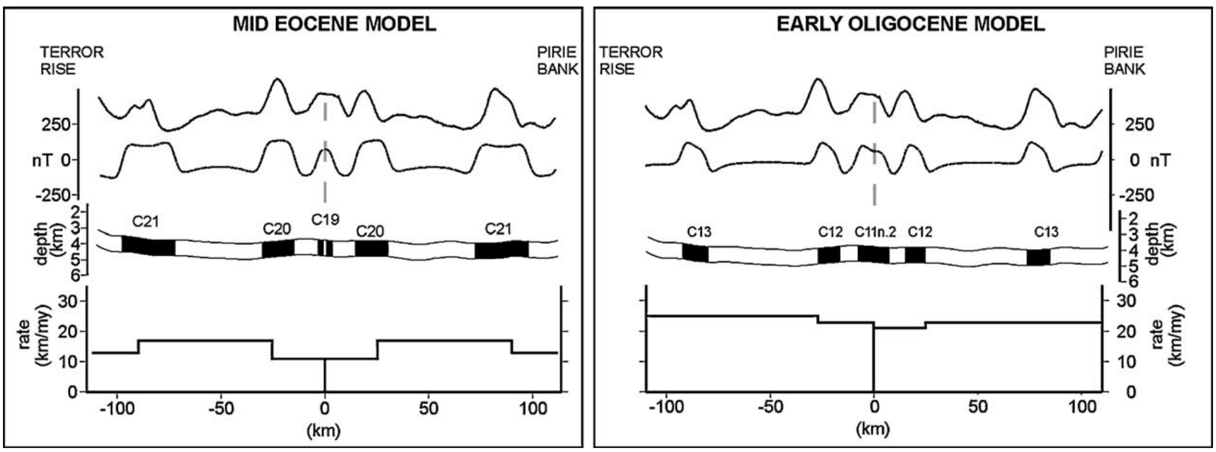


Fig. 5. Two models of the magnetic anomalies in Protector Basin. The data profile (solid line, cruise End690; see Fig. 2 for location) is projected onto 90° and the model profiles (dashed line) are made using the present-day bathymetry as the top surface of a 1 km thick source model with effective susceptibility of 0.005.

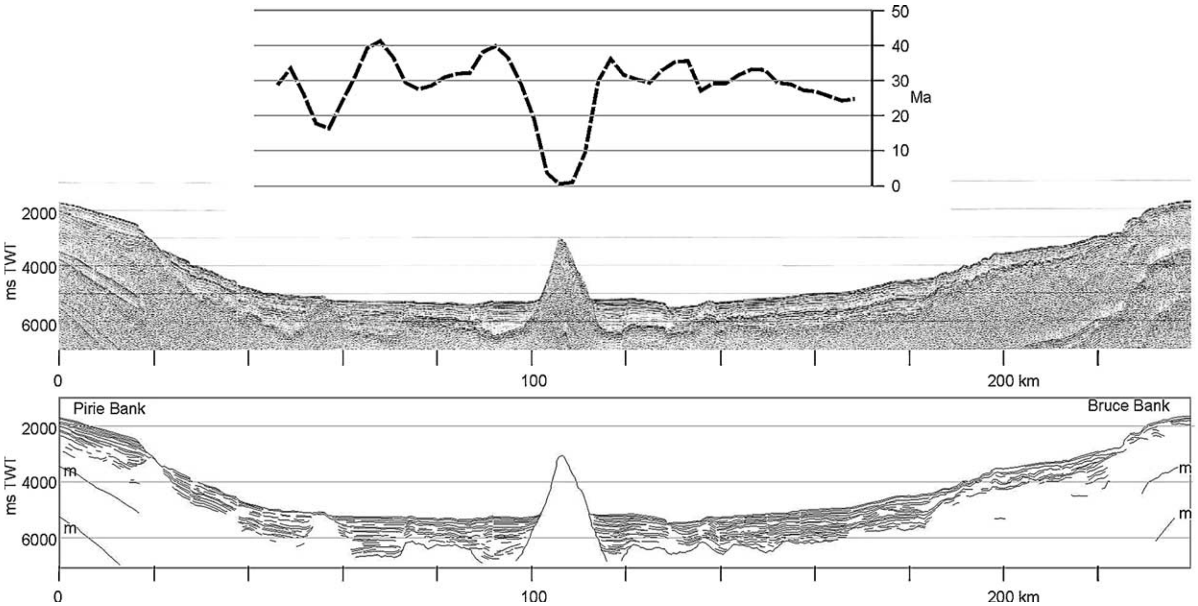


Fig. 6. Dove basin: seismic data for age-depth determination (acquired by the British Antarctic Survey in 1989). The top panel shows model ages determined from the depth of the basin floor in those parts where linear magnetic anomalies, formed in seafloor spreading, occur, after an isostatic correction for the imaged sediment layer is applied to the bathymetry. m: multiple.

reveal some complexity at the axis, with a prominent negative anomaly near 58.5°S and a smaller positive anomaly elsewhere. One prominent linear free-air gravity anomaly, with an ENE azimuth, crosses the eastern flank of the basin. If this anomaly represents a flowline, then spreading was markedly oblique to the ridge axis. Instead, the anomaly may express the trace of a ridge-crest offset that migrated southward. Figs. 2 and 6 show that the basin floor is smooth, due to the presence of sediments, except for a steep-sided seamount which crops out above the sediments at the basin axis, rising to depths of less than 2500 m, and whose elongated outline parallels the spreading anomalies. The seamount coincides with the negative parts of the otherwise-positive axial magnetic anomaly complex, suggesting it may post-date the rest of the basin. Consistent with this, the high resembles a feature at the Antarctic-Phoenix Ridge that has been related to post-

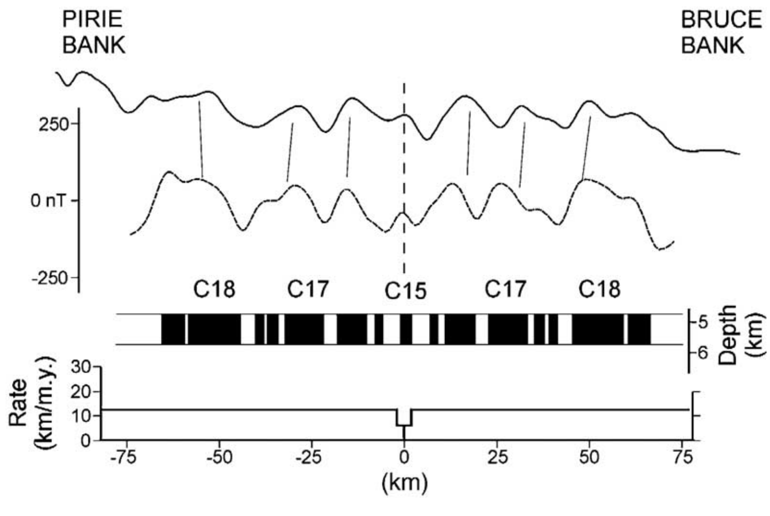


Fig. 7. Model of the magnetic anomalies in Dove Basin. The data profile (solid line, cruise D172; see Fig. 2 for location) is projected onto 115° and the model profile (dashed line) is made using a flat 4.75 km deep layer as the top surface of a 1 km thick source model with effective susceptibility of 0.005.

extinction evacuation of a magma plumbing system [30]. Deep sediment-filled depressions at the seamount flanks resemble the flexural depressions that surround intraplate seamounts, suggesting cooling and strengthening of the oceanic lithosphere by the time of seamount emplacement.

The basement surface is rough, as in Protector Basin and much of the rest of the Scotia Sea, suggesting slow spreading rates. The geodynamic setting and seismic reflection character of oceanic basement appear to be similar to those of Protector Basin, where modelling of distinctive magnetic anomalies confirms the subsidence-derived age. The seafloor in Dove Basin is slightly deeper than in Protector Basin and, once corrected for the presence of sediments, in areas away from the axial seamount, is consistent with an age range of 40–30 Ma (Fig. 6). Bearing in mind the possible presence of a long-wavelength flexural bulge related to the axial seamount, it is possible that the true age range may be a little older than that calculated. The magnetic profiles are not characterised by any broad negative anomalies, meaning that the basin is unlikely to have opened at the same time as Protector Basin or outside of the period between the long reversed-polarity intervals preceding chrons C20 and C12 (~45–32 Ma); the anomaly sequence is otherwise ambiguous. Fig. 7 shows a possible model for a set of anomalies in the southern part of the basin on a profile that does not cross the axial seamount and hence avoids complexity related to possible post-extinction volcanism. The model, which has a reasonable fit to the data in both halves of the basin, is for anomalies C18–C15 (~41–34.7 Ma; middle Eocene), consistent with the age range determined from basin depth.

## 6. Eocene opening of Drake Passage

The simplest interpretation of the bathymetry of both basins is that they formed by seafloor spreading in middle to late Eocene or, in Protector Basin, earliest Oligocene, times. The basins are flanked by deeply subsided continental crust, strongly suggesting that seafloor spreading in them would have been preceded by a period of continental lithospheric stretching, thinning, and subsidence. Palynological and micropalaeontological work on samples from a short core taken from Bruce Bank established that the bank was subsiding within the range of paleodepths 800–2000 m during nannozone CP13b (46.3–44.5 Ma) [11], which is independent evidence for this period of continental subsidence. The evidence for continental stretching and seafloor spreading is fully consistent with the determination of a period of east–west plate divergence in the Scotia Sea that started during the period 53–47 Ma (in the Ypresian stage of the Eocene) [6,20,21].

Depending on which of the magnetic models for Protector Basin is favoured, the oldest oceanic crust in the region may be as old as the reversed interval before chron C21 (~48 Ma; in Protector Basin) or the one before C18 (~41 Ma; in Dove Basin). In the former case, seafloor spreading first occurs in the Protector Basin before 48 Ma, then moves east to Dove Basin before 40 Ma, before stepping back to the west Scotia Sea by ~34–30 Ma [5,6], with a gap in recorded extension after the cessation of Dove Basin spreading around C16 (~36 Ma). There is no indication of a significant change in South America–Antarctica spreading rates during this gap [6], which suggests, if the older interpretation of Protector Basin is correct, a further site of early extension might remain to be identified in the Scotia Sea, bridging the gap between the opening times of the Protector and Dove basins. This site could, perhaps, be in rift basins at the margins of the west Scotia Sea, or in the Discovery Basin.

The latter case, where Dove Basin is the elder, implies a simple, continuous, east-to-west progression in the site of seafloor spreading in the Scotia Sea, starting in the Dove Basin during the period 41–34.7 Ma, moving to the Protector Basin during 34–30 Ma, and then to the west Scotia Sea. We favour this scenario because of the simplicity of the progression in spreading loci that it implies, because it requires a simpler spreading rate history in Protector Basin, and because an earliest Oligocene age is more consistent with the isostatically corrected depth of Protector Basin. Discovery Basin may represent a pre-C18 locus of stretching or spreading in this progression but, although more heavily sedimented than the Dove and Protector basins, it is also far shallower and displays no strong magnetic anomalies, meaning a younger back-arc basin origin (cf [3]) is equally plausible.

### 6.1. Geodynamics

The geodynamic setting of the Dove and Protector basins can be compared to that of the west Scotia Sea. Seafloor spreading in the early stages of west Scotia Sea opening was faster than relative motion between South America and Antarctica. This can be explained if, as seen from Antarctica, the west Scotia Sea opened in the extensional stress field created between the WNW-migrating South America plate to the NW, and an arc plate above an east-migrating trench to the east [5]. At the same time, slow seafloor spreading occurred in the

Powell Basin, in response to the relative motion between the arc plate and Antarctica. Similarly, in the period between chrons C18 and C11, the total amount of extension in the Dove and Protector basins is greater than South America–Antarctica relative motion by an amount similar to the amount of continental stretching that preceded opening of the Powell Basin [5,27]. Variations in the relative motion of the arc plate, in relation to changes in the shape or dynamics of the subduction zone, might be invoked to explain the slightly different spreading azimuths of the Protector and Dove basins.

This setting requires a subduction zone to have been active since before C18 to the east of Bruce Bank and the South Orkney Microcontinent. K–Ar dating of dredged calc-alkaline rocks from southeast of the South Orkney Microcontinent suggest that subduction may already have started there by 76 Ma [31], and interpretations of magnetic anomalies in the Weddell Sea suggest it is likely to have persisted until Miocene times [3]. The forerunner of the South Sandwich subduction zone may well have been present to the east of Bruce Bank at least since the inception of the back-arc East Scotia Sea, at around 20–17 Ma, and possibly since 35 Ma (~C15), based on K–Ar dating of dredged rocks from the forearc [32], but there is no further indication of the presence, or otherwise, of earlier subduction to the east of Bruce Bank.

### 6.2. Antarctic glaciation

A well-known theory [4] links the establishment of the Antarctic Circumpolar Current after the opening of deep ocean gateways, including Drake Passage, to the perennial glaciation of Antarctica that started around the Eocene–Oligocene boundary, via decreased meridional heat transport. Circulation modellers, though, disagree on the effectiveness of high meridional heat transport in their models in warming Antarctica prior to this time [33,34]. Alternatively, newer studies suggest the only requirements for glaciation were an orbital configuration that suppressed the likelihood of warm summers in Antarctica and atmospheric $CO_2$ concentration below a threshold value of 780 ppm [35,36]. However, the date at which this threshold was crossed post-dates the permanent glaciation of Antarctica [37]. What is more, orbital configurations that suppress warm Antarctic summers recur every 2.4 million years [36].

It seems therefore that further conditions needed to be met for the glaciation to occur. One further condition could have been a modest decrease in meridional heat transport due to gateway opening [35]. Consistent with this, our results, showing the onset, around chron C13, of seafloor spreading in the Protector Basin, the second of a series of such episodes in the Scotia Sea, reinforce the suggestion that a through-going, deep (>2000 m), Drake Passage connection and accompanying wide,

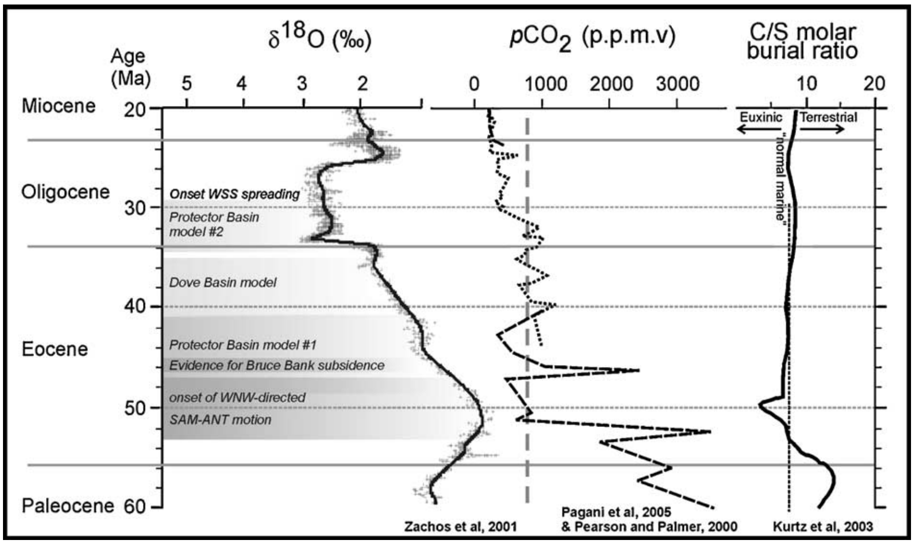


Fig. 8. Scotia Sea extensional events plotted alongside a benthic $\delta^{18}O$ curve (heavier values indicate increased ice volume and decreased bottom water temperature, reprinted with permission from [7], copyright 2001, AAAS), atmospheric partial pressure of $CO_2$ ($pCO_2$: dotted line reprinted with permission from [37], copyright 2005, AAAS; dashed line [38]), and a curve showing the molar burial ratio for carbon and sulphur isotopes [42], which can be interpreted as indicating the dominant sites of organic matter burial. Vertical grey dashed line is the threshold value of $pCO_2$ below which a model Antarctic glaciation occurred [35].

sustained, Antarctic circumpolar flow could have become established by ~34 Ma [6].

## 7. Discussion

Our results, together with previous conclusions [6,11], suggest subsidence in the area of Dove Basin and Protector Basin east of Drake Passage was underway at ~50 Ma, producing a deepening shallow- or intermediate-depth rift that gave way to seafloor spreading in the Dove basin by around C18/41 Ma. Fig. 8 shows these conclusions plotted alongside a smoothed benthic $\delta^{18}$O curve [7] and thus how basin opening coincided with a sustained period of global cooling that started at about 50 Ma. The correlation between this history and determinations of falling ancient partial pressure of atmospheric $CO_2$, which has been linked to global cooling [37,38], is also shown.

The cause of falling atmospheric $CO_2$ concentrations in Eocene times is still not well understood [38]. Fig. 8 prompts the question of whether a shallow- to intermediate-depth opening of Drake Passage may have played a role in the drop of atmospheric $CO_2$. In circulation model experiments, the opening of even a shallow (<1000 m) Pacific-Antarctic gateway at mid-southerly latitudes perturbs global ocean circulation; the diversion of surface and shallow currents through the gateway accompanies the disappearance of vigorous overturning cells around Antarctica, and an increase in the vigour of meridional overturning (e.g. [33,34,39]). Changes of this sort might therefore be expected coinciding with the period of stretching and subsidence leading up to seafloor spreading in Dove Basin. Differences between Pacific, Atlantic, and Southern Ocean $\delta^{18}$O and $\delta^{13}$C profiles [40] and $\varepsilon_{Nd}$ profiles from Maud Rise [41] provide evidence for large changes in bottom water constitution during this period, consistent with such an idea.

These observations may be signs of the initiation of an ocean that could sequester more carbon than before. There is evidence from carbon and sulphur isotopes in DSDP and ODP records [42] for changes in the global carbon cycle during Ypresian times (Fig. 8). Before ~52 Ma, organic carbon was stored in coals, coal swamps, and peatlands, and was easily and frequently remobilised, for example by wildfires, sustaining high atmospheric concentrations of $CO_2$ [42]. Later, carbon burial switched to the oceans, at first in euxinic seas for a short period that coincides with a proposed period of 'Warm Salty Deep Water' production [40], and later in deep ocean sediments, where it could be locked away from the atmosphere over far longer timescales. These changes led up to the first in a series of postulated pulses of bipolar glaciation [43], coincident with the inception of seafloor spreading in Dove Basin, which would have been accompanied by a phase of accelerated subsidence in Drake Passage. With appropriate feedbacks taken into account, for example involving changes in nutrient supply via continental runoff as rainfall patterns adjusted to the reorganisation in ocean circulation, it may be possible that the Eocene greenhouse to icehouse transition indeed was set in train by the initial opening of Drake Passage.

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