Scotia Sea regional tectonic evolution: implications for mantle flow and palaeocirculation

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Abstract

The Scotia Sea and surrounding Scotia Arc have evolved over the past 40 Ma, by extension behind an east-migrating subduction zone, at the boundary between the South American (SAM) and Antarctic (ANT) plates. The considerable data set now available (regional geology and geophysics, earthquake seismology, satellite altimetry, global plate analyses) suggest why east-migrating subduction began, what has been the driving force that has sustained it, and what other processes have controlled the mode of back-arc extension in the Scotia Sea. A suite of six reconstructions has been developed, based on this data set. The reconstruction to 40 Ma creates a compact, cuspatc continental connection between South America and the Antarctic Peninsula at the subducting Pacific margin, with fragments (now dispersed around the Scotia Arc) occupying positions within it compatible with their known geology. The driving force has been subduction of South American ocean floor, which began as a result of southward migration of the pole of South American–Antarctic plate rotation, and a key modulator of back-arc extension has been collision of ridge crest sections of the South American–Antarctic plate boundary with the east-advancing trench. Cenozoic regional tectonic evolution has two other likely consequences which greatly increase its importance. Firstly, this region saw the tectonic disruption of the final barrier to complete circum-Antarctic deep water flow, that may have had a profound effect on palaeoclimate. Secondly, it is possible that the rapid roll-back of the hinge of subduction is related to shallow eastward flow in the sub-lithospheric mantle. Both of these consequences are explored. The reconstructions show that rapid roll-back of the subduction hinge (averaging 50 mm/a over the last 40 Ma with respect to the South American plate) has been a feature of all of Scotia Sea evolution, and provide a history of motion of several oceanic microplates, most of which are now welded together within the Scotia Sea. This will guide the location of seismometers and/or dredge hauls to test the hypothesis of shallow mantle flow, and help interpret the results. The reconstructions also allow an assessment of the creation of deep-water pathways that would have permitted the development of the present-day Antarctic Circumpolar Current (ACC). An early Miocene onset (within the period 22–17 Ma) seems likely for the ACC, depending on the structure and palaeo-elevation of Davis Bank and Aurora Bank, sections of the North Scotia Ridge. However, the study shows there was a delay (of one or more million years) between initial provision of a deep-water pathway and the major mid-Miocene change in global climate (involving the general level of Antarctic glaciation) that may have been related. If these changes were related, then the delay suggests that other factors, possibly rough elevated ocean floor but also non-tectonic factors (such as atmospheric CO₂), were important in determining palaeoclimate. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Scotia arc; subduction; back-arc extension; mantle flow; palaeoceanography; Antarctic glaciation; Antarctic circumpolar current

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1. Introduction

The Scotia Sea region, extending from about 75° to 25°W, 61° to 53°S, is mainly of oceanic crustal structure and origin. It is bounded on three sides by the Scotia Arc, islands and submarine ridges of the North and South Scotia Ridge and South Sandwich island arc that are a mixture of old continental fragments, arc volcanoes (active and dead), remnant arc and accretionary prism. At present, the Scotia Sea region comprises two small plates, between the major South American and Antarctic plates (Fig. 1). Most of the boundaries of those plates lie within the Scotia Arc, and almost all plate motion is east–west. However, this relatively simple situation has not existed for long: although the region has always lain at the South American–Antarctic plate boundary, its tectonic evolution over the past 40 Ma has been far more complex.

Regional tectonic evolution here is interesting because of that complexity, but is particularly important for two main additional reasons. Firstly, the continental connection between southernmost South America and the Antarctic Peninsula was most probably the final barrier to continuous circum-Antarctic deep-water circulation (Barker and Burrell, 1977), represented today by the Antarctic Circumpolar Current (ACC). It has been suggested by many (e.g. Gill and Bryan, 1971; Kennett, 1977) that development of the ACC greatly reduced north–south ocean circulation and heat transport, and may thus have had a profound effect on Antarctic climate by isolating the continent within an annulus of cold water. The ACC also provides at present the most effective means of water exchange between the three main ocean basins. The details of its onset and development are therefore of considerable interest to palaeoceanography and palaeoclimate. Second, Alvarex (1982) proposed that the mass balance in the mantle, between a shrinking Pacific region and expanding (intra-Gondwana) Indian and Atlantic regions, has been achieved (at least partly) by shallow eastward mantle flow, first through the Caribbean and then through the Scotia Sea region, where such flow is not impeded by subducted lithosphere or by deep, static sub-continental mantle. An understanding of regional tectonic evolution is therefore valuable in order to help define the constraints on such flow, and identify ways of trying to investigate it more precisely and more directly.

The requirements of these two fields of study are different. To investigate shallow mantle flow, the most effective methods at present are geochemical, by sampling rocks for tracers of Pacific or Indian/Atlantic mantle, and seismological, by examining mantle shear through the preferred orientation of olivine crystals, by shear-wave splitting of earthquake S and SKS phases. For the simple application of either method in the Scotia Sea region, it would be beneficial to work with oceanic lithosphere, which has potentially a simpler history and composition than continental lithosphere: thus, an understanding of the ages and history of motion of the oceanic areas of the Scotia Sea would be a useful contribution.

The palaeoceanographic study is more demanding. Ocean circulation depends critically upon both the width and depth of pathways. The focus here is therefore on all aspects of the tectonic history of the various elevations within the Scotia Ridge, not only the history of their lateral dispersal, as would create pathways between diverging elevations, but also the uplift and subsidence history of several key elements that might have controlled circulation. To determine a subsidence history requires a detailed knowledge of structure and origin. Where subaerial exposure of a fragment is limited or absent, this can be gained only from marine geophysical mapping and direct submarine sampling. For continental fragments such work also aids reconstruction, as if describing the pattern on a jigsaw puzzle piece.

There have been innumerable studies of individual parts of the Scotia Arc and Scotia Sea, and many previous attempts to describe and understand regional tectonic evolution (e.g. Hawkes, 1962, Barker and Griffiths, 1972; DeWit, 1977; Dalziel, 1983; Barker et al., 1984; Garrett et al., 1987; Barker et al., 1991). These all produced insights that remain useful today, but inevitably were limited by the conceptions and background information of their time. Such long-term study of the region has led to a general view of the major elements of its evolution, which should be stated here as it pervades the detailed description and analysis that follow. Fundamentally, the geology of the continental fragments now distributed around the Scotia Arc betrays an origin
Fig. 1. Major plate and microplate boundaries and motions. (A) Major plate boundaries and motions in the Southwest Atlantic and Southeast Pacific, showing vectors of plate motion (SAM–ANT motion is 20 mm/a at the Chile Trench, other vectors are to scale and Nazca–SAM motion, north of the Chile triple junction, is much faster—75–80 mm/a). BTJ is the Bouvet triple junction and CR the Chile Rise. Inset (B) shows smaller plates in the Scotia Sea region (Scotia SCO, Sandwich SAN and Shetland SHE), with directions of motion at boundaries, epicentres of shallow earthquakes and locations of features described in the text: along the North Scotia Ridge MB is Magallanes Basin, CH Cape Horn, SI Staten Island (Isla de los Estados), BuB Burdwood Bank, DaB Davis Bank, AuB Aurora Bank, SR Shag Rocks, and SG South Georgia. Along the South Scotia Ridge HB is Herdman Bank, DiB Discovery Bank, BrB Bruce Bank, PiB Pirie Bank, JaB Jane Bank, SOM the South Orkney microcontinent, EI the Elephant Island group, BS Bransfield Strait, and JRI the James Ross Island group. Also, NGR is the Northeast Georgia Rise, MEB Maurice Ewing Bank, SSI the South Sandwich Islands, SFZ the Shackleton fracture zone, SSFZ the South Sandwich fracture zone, PB Powell Basin, and PrB Protector Basin. The coastline is from the GMT database (Wessel and Smith, 1991) except for the Antarctic Peninsula (ADD, 1993), and the 2000-m isobath is from Tectonic Map (1985).
within a continuous continental connection between southernmost South America and the Antarctic Peninsula, at a subducting Pacific margin. Scotia Arc evolution, however, has at its heart a second, separate subduction system. The Scotia Sea formed by back-arc extension behind this second arc and trench, that developed close to the Pacific margin but migrated eastward and subducted South Atlantic oceanic lithosphere belonging to the South American (SAM) plate. Regional tectonic evolution has been driven by the continued sinking of South Atlantic oceanic lithosphere, which has involved rapid eastward rollback of the subduction hinge. An additional influence has been collision of the subduction zone at intervals with ridge crest sections of the South American–Antarctic (SAM–ANT) plate boundary. Collisions are considered to have controlled the mode of back-arc extension, which has changed more often than in other back-arc regions.

In a sense, this paper offers a progress report on Scotia Sea and Scotia Arc evolution over the past 40 Ma or so. Although large areas are well understood, the region is tectonically complex, and some uncertainties remain. It is useful to identify these uncertainties in the hope that they can be eliminated, and to assess their importance for an understanding of regional palaeocirculation, and the detection and history of sub-lithospheric mantle flow. The paper begins Sections 2 and 3 by reviewing the main published contributions to our understanding of the Scotia Sea and Scotia Arc, of present plate motions and boundaries and of regional tectonic evolution, and describes the major remaining uncertainties. It then presents an evolutionary model through a series of reconstructions (Section 4), considers why the region may have evolved as it has done (Section 5), and finally (Sections 6 and 7) discusses the consequences of the model (and its uncertainties) for the two fields of study described above.

2. Strategy and constraints

Before reviewing the geologic data and interpretations on which an evolutionary model is built, it is useful to outline the strategy to be employed in building such a model, and to list any assumptions and constraints. The evolutionary model is illustrated by a series of reconstructions of the region, back in time through the past 40 Ma. The procedure is given below.

(a) Reconstructing the relative positions of the major continental plates, South America and Antarctica, and identifying the trace of their common boundary in the South Atlantic.

(b) Within this framework, reconstructing the Scotia Sea by eliminating dated ocean floor younger than the age of the reconstruction, making assumptions about the nature of coupling between the several spreading systems involved and about the age of undated ocean floor.

(c) Testing the assumptions of (b) using such features as arc volcanic products of known age which should be close to an actively subducting margin of that age, and checking for the survival and geologically plausible movement of older features (such as continental fragments) between successive reconstructions.

(d) Making the significant assumption, based on regional geology, that discrepancies between (a) and (b) are accommodated by closure of the Magallanes Basin in southernmost South America—checking that such closure is relatively steady between successive reconstructions.

(e) although reconstruction to a compact, continental connection of South America and the Antarctic Peninsula at a continuous, subducting Pacific margin is not a required outcome of these reconstructions, it is important that, if such a reconstruction emerges, the various component fragments should lie in geologically plausible positions.

The incorporation of progressive Magallanes Basin closure is a crucial difference, for palaeocirculation, between this series of reconstructions and the studies of Lawver et al. (1992), and Lawver and Gahagan (1998). The earlier of those studies considered only the major plates but noted potential complications in the Scotia Sea region, yet was taken by many to indicate the creation of a deep-water channel between South America and Antarctica at a much earlier time than is proposed here. That conclusion was adopted by Lawver and Gahagan in the later work. However, neither study included a detailed examination of the Scotia Sea region, such as is carried out here.
2.1. Age determinations

In this paper, reconstructions and the geological information on which they are based, are given ages. Where these are based on radiometric determinations, they are subject to accepted and understood uncertainties, mainly associated with the chemistry of the rocks. Most other sources of age information (magnetic anomalies, bathymetry and heat flow, microfossil zonation) are related to various versions of the Magnetic Reversal Time Scale (MRTS). This has been revised several times over the 20–30-year period of the publications referred to here. Where oceanic magnetic anomalies are concerned directly, I have revised their ages to fit the most recent version of the MRTS (Cande and Kent, 1995). This usually makes the ages given in the older references no more than 1–2 Ma older or younger. Heat flow- and bathymetry-based determinations of oceanic basement age are also based on the MRTS, but indirectly, via analyses of global heat flow and bathymetric data sets (Parsons and Sclater, 1977), the MRTS basement ages of which were known. The validity of the bathymetric correlation is doubtful for back-arc basins (Sclater et al., 1976) because ridge crest elevation is undefined and uncertain, but heat flow does not suffer this difficulty. The heat flow analysis of Parsons and Sclater (1977) has never been updated for MRTS changes, but a second analysis (Stein and Stein, 1992) has reached different conclusions, based on different assumptions about the validity of parts of the global data set. Here I retain the published age estimates, which are based on the heat flow component of the study by Parsons and Sclater (1977): the age difference from a “revised MRTS” version should be no more than 1–2 Ma, and the other uncertainties associated with age determinations based on heat flow measurements are at least as large. Similarly, where “absolute” ages are deduced from microfossils, these also depend upon an MRTS model which may now be out of date, but the associated uncertainties are usually at least as great. Overall, these various uncertainties are limited in extent, and do not significantly distort the reconstructions.

Some ages have been estimated, by some workers, on the basis of seismic sequence stratigraphy. In this review and attempted reconstruction, I have generally discounted correlation and dating based on this strategy. There is a long history of attempts to correlate sedimentary sequences around Antarctica, on the basis of their seismic character. Such attempts have never survived the test of direct sampling, and there is little doubt that local depositional conditions are often dominant, and that seismic character can be misleading.

3. Sources of data and interpretations

The major source of bathymetric, geological and plate tectonic information for the Scotia Sea region is the Tectonic Map (1985), interpreted subsequently by Barker et al. (1991). Considerable additional work has now been accomplished in many relevant fields, but most elements of the data and interpretations presented there persist. Major additional data sources are marine geophysical survey of Scotia Arc components (by very many authors), Geosat and ERS-1 satellite altimetry-derived gravity (e.g. Livermore et al., 1994; Sandwell and Smith, 1997), earthquake locations and first motions (e.g. Dziewonski and Woodhouse, 1983; Pelayo and Wiens, 1989) and both local and global analyses of major plate motion (e.g. Barker and Lawver, 1988; DeMets et al., 1990, 1994).

3.1. The Scotia Sea

Large areas of the Scotia Sea that are oceanic (e.g. Ewing et al., 1971) have been dated through use of marine magnetic anomalies (Barker, 1972; Barker and Burrell, 1977; Hill and Barker, 1980; Barker and Hill, 1981; Tectonic Map, 1985; Barker, 1995). It was easy to see that spreading within the Scotia Sea had usually been faster than the motion of the major (SAM–ANT) plates, and often in a different direction. This could have occurred only with complementary subduction, and it became clear that all identified spreading in the Scotia Sea was almost certainly back-arc.

Other, probably oceanic areas cannot be dated by means of magnetic anomalies: they are too small for an unambiguous match of their anomalies to the Magnetic Reversal Time Scale (MRTS), or for a range of possible reasons do not show clear magnetic
lineations. Being most probably back-arc, they cannot with confidence be dated using bathymetry, suitably corrected for unloaded sediment cover (Sclater et al., 1976; Parsons and Sclater, 1977). Heat flow is useful in small basins, but may be subject to other effects (Barker and Lawver, 2000). In addition, the Scotia Sea shows several spreading systems to have been active simultaneously. For a complete understanding of regional tectonic evolution it is necessary to know how these systems were coupled, which is sometimes obvious but may otherwise be extremely difficult to determine.

Some areas within the Scotia Sea are more elevated than normal ocean floor. They may be fragments of continent (as are some components of the Scotia Arc), but more thinned by extension, or may be elements of island arc or remnant arc. Some have been identified and dated by submarine dredge or core sampling (see Sections 3.2, 3.6.4 and 3.7), but in many cases this remains to be done.

Fig. 2 shows a simplification of the results of marine magnetic surveys within the Scotia Sea region from the Tectonic Map (1985), with subsequent revision where possible. The figure shows the direction of opening and time extent of several spreading regimes within the Scotia Sea region. Only the region east of the Shackleton Fracture Zone is considered here. Farther west there was subduction at the Pacific margin during the past 40 Ma (Barker, 1982; Cande and Leslie, 1986; Larter and Barker, 1991). At some stage, a Phoenix–Farallon (Nazca) extensional plate boundary was subducted at this margin, probably end-on, but it is impossible to tell from the unsubducted ocean floor or from onshore geology when or where this might have been. No evidence has been reported that shows Pacific margin subduction was ever a significant influence on Scotia Sea evolution (but see speculation in Sections 6.4. and 7.3).

In Drake Passage, east of the Shackleton Fracture Zone, an area of ocean floor approximately 600 × 1000 km was produced, by the largest single spreading regime within the Scotia Sea. Coherent spreading began at Anomaly 8 time about 27 Ma (Cande and Kent, 1995) and ended at some time after Anomaly 5 (Barker and Burrell, 1977). The general orientation was between NW–SE and WNW–ESE. There was a reduction in spreading rate at about Anomaly 5C.

Fig. 2. Summary of ocean floor ages and directions of opening in the Scotia Sea region from Tectonic Map (1985), updated from Lawver et al. (1991), Barker (1995), King et al. (1997) and elsewhere. Areas of likely oceanic crustal structure but unknown age are marked “?”. Ridge crests and transforms of active or known abandoned spreading systems are shown as a grey dashed line. Actively subducting trenches are marked in Fig. 1. The 2000-m isobath and coastline are as in Fig. 1B.
time (about 16.5 Ma) and spreading after 11 Ma was less in the east than in the west (that is, spreading there was probably about a near pole of opening to the east: see also Maldonado et al., 2000). There may have been an even earlier onset to slow spreading in the east, or possibly an interaction with the adjacent spreading regime in the central Scotia Sea (see below). This area is not well-understood. However, the abandoned spreading centre is a prominent bathymetric feature of Drake Passage (Tectonic Map, 1985), reflected also in the satellite-derived gravity field (Sandwell and Smith, 1997). There is some uncertainty as to whether Drake Passage spreading was a simple two-plate regime throughout its life, or if for some of the time the southern flank was two semi-independent plates (Barker and Burrell, 1977, and Fig. 2). There is some evidence of spreading at least as old as Anomaly 10 (29 Ma), off both Tierra del Fuego (LaBrecque, 1985) and the South Scotia Ridge near Elephant Island (Lodolo et al., 1997), but the spreading before Anomaly 8 seems to have been significantly less coherent (Barker and Burrell, 1977).

In the central Scotia Sea, in the third largest area of ocean floor created by a discrete spreading system (approximately 400 × 250 km), magnetic anomalies are oriented east–west (Fig. 2). This was interpreted by Hill and Barker (1980) as reflecting north–south extension beginning just before Anomaly 6 time (about 20 Ma: Cande and Kent, 1995). Hill and Barker (1980) identified a speed reduction at about Anomaly 5C time, and stoppage sometime after Anomaly 5, most probably at about 7 Ma (MRTS of Cande and Kent, 1995), both of which are features of spreading in Drake Passage also. While not establishing the exact mode of coupling between these two adjacent spreading regimes, this degree of coupling lends credence to the central Scotia Sea identifications. However, the anomaly sequence is short, and an alternative, slightly older section of the MRTS (22–31 Ma) provided a reasonable alternative fit (Hill and Barker, 1980). Further, neither the bathymetry nor the satellite gravity maps show a clear image of an abandoned spreading centre. This last absence could be explained if spreading, perhaps because of its proximity to the subduction zone, did not here give rise to the exaggerated topographic relief typical of slow-spreading ridges. An alternative interpretation (DeWit, 1977), in terms of “captured” Mesozoic ocean floor, is rejected here because of the similarities in oceanic basement depth and sediment cover between this area and Drake Passage to the west.

In the East Scotia Sea, spreading that continues today has produced an area of ocean floor approximately 600 × 500 km and has created the small, eastward-moving Sandwich plate (Figs. 1B and 2). Early descriptions (Barker, 1972; Barker and Hill, 1981) have been revised in light of additional data (Barker, 1995). Spreading was symmetric at about 27 mm/a until about 7–5 Ma, then accelerated, and for the past 1.7 Ma has been at an overall rate of 65 mm/a and up to 15% asymmetric, favouring the arc flank. For much of its length, the ridge crest is 500 m deeper than the global average. On the western flank, magnetic lineations are recognised back to Anomaly 5 (10–11 Ma) and less certainly to before Anomaly 5B (about 15 Ma), but on the eastern flank the island arc rests on ocean floor aged between 3 and 10 Ma, formed during the present spreading episode, and ocean floor older than about 10 Ma is generally not seen, suggesting significant tectonic erosion in the fore-arc. In the south, the present back-arc spreading centre has existed for only 3 Ma, probably (Hamilton, 1989; Barker, 1995) because of an eastward jump of the spreading centre following ridge crest–trench collision. There is a possible coincidence between the onset of East Scotia Sea spreading and the abrupt deceleration of spreading in both Drake Passage and the Central Scotia Sea, at about Anomaly 5C time (16.5 Ma) that would (if correct) support the interpretation of Scotia Sea evolution as essentially back-arc and secondary, driven primarily by rollback of the subduction hinge (e.g. Barker and Hill, 1981; Barker et al., 1991).

The cessation of spreading at around 7 Ma in both the central and western Scotia Sea (Drake Passage), and subsequent acceleration of spreading in the East Scotia Sea, may have been a response to ridge crest–trench collision along the South Scotia Ridge: collisions remain poorly defined and dated, particularly in the east (Hamilton, 1989; Barker, 1995) and such an origin is at least possible. However, a different cause is also possible—a collision between South Georgia and the elevated Northeast Georgia Rise. The reconstructions show quite rapid northeastward motion of South Georgia from about 20 Ma onward,
that has now ceased, and the microcontinent is now at the southern margin of the Rise, thought to lie on oceanic crust of mid-Cretaceous age, and be associated with the Agulhas Plateau and Maud Rise (Kristoffersen and LaBrecque, 1991). Work on the Northeast Georgia Rise associated with ODP Leg 114 showed faulting, which was assigned a Miocene age and attributed to interaction with an approaching South Georgia block and proto-South Sandwich trench, as the Scotia Sea developed (Ciesielski et al., 1988; Kristoffersen and LaBrecque, 1991).

Protector Basin contains a short sequence of north–south oriented magnetic lineations (Hill and Barker, 1980), that appear symmetric and can be fitted easily using more than one section of the MRTS. Of the two age ranges shown in Fig. 2, the older option is used in these reconstructions. There are other small basins, east of Protector Basin and separating the intermediate-depth elevations of Pirie Bank, Bruce Bank and Discovery Bank. The basins are most probably oceanic in nature, having a range of (sediment-unloaded) basement depths appropriate to Cenozoic ocean floor (Tectonic Map, 1985), but magnetic lineations cannot be distinguished labelled “?” in Fig. 2. This is the main area of uncertainty within the Scotia Sea. Of the elevations, Discovery Bank is known from dredging to have been part of an intra-oceanic island arc ancestral to the present South Sandwich arc: dredging has yielded arc tholeiites radiometrically dated at 12–20 Ma (Barker et al., 1982). A sediment core on the southern flank of Bruce Bank yielded middle Eocene microfossils indicating a shallow continental margin palaeoenvironment (Toker et al., 1991). While placing only broad (but plausible) bounds upon the ages of the intervening basins, these samples are more precise in defining the likely age and nature of the elevations.

3.2. Other oceanic areas

Powell Basin, measuring 300 × 250 km and lying between the Antarctic Peninsula and the South Orkney microcontinent, has been the subject of several studies (King and Barker, 1988; King et al., 1997; Shimizu et al., 1989; Kavoun and Vinikovskaya, 1994; Lawver et al., 1994; Coren et al., 1997; Rodriguez-Fernandez et al., 1997; Maldonado et al., 1998). Mostly of oceanic crustal structure, it formed by the ENE–WSW separation of the South Orkney microcontinent from the end of the Antarctic Peninsula. There is some uncertainty over its age: sediment-corrected bathymetry (King and Barker, 1988; King et al., 1997) and heat flow (Lawver et al., 1994; Lawver and Gahagan, 1998) suggest an Oligocene age (32–24 Ma) but a single magnetic profile showing low-amplitude anomalies has been interpreted by Coren et al. (1997) as younger. Here, until the matter is resolved, I use the older age (Fig. 2).

Jane Basin lies east of the South Orkney microcontinent. It is narrow and shows no recognizable magnetic lineations, but heat flow measurements by Lawver et al. (1991) suggest an age range of 32–25 Ma. Barker et al. (1984) proposed, from identification of magnetic anomalies in the northernmost Weddell Sea, that a ridge crest–trench collision at Jane Bank, the eastern boundary of Jane Basin, had caused back-arc extension in Jane Basin to end at about 20 Ma, but the heat-flow ages may indicate an earlier cessation, and alternative, younger magnetic anomaly ages have been suggested for parts of the northern Weddell Sea (Hamilton, 1989; Livermore and Woollett, 1993: but see Section 3.5). The relation between the opening of Jane Basin and of Powell Basin is uncertain, from the available age constraints: a jump towards the subduction zone (here eastward) is usual in back-arc regions, but not universally so. The two basins are connected by another basin, south of the South Orkney microcontinent, which is most probably of the same age and also back-arc in origin, behind an ancestor of the present South Sandwich arc (similar to Discovery Bank and Jane Bank: Barker et al., 1982, 1984, 1991). It has been suggested that the zone of subduction and back-arc spreading extended to the eastern end of the Antarctic Peninsula near 50°W (Barker et al., 1991; Maldonado et al., 1998): the Eocene alkali basalt (K–Ar ages of 49.1 and 47.7 Ma) dredged from the SW corner of Powell Basin (Barber et al., 1991) may be an expression of the precursor of both processes.

An extensional origin is also generally agreed for Bransfield Strait, although the exact nature of the crust there and precise details of the processes acting remain uncertain (e.g. Ashcroft, 1972; Barker and Austin, 1994, 1998; Lawver et al., 1995; Grad et al.,
It is generally agreed that virtually all of the extension, considered by some to reach 60 km, has taken place within the past 4 Ma, possibly in response to the end of Phoenix–Antarctic spreading.

### 3.3. Present plate motions and boundaries

Present plate boundaries and relative motions in the region (Fig. 1) have been investigated using earthquakes, by Forsyth (1975) and Pelayo and Wiens (1989), with additional studies in the South Sandwich arc-trench region by Isacks and Molnar (1971), Brett and Grifiths (1975) and Brett (1977). More recent regional studies, using broadband stations (e.g. Vuan et al., 2000) may allow better definition of plate boundaries in due course. Present-day relative motions of the major plates have been determined from global models DeMets et al., 1990, 1994, and absolute vectors have been estimated, relative to hotspot traces (Gripp and Gordon, 1990). Relative motion of the major (South American—SAM, and Antarctic—ANT) plates is slow (17 to 20 mm/a) and east–west. Present motions of major plates in the hotspot reference frame are also slow: ANT and AFR are near-stationary and SAM moves slowly westward. The SAM–ANT boundary east of the South Sandwich Trench is a long-offset, short spreading section boundary extending to the Bouvet triple junction in the South Atlantic. SAM–ANT motion becomes simple, slow east–west convergence at the Chile Trench in the west, but the intervening Scotia Sea region has the added complexity of the small Scotia (SCO) and Sandwich (SAN) plates (Fig. 1B). The SAM–SCO boundary runs through Tierra del Fuego and the North Scotia Ridge, and the SCO–ANT boundary along the Shackleton Fracture Zone (SFZ in Fig. 1) and South Scotia Ridge. SAM–ANT motion is divided between the North and South Scotia Ridge, and is sinistral and approximately east–west at both. Pelayo and Wiens (1989), on the basis of earthquake focal mechanisms and plate boundary orientations, calculated plate motions (using the SAM–ANT motion of DeMets et al., 1990) as follows:

- SCO–SAM 0.08°/Ma about 18.7°S 58.9°W
- ANT–SCO 0.30°/Ma about 79.1°S 64.4°W

Calculated present motion along the South Scotia Ridge was approximately twice as fast as along the North Scotia Ridge. More CMT (Centroid Moment Tensor; Dziewonski and Woodhouse, 1983) earthquake focal mechanism solutions are now available, but this calculation has not recently been revised. For many sections of plate boundary, earthquakes are sparse, and uncertainty persists about the exact boundaries and processes occurring, particularly in Tierra del Fuego, around South Georgia and along the eastern South Scotia Ridge. Also, many CMT directions are discrepant: although this may indicate merely the importance of existing lineaments in channelling stress release, it may be worth examining more complicated models than the simple SAM–SCO–ANT rigid plate model adopted by Pelayo and Wiens (1989).

In contrast to the other plates (SAM, SCO, ANT), the small Sandwich (SAN) plate is moving rapidly eastward, both with respect to the major plates and in an “absolute” (hotspot) reference frame (e.g. Gripp and Gordon, 1990). The northern and southern SAN boundaries continue those of the Scotia plate, but there is rapid subduction of SAM oceanic lithosphere (and rollback of the subduction hinge) at the eastern SAN margin, and rapid back-arc extension at the SAN-SAM boundary along 30°W in the East Scotia Sea. Older SAM ocean floor is subducted at the northern end of the South Sandwich Trench than in the south, and it has been suggested (Forsyth, 1975) that extensional earthquake fault-plane solutions at depth within the northern part of the sinking slab, compared with compressional solutions in the south, show that the old, dense northern part is towing down the younger, less dense southern part. The northern end of the subducting slab is considered (from earthquake distribution and focal solutions) to be tearing along an east–west line, at depths down to 120 km (Forsyth, 1975). In future, regional GPS measurements (e.g. Larter et al., 1998) will complement or replace estimates of SAN motion made from global studies, earthquake focal mechanisms and marine magnetic anomalies, and earthquake tomographic studies (e.g. Vuan et al., 2000) may be able to determine the locus of the subducted slab.

An additional complication at the southwest margin of the Scotia plate is the existence of a small relic of the Phoenix plate (now joined to the Antarc-
tic plate since Phoenix–Antarctic spreading ceased 3–4 Ma ago) west of the Shackleton Fracture Zone (SFZ), together with likely subduction at the South Shetland Trench and back-arc extension in Bransfield Strait, creating a very small “Shetland” microplate (She in Fig. 1B). Bransfield Strait is undoubtedly opening (Barker and Austin, 1994, 1998), which has been interpreted as a result of roll-back of the hinge of South Shetland Trench subduction of the erstwhile Phoenix plate (Barker, 1982; Barker and Dalziel, 1983). The great majority of earthquakes along the SFZ are strike–slip, despite the angular discordance between the SFZ and South Scotia Ridge, and other earthquakes occur to the west, possibly associated with the old Phoenix–Antarctic plate boundary. This combination led Pelayo and Wiens (1989) to suggest a zone of diffuse compression west of the SFZ, but the activity may reflect also the persistence of stresses in oceanic lithosphere after plate motion has ceased, and a tendency for earthquakes to be constrained by existing lithospheric fabric (but see also Lawver et al., 1995). This complexity does not concern us here, except in that it fosters uncertainty about the nature of present plate motion at the SFZ and western South Scotia Ridge, and could affect views of the elevation history of the southern SFZ ridge, which is considered to have been a barrier to ocean circulation in the past (Barker and Burrell, 1977; and Section 7.3).

3.4. Major plate motions through time

There is no agreed determination of “absolute” plate motion through the Cenozoic, which prevents estimation of absolute vectors of mantle flow. Certainly, there has been no change in the relative motion of the major plates (in particular, SAM and AFR) through the Cenozoic, and present SAM absolute motion is slow (2.3 cm/a along 239°T at the S Sandwich trench: Gripp and Gordon, 1990). It is sufficient for all purposes here (regional tectonics, mantle flow, palaeoceanography) to determine relative motion.

It is generally considered that, for a while after Gondwana breakup, East Antarctica and the various fragments of West Antarctica moved separately (e.g. Barker et al., 1991; DiVenere et al., 1996). By the mid-Cretaceous however, South Atlantic opening was under way, and East Antarctica and the Antarctic Peninsula were acting as a single plate. The Weddell Sea floor formed on the southern flank of the SAM–ANT plate boundary, the northern flank having been subducted in the west beneath an eastward-expanding Scotia Sea. Ocean floor fabric in the Weddell Sea, first identified on shipboard profiles (Barker and Jahn, 1980) and subsequently made clear by satellite gravity data (McAdoo and Laxon, 1996; Sandwell and Smith, 1997), showed prominent small-offset fracture zones oriented NW–SE, that disrupted all but the longer-wavelength magnetic anomalies (for example Anomaly 33/34: LaBrecque and Barker, 1981; Livermore and Woollett, 1993). Spreading was generally slow, but rather faster in the east than in the west, with a likely near pole of opening in the SE Pacific. At about 20 Ma (Barker and Lawver, 1988), the direction of SAM–ANT separation changed relatively quickly from WNW–ESE to W–E. This change was accompanied by creation of a small number of long-offset transform faults and short ridge crest segments at the plate boundary, which would have involved rupture of existing (probably very young) ocean floor at many of the existing small-offset transform faults. No local cause was identified for the 20 Ma change, and Barker and Lawver (1988) drew attention to the possibility that the cause or causes of a rapid change in plate motion could be remote in both time and space from the particular change. The changes in plate motion over the past 150 Ma provide the background (and perhaps the cause: see Section 5) for Scotia Arc evolution. In the reconstructions that follow (Section 4), major plate (SAM–ANT) motion is represented by the poles and rates of Barker and Lawver (1988), in Table 1: differences from data used in subsequent assessments of major plate motion (e.g. Cunningham et al., 1995; Lawver and Gahagan, 1998) are minor. Data for Anomaly ASCy (ca. 16 Ma) are interpolated.

3.5. Ridge crest–trench collisions

Subduction of a spreading ridge crest is an inevitable consequence of global plate motions: during the Cenozoic for example, it has happened off North, Central and South America and the Antarctic Peninsula (De Long et al., 1978; Lonsdale and Klitgord,
Table 1
South American–Antarctic motion used in reconstructions

<table>
<thead>
<tr>
<th>Period (Ma)</th>
<th>Anomaly</th>
<th>Pole latitude</th>
<th>Pole longitude</th>
<th>Rotation angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0–10.95</td>
<td>A5o</td>
<td>79.65</td>
<td>-29.87</td>
<td>-2.91</td>
</tr>
<tr>
<td>0.0–20.13</td>
<td>A6o</td>
<td>76.43</td>
<td>-26.81</td>
<td>-5.81</td>
</tr>
<tr>
<td>0.0–26.55</td>
<td>A8o</td>
<td>76.01</td>
<td>-6.26</td>
<td>-7.70</td>
</tr>
<tr>
<td>0.0–33.01</td>
<td>A13y</td>
<td>77.21</td>
<td>2.08</td>
<td>-9.97</td>
</tr>
<tr>
<td>0.0–40.13</td>
<td>A18o</td>
<td>74.30</td>
<td>11.84</td>
<td>-12.23</td>
</tr>
</tbody>
</table>

SAM is the fixed plate. North and East are positive. Rotation angle is positive if ANT motion is clockwise viewed from above the specified pole. From Barker and Lawver (1988). Ages from Cande and Kent (1995). ASCy data are interpolated.

1978; Cande et al., 1987; Larter and Barker, 1991). It has been proposed that collisions have occurred during Scotia Sea evolution between ancestors of the present South Sandwich trench and fore-arc, lying originally along the South Scotia Ridge, and ridge crest sections of the SAM–ANT plate boundary located west of where the plate boundary exists today. Arc tholeiitic volcanic rocks have been dredged from Discovery Bank (Barker et al., 1982), and Jane Bank (Barker et al., 1984), which are considered remnants of the ancestral arc, and magnetic anomalies within the northern Weddell Sea south of the Scotia Sea become younger northward (Barker et al., 1984; Hamilton, 1989; Livermore and Woollett, 1993), suggesting ridge–crest subduction. Collisions are considered youngest in the east, close to the extant subduction zone (Hamilton, 1989; Barker, 1995), and oldest in the west, extending probably as far west as the Antarctic Peninsula at about 50°W (Barker et al., 1991). It has been proposed (Barker and Hill, 1981; Barker et al., 1982) that such collisions could have controlled changes in the rate, direction and location of back-arc extension.

The systematics of ridge crest–trench collision appear to have been fairly constant through the period of eastward expansion of the Scotia Sea. Virtually all available South American plate has been subducted, but no Antarctic plate. At each collision, subduction and coupled back-arc extension both stopped where the Antarctic flank of the ridge crest met the trench. Subduction elsewhere continued and there was most probably a change in the locus, speed and direction of back-arc extension. Because of the intra-oceanic environment and the young age of ocean floor being subducted, sediment cover is likely to have been sparse, and a significant accretionary prism at the time of ridge crest collision is unlikely, so the preserved relics of collision are probably an arc and forearc, and an oceanic ridge flank, with perhaps (as hypothesised at Jane Bank: Barker et al., 1984) a topographic trough between them.

The process is best appreciated by observing that the present rate of eastward trench migration is much faster than the half-spreading rate on the SAM–ANT boundary, so that in 5–6 Ma from now the present trench will overtake the ridge crest section now lying at about 20°W (Fig. 1). It is suggested that when that happens, spreading at that section and subduction at the opposed part of the trench will both cease (the newly opposed, young and buoyant Antarctic plate will not subduct), whereas subduction (of South American plate) at the trench will continue farther north, and the mode (location, direction, rate) of accompanying back-arc extension will probably change.

This example, however, highlights an additional feature of the process. It has been noted, from studies of earthquakes (Farmer et al., 1982) and plate motions (Barker and Lawver, 1988; DeMets et al., 1990; Livermore and Woollett, 1993) that the area of S Atlantic ocean floor between 20°W and the S Sandwich Trench (Fig. 1) may already be acting independently of the major plates (though the effect, at present, is small). Isolation of small plate fragments and their independent motion before final subduction are well-known features of spreading close to a subduction zone (Menard, 1978). In the extreme, as has been shown off Baja California (Atwater, 1989; Lonsdale, 1991), spreading and subduction may both cease before the ridge crest has reached the trench. In the case of ridge crest–trench collision in the northernmost Weddell Sea, the effect of decoupling is to render correspondence to major plate motion (as determined elsewhere) no longer a requirement for spreading rates and directions, and thus a criterion for magnetic anomaly identification, in the region directly south of the collision zone. This broadens the range of possible magnetic anomaly identifications, in a region where major plate separation was slow and anomaly identification therefore already difficult. As a result of these inter-
pretational uncertainties, although many changes in the mode of back-arc extension have been identified within the Scotia Sea, their coincidence with a collision has not been firmly established.

3.6. The South Scotia Ridge

Several different tectonic elements occur within the South Scotia Ridge. It is more informative to describe the larger components first, because the composition of the smaller components has usually been interpreted in terms of the larger ones.

3.6.1. The Antarctic Peninsula

The Antarctic Peninsula has lain at the subducting Pacific margin (of Gondwana initially) most probably for several hundred million years. Palaeozoic gneissic basement is exposed in places, and the oldest rocks show evidence of the presence of Palaeozoic continental rocks nearby (from detrital zircons: e.g. Hervé et al., 1991), and of subduction from the early Mesozoic or earlier. A late Mesozoic accretionary prism is well-exposed on land only in Alexander Island in the south (e.g. Doubleday et al., 1994), and Cenozoic accretion is represented, though not extensively, offshore (Larter and Barker, 1991; Maldonado et al., 1994; Larter et al., 1997). In places older metamorphic components of a palaeo-forearc are exposed (including low-temperature, high-pressure rocks on Smith Island: Smellie and Clarkson, 1975; Rivano and Cortes, 1975). Apart from more recent, probably minor intrusions and volcanic components (Hole and Larter, 1993) the accretionary prism is non-magnetic. The Antarctic Peninsula Pacific margin is now effectively passive except for the short section of the South Shetland trench because of Cenozoic SW–NE migration along the margin of a ridge crest–trench collision (Barker, 1982; Larter and Barker, 1991), whereupon subduction ceased.

The Antarctic Peninsula contains a well-developed Mesozoic–Cenozoic batholith (e.g. Leat et al., 1995) produced by subduction-related magmatism, together with related volcanics and volcanioclastics. Although not all components of the batholith are strongly magnetised, a prominent “Pacific Margin Anomaly” (PMA) occupies much of the Antarctic Peninsula (Renner et al., 1985; Garrett, 1990; Maslanyj et al., 1991; Johnson, 1996). In the north-east magnetic material, plutonic and volcanic, is seen in both the Antarctic Peninsula and the offshore South Shetland Islands (compatibly with a simple, recent opening of the intervening Bransfield Strait), and PMA-like magnetic anomalies extend to and are truncated by the northeastern margin of the Antarctic Peninsula, at Powell Basin (Barker and Griffiths, 1972; Garrett et al., 1987). Because almost all subduction-related magmatism along the Antarctic Peninsula ceased well before ridge crest collision (Barker, 1982; Pankhurst, 1982), the batholith pre-dates formation of the Scotia Arc.

Between the magnetic western edge of the batholith and the accretionary prism along the Antarctic Peninsula margin lies the non-magnetic “mid-shelf high” (MSH: Larter and Barker, 1991; Larter et al., 1997). The structural high is interpreted as the effective edge of the over-riding plate at the subduction zone: it underwent uplift associated with ridge crest collision, and probably includes the older, palaeo-forearc elements such as Smith Island. Such rocks, taken usually to reflect pre-late Mesozoic subduction, are sparse but widely distributed around the Scotia Arc (see Dalziel, 1984; Grunow et al., 1992). Above and inboard of the MSH lie the remains of a sedimentary basin that probably developed on the upper fore-arc during subduction. These features (minus the collision-related uplift) may also be identifiable within continental fragments. Off the South Shetland Islands, the PMA occupies much of the shelf, and any palaeo-forearc is much attenuated. At the northeast end of the Antarctic Peninsula, metamorphic rocks (of the palaeo-forearc) are exposed on Elephant and Clarence Is, and nearby islands, in an area of complex present plate boundaries.

The back-arc is sparsely represented onshore. It is generally considered that the oldest part of the Weddell Sea was formed as the Antarctic Peninsula first separated from Gondwana, but the geography of a Gondwana reconstruction remains in dispute. Anoxic Jurassic sediments on the Weddell Sea side of the Peninsula reflect conditions during an early phase of opening, but younger margin sediments are generally buried beneath the continental shelf, and exposed onshore mainly where, as within the James Ross Island group, they have undergone uplift related to young alkali basaltic magmatism.
3.6.2. The South Orkney microcontinent

Separated from the Antarctic Peninsula by Powell Basin, islands of the South Orkney microcontinent expose metamorphic rocks akin to those (e.g. Elephant and Clarence Islands) found in places within the Antarctic Peninsula palaeo-forearc, but including Late Triassic radiolarian chert (Dalziel et al., 1981), and with unconformably overlying, probably Upper Jurassic–Lower Cretaceous, deformed greywacke-shales resembling those of South Georgia and Tierra del Fuego (Sections 3.8.1 and 3.8.2). The islands, elongated east–west, lie along the northern edge of a large microcontinental block. To the south of the islands lies an east–west sedimentary basin, truncated at its western end at the shelf edge but closed at its eastern end, and south again lies a zone of strongly magnetised material, with high seismic velocities at shallow depth (Harrington et al., 1972; King and Barker, 1988). The magnetised material is truncated at the western shelf edge, but curves northeastward towards the eastern margin of the block, to close the basin lying to the north. Its geophysical character, together with Late Cretaceous calc-alkaline basalt from a dredge haul close to the eastern margin (Barber et al., 1991) identifies the magnetic material as an extension of the Pacific margin batholith of the Antarctic Peninsula (although the addition of younger magmatic components related to Weddell Sea subduction during Scotia Sea evolution, before the opening of Jane Basin, cannot be ruled out). Similarly, the South Orkney Islands closely resemble the palaeo-Pacific margin metamorphic rocks seen along the Antarctic Peninsula margin, with possibly an upper slope basin to the south. The eastern and western margins of the microcontinent are block-faulted (King and Barker, 1988), compatible with an extensional origin for Powell and Jane Basins.

3.6.3. The western South Scotia Ridge

Between Elephant Island and the South Orkney microcontinent lies a pair of ridges, separated by the presently active SCO–ANT plate boundary. The northern ridge, remarkably thin and uniform, is non-magnetic and shows high-velocity material at shallow depth in its western part (Watters, 1972). It has been interpreted as a remnant of a palaeo-Pacific margin fore-arc similar to the South Orkney Islands and parts of the Antarctic Peninsula. South of the present plate boundary, most of the southern ridge (generally, not its northern edge) is strongly magnetised, and has been identified with the Pacific margin batholith of the Antarctic Peninsula and South Orkney microcontinent (Watters, 1972; Barker and Griffiths, 1972; Barker et al., 1991; Garrett et al., 1987; King and Barker, 1988). It is possible also that it contains remnants of an upper fore-arc basin on its northern margin.

These two ridges appear to have preserved their continuity and original polarity through Scotia Sea evolution. The present (quite slow: Pelayo and Wiens, 1989) sinistral strike–slip motion along the SCO–ANT plate boundary, which lies between them, has probably continued for only a few million years. There is an extensional offset in the plate boundary around 51°W, and the limited size of the pull-apart basin there supports this view. Previous reconstructions of this area (e.g. King and Barker, 1988; King et al., 1997; Barker et al., 1991) have assumed that the southerly, magnetic ridge component moved as a small independent block during Powell Basin opening, since the apparently coherent South Orkney microcontinent is longer north to south than is Powell Basin. This may well have involved movement of some kind between the southern (magnetic) and the northern (non-magnetic) component of the western South Scotia Ridge, more or less along the line of the presently active plate boundary. In the period intervening between Powell Basin opening and the beginning of the current phase, the opening of several small basins in the southern Central Scotia Sea (Protector Basin and others to the east) would have involved dextral strike–slip motion along the northern flank of the northern (non-magnetic) ridge, and it seems unlikely that two parallel strike–slip boundaries so close together would both have been active at the same time.

Acosta and Uchupi (1996) and Galindo-Zaldívar et al. (1996) have described seismic reflection surveys of the western South Scotia Ridge. Acosta and Uchupi (1996) confirm the nature of the pull-apart basin (Hesperides Deep) at 51°W and detect sediment deformation along the north flank of the northern (non-magnetic) ridge, concluding that it occurred only during the past few Ma, as a result of differential motion of separate blocks of the northern (non-
magnetic) ridge in association with the sinistral strike–slip motion along the present SCO–ANT plate boundary. Galindo-Zaldívar et al. (1996) propose that this northern boundary is active today, a conclusion not supported by the earthquake data (Pelayo and Wiens, 1989 and Section 3.3). A possible alternative interpretation would be for the deformation at the northern margin to have been related to the intermediate phase of Scotia Sea opening mentioned above, that involved Protector Basin and the other small basins of the southern Central Scotia Sea (Section 3.1, above), for which the northern (non-magnetic) ridge would have formed a southern, dextral strike–slip boundary.

3.6.4. The eastern South Scotia Ridge

The existence of a South Scotia Ridge east of the South Orkney microcontinent is in the nature of a topographic convenience (see Tectonic Map, 1985) rather than a unified geological reality. Jane Bank and Discovery Bank are elevations, but are old, subduction-related volcanic island arcs which have already been described. On Jane Bank, individual volcanoes can be identified and there is additional, altered material with arc tholeiitic affinities exposed at a major scarp. Discovery Bank is a more substantial elevation and, although the chemistry of arc volcanic rocks dredged from it betrays an intra-oceanic origin (Barker et al., 1982), it is not impossible that a continental fragment lies hidden within it. Herdman Bank, farther east, was part of the South Sandwich arc and fore-arc before the eastward jump in back-arc spreading about 3 Ma ago (Hamilton, 1989; Barker, 1995), but may contain a similar fragment, though small. This possibility is addressed because of the composition of the present South Sandwich fore-arc (Section 3.7 below). To the southeast of these larger fragments, east of Jane Bank, lie several very small but prominent elevations, well-imaged in the satellite-derived gravity field, that may be fragments of a palaeo-arc, tectonically dissected following ridge crest–trench collisions.

3.7. The South Sandwich arc and forearc

Most of the volcanic South Sandwich islands and associated seamounts lie equispaced in an eastward-convex arc, on ocean floor 3–10 Ma-old formed during the present episode of “back-arc” spreading (Barker, 1995; Pearce et al., 1995). Both the spreading and the island arc are secondary effects of subduction at the South Sandwich Trench. The subducting South American oceanic lithosphere is much older, and dips slightly more steeply, in the north than in the south (Brett, 1977). It is the major source of earthquakes within the region (Section 3.3). There is no systematic north–south variation in arc chemistry, and the volcanoes are almost all low-K intra-oceanic arc tholeiites. The arc lies about 80 km west of the eastern edge of the Sandwich plate, which is marked by a prominent topographic and gravity high (Barker, 1995). The gravity high is best-developed in two locations: at the more northerly location, serpentinised ultrabasic rocks (Barker, 1995; Pearce et al., 2000), and at the more southerly, calc-alkaline basalts, basaltic andesites and andesites with an average K/Ar age of 31.0 Ma (Barker, 1995), have been dredged from the outer scarp. Both occurrences, and the absence of older magnetic anomalies and poor development of an accretionary prism to the east, suggest the operation of tectonic erosion in the fore-arc. The dated calc-alkaline rocks suggest additionally that a fragment of the original arc, created at the Pacific margin or in the earliest stage of Scotia Arc evolution when there was still a continental influence on arc magmatism, has been carried east by continued subduction.

Lallemand (1995) has suggested that tectonic erosion (landward migration of the arc–trench system, by consumption in the subduction zone of material from the over-riding plate) can reach rates of $7 \pm 3$ mm/a, a significant fraction of back-arc spreading rates. The effect in the Scotia Sea region would be to reduce the actual eastward migration of the trench, compared with the measured and computed amount of SCO–SAN back-arc extension and SAM–SCO strike–slip motion, because part of the new lithosphere produced by extension in the back-arc does not survive. For the Sandwich plate, the absence in the forearc of older magnetic anomalies of the present spreading episode suggests consumption of some 30 km of oceanic crust, or 2 mm/a over 15 Ma (subject to the uncertain identification of older anomalies on the western flank: Barker, 1995). This represents a minimum value for tectonic erosion, if it is considered that other crustal material, east of those
older anomalies on the Sandwich plate, might also have been consumed. [Pearce et al., (2000) propose that ultrabasic rocks dredged from the northern fore-arc have interacted with arc magma: if this is taken to indicate a palaeo-arc now removed, then the amount of tectonic erosion is greater. For a somewhat larger estimate, see Vanneste and Larter (in press). Essentially however, by comparison with the rapid eastward growth of the Scotia Sea region, the effect is small.

3.8. The North Scotia Ridge

As with the South Scotia Ridge, it is most useful to begin description of the North Scotia Ridge by considering southernmost South America, a relatively intact area containing the main tectonic elements of a subducting margin that might subsequently be identified within smaller fragments. In addition to links of this kind, the foreland fold-thrust belt of the Magallanes Basin of southern South America, east of the Pacific margin, was continued southeastward and eastward as convergent deformation within the lengthening North Scotia Ridge (for an interpretation, see Section 5).

3.8.1. Southernmost South America

A typical cross-section of Tierra del Fuego, from west to east (or southwest to northeast), shows a very poorly developed accretionary prism at the Pacific margin, thin palaeo-forearc, well-developed batholith (with related lavas and arc-derived sediments in places), closed marginal basin and associated closed (or still closing) Magallanes Basin foreland fold-thrust belt (Fig. 1; see also maps and cross-sections in Tectonic Map, 1985; Biddle et al., 1986; Hanson and Wilson, 1991; Klepeis, 1994). The modern accretionary prism is not particularly well-developed anywhere along the Pacific margin of South America, but is more prominent north of 46°S where the Chile Rise intersects the margin. Farther south, it seems limited to the lower fore-arc (e.g. Herron et al., 1977). The Chile Rise has migrated north to 46°S, and only 13–14 Ma ago (Barker, 1982; Cande and Leslie, 1986) the ridge crest was subducted at 54–56°S. Before then, a third spreading arm, and then the Nazca/Phoenix/Antarctic triple junction, was subducted. Subduction (of Antarctic plate) continues at this margin at a rate of about 20 mm/a beneath the South American plate and slower still beneath the Scotia Plate, south of the western end of the Magellan Straits, at the Pacific margin of southern South America near 52°S (Fig. 1). It seems plausible that a late Cenozoic history of subduction of young ocean floor, followed by ridge crest collision and then slow subduction, should have produced only a poorly developed accretionary prism, because sediments would have been thin, and young ocean floor rough and buoyant. Probably, a well-developed early Cenozoic Pacific margin accretionary prism should not be sought eastward, among translated fragments of an original South American–Antarctic Peninsula continental connection.

Elements of the older, palaeo-forearc are exposed in places on the most westerly islands (in particular, on the Diego Ramirez Islands: Wilson et al., 1989), and part may have been sliced off to form the Shackleton Fracture Zone ridges (Barker and Burrell, 1977). The batholith is well-developed along the margin, but with a suggestion that it thins laterally towards the southeast (Barker and Griffiths, 1972). Mainly to the north and east of the batholith lie the remnants of the latest Jurassic or earliest Cretaceous Rocos Verdes ophiolitic back-arc extensional basin (Dalziel, 1981), extending northward to at least 51°S. Formation of the back-arc basin was preceded by widespread siliceous volcanism (the Tobifera Formation: Hanson and Wilson, 1991) which today is exposed mainly inboard of the ophiolite and associated volcaniclastic basin fill, and is found also beneath younger sediments in boreholes within the Magallanes Basin to the northeast, and as far east as Staten Island (Dalziel and Palmer, 1979). Large parts of the batholith are Cretaceous in age, so have intruded older units.

The Magallanes Basin is a foreland fold-thrust belt produced by the progressive closure of a Late-Jurassic Pacific-margin subduction-related extensional basin (floored initially by siliceous, partly marine Jurassic Tobifera Formation, then by oceamic Rocos Verdes ophiolites). The basin closed from the mid-Cretaceous on (Dalziel, 1985), with uplift in the west and southwest (around the bend in southernmost South America) recycling sediment fill, and the slow, progressive eastward and northeastward migra-
tion of the depocentre and deformational front. Convergent deformation continues today in the north, but the basin has become non-marine, which hinders stratigraphic correlation. The basin has been described in detail by Biddle et al. (1986).

Since it is proposed that the SAM–SCO plate boundary runs through southernmost South America (Forsyth, 1975; Tectonic Map, 1985; Pelayo and Wiens, 1989), along the western Straits of Magellan to the Pacific (Fig. 1), and plate motion (once convergent) is now sinistral strike-slip, it is important to see if the history of deformation in the area can be used to date the change to the present regime. Winslow (1982) noted a diachroneity in the cessation of shortening within the basin, whereby Pliocene sediments and Plio–Pleistocene dykes and flows are deformed in the north, whereas firstly Pliocene sediments and then Miocene sediments are undeformed towards the south. Strike-slip earthquakes are found along the major NW–SE lineaments near the Pacific margin, but the extent to which reactivated older structures are constraining earthquake mechanisms is unknown. Klepeis (1994) estimated 25 km sinistral offset at the Magallanes fault zone (that continues to the western Straits of Magellan) subsequent to Magallanes Basin closure, which is of the same order as SAM–SCO motion of 5–6 mm/a (Pelayo and Wiens, 1989) acting for 6–7 Ma (Barker et al., 1991; Cunningham et al., 1998), but he was not able to rule out a model of more widely distributed strike-slip acting over a longer period.

Rocks of the palaeo-fore-arc, Patagonian batholith and Cretaceous arc volcanics, Rocas Verdes ophiolites and basin fill, are probably truncated at the Scotia Sea margin near Cape Horn (Fig. 1). Deformed Tobifera Formation volcanics and sediments are found on Isla de los Estados (Staten Island) off the southeastern tip of Tierra del Fuego (Dalziel and Palmer, 1979), suggesting continuity eastward along Burwood Bank towards the North Scotia Ridge (see also Ludwig et al., 1968; Davey, 1972). A gravity high continues eastward along the southern margin of Burwood Bank (Sandwell and Smith, 1997) and it is likely that proximity to southern South America has ensured abundant terrigenous sediment supply to the Burwood Bank part of the accretionary prism. At present Burwood Bank has a flat top, planed off at 40–100 m depth, essentially close to wave base during glacial maxima. This likely combination of continental backstop (see Section 3.8.3) and well-developed accretionary prism suggests that the Burwood Bank section of the North Scotia Ridge has remained shallow through Scotia Sea development.

3.8.2. South Georgia and Shag Rocks

The largest fragment within the North Scotia Ridge, including almost the only and certainly the most varied onshore exposure, is the South Georgia microcontinent, which measures 300 × 150 km and is elongated slightly south of east. Apart from South Georgia, the only subaerial exposure along the North Scotia Ridge is the very small outcrop of Shag Rocks, near 42°W.

The onshore geology of South Georgia is relatively well-known (Tectonic Map, 1985; Macdonald et al., 1987) and may be extended to the continental shelf edge using marine geophysics (e.g. Simpson and Griffiths, 1982). An ophiolite suite virtually identical to the Rocas Verdes ophiolites of Tierra del Fuego is exposed in the east of the islands and the most extensively exposed rocks are deformed Lower Cretaceous andesitic greywackes equivalent to the Rocas Verdes marginal basin cover rocks (Dalziel et al., 1975). High seismic velocities and an absence of magnetic anomalies characterise the northern shelf, so it is possible that these deformed sediments extend to the shelf edge. Exposed on offshore islands in the south, and continuing across the southwest shelf on seismic evidence, are gently folded interbedded andesitic lavas and volcaniclastic sediments of Cretaceous age, similar to the batholith-related arc-derived material exposed on the offshore islands of Tierra del Fuego. The batholith itself may occur close to the southwest shelf edge, and the ophiolite may continue offshore. Satellite-derived gravity shows negative anomalies beneath sections of both outer shelves, suggesting an east–west sinistral strike-slip fault offsetting the western quarter of the microcontinent (Barker, 1995).

The Shag Rocks block lies west of South Georgia, measures about 200 × 50 km and is elongated slightly south of east. The only outcrop comprises two very small island groups that have yielded greenschists, related by Tanner (1982) to the palaeo-forearc rocks of the South Orkney Islands and Elephant Island.
The continental block on which they lie is non-magnetic (Barker and Griffiths, 1972).

3.8.3. The North Scotia Ridge

The North Scotia Ridge (NSR) extends from southernmost South America at 64°W to the eastern end of the South Georgia microcontinent, a distance of 2000 km. The NSR is remarkably coherent, in that a deep gravity low is continuous from the Magallanes Basin of Tierra del Fuego, along the northern flank of the NSR and beyond into the northern arm of the South Sandwich Trench (e.g. Sandwell and Smith, 1997). The gravity low lies south of the bathymetric axis of the Falkland Trough (which lies north of the Ridge along most of its length), and reflects a thick pile of sediments, forming a well-developed accretionary prism (Ludwig and Rabinowitz, 1982; Ludwig et al., 1968; Ewing et al., 1971; Platt and Philip, 1995; Cunningham et al., 1998). Northward again lies the Falkland Plateau (also thickly sedimented) which most probably has been a rigid part of the South American plate since the Jurassic.

It has been suggested (Barker, 1995) that the northward-convex shape of the NSR results from the contrast between an oceanic central basin province of the Falkland Plateau, which was thus capable of being subducted beneath an advancing NSR, and the continental components (Falkland Islands, Maurice Ewing Bank) to west and east, which were not.

The gravity low continues westward into the Magallanes Basin of Tierra del Fuego, and the accretionary prism may be seen as an eastward extension of the foreland fold and thrust belt. The main difference is that, whereas in the Magallanes Basin convergence has been limited by the existence of stable continental crust of the South American foreland, farther south and east there has been no such constraint, so that more extensive convergence was able to develop. However, Cunningham et al. (1998) showed that convergence ceased some time ago, in the central zone of the NSR (46–54°W) where sidescan sonar and seismic reflection data were available, and probably as far east as South Georgia, to be replaced by the current east–west sinistral strike–slip regime, and that the present plate boundary does not necessarily coincide with the frontal fold of the accretionary prism. Barker et al. (1991) suggested that this change took place about 7 Ma ago, when spreading ceased in Drake Passage and the Central Scotia Sea. It remains possible that oblique convergence takes place farther west along the NSR (Tierra del Fuego and Burdwood Bank), within an essentially east–west sinistral strike–slip regime, as a result of a change in orientation of the plate boundary, but generally convergence has ceased. In places, an illusion is created that convergence continues, by non-deposition as a result of vigorous bottom current action, above a fault trace marking the toe of the accretionary prism, that therefore reaches the seabed (Cunningham et al., 1998).

The other, principal concern of a reconstruction is the nature of the “backstop” against which the accretionary prism was built. In some places, such as the Shag Rocks block and South Georgia, and close to Tierra del Fuego, the backstop is clearly a continental fragment which must be considered in reconstructions. Elsewhere, however, the nature of the backstop is uncertain. It may be that in places young ocean floor (or an intra-oceanic island arc), opposed to the north by much older SAM ocean floor already downwarped, was sufficient of a backstop for an accretionary prism to develop. An example of such asymmetry might be the northern arm of the present South Sandwich trench, or the South Sandwich fore-arc. The nature of the backstop, however thin, is clearly important for an understanding of palaeoelevation, relevant to palaeocirculation studies.

An interesting feature of the North Scotia Ridge (NSR) is the seeming prevalence of east–west sinistral strike–slip as a mode of dissection and elongation. Eastward elongation of the NSR is highly likely, given the strong similarities between the geology of the South Georgia microcontinent and of southernmost South America close to Cape Horn, areas now separated by some 1700 km, and the dominance of east–west extension within the Scotia Sea back-arc. Sinistral strike–slip motion oriented approximately east–west has been suggested to have deformed the South Georgia microcontinent (Barker, 1995), and may explain the relative positions of the South Georgia and Shag Rocks blocks. It is uncertain if all of the component blocks of the NSR contain a continental fragment as backstop to the accretionary prism, but similar offsets may be imagined between the Shag Rocks and Aurora Bank blocks, within the Davis Bank block near 50°W, and possibly even
between Davis and Burdwood Banks (here dextral, but serving still to elongate the NSR).

It is possible that the most easterly offset, through the South Georgia block, is still active. The locus of the present SAM–SCO plate boundary is uncertain: conventionally (e.g. Tectonic Map, 1985) it is taken around the northern margin of the South Georgia block, where the frontal fold of past northward motion and accretion occurs. However, a single earthquake on the southern margin, with a thrust fault first motion (Forsyth, 1975), is the only available evidence of present motion, and elsewhere the plate boundary has been shown (by Cunningham et al., 1998) to be independent of the frontal fold created during the previous episode of north–south convergence. It would be possible for this earthquake to lie on the present plate boundary, which might then continue eastward through the block, taking the line suggested by the South Georgia gravity anomaly, to the northern arm of the South Sandwich Trench. In order to stimulate further investigation, it is shown in this position in Fig. 1B.

4. Scotia Arc reconstructions

A series of reconstructions is provided, to illustrate Scotia Sea/Scotia Arc evolution, using the information described in Section 3. Reconstructions have been attempted for six times corresponding to easily identifiable parts of the MRTS, that may change their absolute age as the MRTS is revised but will remain valid in terms of ocean floor creation, both within the Scotia Sea (Sections 3.1 and 3.2) and outside (Section 3.5). They are the times of magnetic anomalies A5o, A5Cy, A6o, A8o, A13y and A18o, where “y” and “o” denote the younger and older ends of normal magnetic polarity intervals. Currently (Cande and Kent, 1995) these have ages of 10.95, 16.01, 20.13, 26.55, 33.06 and 40.13 Ma, respectively. Reconstructions are shown in Fig. 3A–F relative to the rigid part of South America, represented in Fig. 3 by the Falkland Islands, Falkland Plateau and Atlantic coast of Argentina.

Reconstructions followed a common strategy (outlined in Section 2). The six presented here are described below, with comments on consequences of regional tectonic interest, and brief comments on the remaining unknowns. The significance of the reconstructions for palaeoceanography and for studies of mantle flow is considered in following sections, where additional unknowns relevant to those particular applications are identified. Included in Fig. 3 is the position of the ancestor of the present South Sandwich Trench, since this is an integral component of regional tectonic evolution. However, subduction at the Pacific margin is not shown: its extent is poorly known, and there is no indication that it has affected Scotia Sea region tectonic evolution over the past 40 Ma.

4.1. Reconstruction to A5o (10.95 Ma)

This youngest reconstruction (Fig. 3A) may be compared with the present-day Scotia Sea (Fig. 1B) and data summary (Fig. 2). Bransfield Strait is closed and the eastern South Scotia Ridge is not dissected. There is very little difference in the Central Scotia Sea and Drake Passage, where spreading is thought to have ceased at about 7 Ma, and to have been slow previously. It is assumed that none of the areas of ocean floor of unknown age in the southern Central Scotia Sea formed within the past 11 Ma. Northward convergence of the North Scotia Ridge upon the Falkland Plateau was active at A5o time most probably, the eastern North Scotia Ridge converged faster than the western but ceased shortly afterwards. All of the offset along the east–west strike–slip fault crossing the South Georgia block (essentially a very small part of the elongation of the North Scotia Ridge) has been restored, but the North Scotia Ridge is otherwise unchanged. The major change from the present day is in the East Scotia Sea where spreading over the past 11 Ma has been most rapid. A continental fragment is assumed to occupy the southern end of the proto-South Sandwich fore-arc, but from there to South Georgia the fore-arc was probably young ocean floor as today, possibly undergoing active tectonic erosion.

4.2. Reconstruction to A5Cy (16.01 Ma)

This is the time at which spreading in both Drake Passage and the Central Scotia Sea slowed down, and spreading in the East Scotia Sea may have begun. Again (Fig. 3B), I have assumed that all of the small ocean basins of unknown age in the southern Central Scotia Sea had already formed by this
time. The North Scotia Ridge was converging northward and northeastward on the Falkland Plateau, and another small part of the elongation of the North Scotia Ridge has been restored, along an east–west strike–slip fault between the South Georgia and Shag Rocks blocks. Despite this northward convergence, which itself had to involve northward roll-back of the subduction hinge, it seems most likely that the major example of trench hinge roll-back was at the eastern end of the trench, from Discovery Bank in the south to South Georgia in the north.

4.3. Reconstruction to A60 (20.13 Ma)

The major changes in this reconstruction (Fig. 3C) from the reconstruction of Fig. 3B are that both Drake Passage and the Central Scotia Sea are smaller, and the North Scotia Ridge is more compact. More of the strike–slip offset between the South Georgia and Shag Rocks blocks is restored, and there is now an overlap between Davis and Aurora Banks. The conjectured 3-plate nature of Drake Passage opening (Fig. 2) is allowed for, by removing an east–west sliver of ocean floor to the south of the eastern Drake Passage ocean floor, moving the spreading centre closer to the South Scotia Ridge. In this reconstruction, part but not all of the southern part of the Central Scotia Sea has been eliminated. The age of any particular small basin is unknown, but they are assumed to range in age between 16 and 27 Ma (Fig. 3B and D).

The time of this reconstruction is very little earlier than that of the reconstruction in Fig. 3B, but it
marks an important change in both external constraint and internal response. At about this time, the separation of the major plates (SAM–ANT) changed from WNW–ESE to W–E, and N–S spreading in the Central Scotia Sea began. Although the latter change has been attributed to a ridge crest–trench collision at Jane Bank (Barker et al., 1984), these two events may be connected in some way. This time is also important in palaeoceanographic terms: although the two ridge ends of the Shackleton fracture zone had by then cleared, creating a deep-water pathway, it is possible that a more compact North Scotia Ridge would have prevented continuous circumpolar deep water flow (Barker and Burrell, 1977, 1982: see Section 7.3).

4.4. Reconstruction to A8o (26.55 Ma)

Anomaly 8 is the oldest magnetic anomaly observed consistently at the outer edges of ocean floor produced by the Drake Passage spreading regime. Despite this, it is clear (Fig. 3D) that older ocean floor did exist within the Scotia Sea. Most of the area of ocean floor of unknown age in the small basins of the southern Central Scotia Sea is presumed younger than A8o, and has therefore been removed. Jane Basin has been closed, but Powell Basin remains open. Bruce Bank is assumed to have undergone north–south extension (and is therefore shown smaller in Fig. 3D). The North Scotia Ridge is more compact, but South Georgia remains at some distance from its probable origin close to Cape Horn. It seems likely that the older ocean floor within the Scotia Sea was formed in the wake of an east-migrating South Georgia block.

4.5. Reconstruction to A13y (33.01 Ma)

Although the previous reconstruction (Fig. 3D) is the oldest in which the internal Scotia Sea evolution is constrained by oceanic magnetic anomaly data, the external, major plate motion remains constrained in this way, through this reconstruction (Fig. 3E) and the A18o reconstruction that follows. Also, as the Scotia Sea ocean floor age constraints are lost, the geological nature of the continental fragments within the Scotia Arc takes on a greater significance. Thus, this reconstruction includes the closure of Powell Basin (bringing the South Orkney block to the Antarctic Peninsula as proposed elsewhere: e.g. King and Barker, 1988; King et al., 1997) and assumes the active eastward migration of South Georgia, in response to eastward migration of the subduction zone, creating a narrow corridor of ocean floor in its wake south of the attenuated North Scotia Ridge.

4.6. Reconstruction to A18o (40.13 Ma)

In this reconstruction (Fig. 3F), all ocean floor has been eliminated from the back-arc, and the east-directed subduction represented by the locus of a palaeo-trench must be at a very early stage. This reconstruction is assumed to be the earliest worthy of consideration: the (fairly well-constrained) major plate reconstruction has opposed the ends of the coherent continental blocks of southernmost South America and the Antarctic Peninsula (assuming a slow and simple movement of the converging Pacific margin—the closing Magallanes Basin). It is possible to fit all of the component fragments of the North and South Scotia Ridge (plus compacted versions of Pirie and Bruce Bank) into a connecting mass of approximately the correct area. In Fig. 4, the geology of the continental fragments (including what may be adduced from offshore marine geophysics) is superimposed on the reconstruction to A18o. The superimposition shows a systematic distribution of fore-arc and batholith fragments with respect to a subducting Pacific margin, which provides support to the reconstructions, and suggests that Pirie Bank and Bruce Bank, the nature of which is unknown, could originally have been mostly palaeo-forearc too. It suggests also a “fore-arc sandwich” (King and Barker, 1988; Barker et al., 1991), in which elements of a subducting Pacific margin (fore-arc and batholith) are found (at 40 Ma) rather too far from the then Pacific margin, implying a prior history in which a cusptate Pacific margin was shortened by north–south convergence. It is likely that these reconstructions will be modified in detail, as major plate motions become better defined, but right now it seems difficult to avoid the conclusion that the essential elements of a reconstruction (and the likely causes of regional tectonic evolution—see Section 5 and Fig. 5) have been resolved.
Fig. 4. Geology of continental fragments, as available from onshore outcrop and offshore marine geophysics, superimposed on the 40 Ma reconstruction of Fig. 3F (the “fore-arc sandwich”, revised from King and Barker, 1988). Two provinces are distinguished: in dark grey the Pacific margin batholith and associated arc volcanics (where strongly magnetised, or mapped in outcrop), and in light grey a non-magnetic fore-arc and (partly relict but in situ) palaeo-forearc. The batholith has been mapped along the Antarctic Peninsula, South Orkney continent, part of the South Scotia Ridge and (possibly) within the South Sandwich forearc, on the southern margin of South Georgia and in Tierra del Fuego. Representative rocks of the palaeo-forearc occur on the Antarctic Peninsula margin, South Scotia Ridge, South Orkney Islands and western Tierra del Fuego. Most of South Georgia and (probably) the Shag Rocks block appear to have originated in the continental back-arc. Also shown are Pacific margin and Atlantic-directed subduction zones. The overall pattern of provinces is consistent with the model presented in Fig. 5.

4.7. Uncertainties, and other comments on reconstructions

The major uncertainties in regional tectonic evolution concern the coupling between adjacent spreading systems within the Scotia Sea, particularly those that were contemporary, and the ages of areas of Central Scotia Sea floor of probable oceanic crustal structure. The latter can perhaps be estimated from heat flow measurements, and it may be possible to determine the former in a few cases by examining the overlying sediments on seismic profiles. A history of ridge crest collision along the South Scotia Ridge is also desirable, but will be difficult to achieve without additional detailed survey, and it seems likely that estimates of SAM–ANT motion will be refined (though major plate motion will not be diagnostic of Scotia Arc evolution because of Magallanes Basin closure).

Despite these uncertainties, the reconstructions have a coherence which reinforces their plausibility. Several themes continue through the series. Some are in part artificial: they represent the application of assumptions about processes. Others are consequences, some of them previously recognised and others not. Both kinds of theme provide interesting opportunities for testing aspects of the model. Examples are given below.

- The position of the most westerly spreading section of the SAM–ANT boundary, the “locus” of ridge crest–trench collision, has been constrained to migrate eastward with time. The major plate (SAM–ANT) motion was WNW–ESE for the three earlier reconstructions (Fig. 3D–F), and transforms were typically small-offset, rather than the large-offset transforms of the past 20 Ma. This may have meant that the earlier ridge crest–trench collisions along the western South Scotia Ridge were smaller events, more closely spaced in time, than the later events, after the spreading direction had changed. Of course it is possible that, as off western North America (Atwater, 1989), subduction stopped in places before the ridge crest reached the trench.
- South Georgia remained at the leading edge of the back-arc system, from its initiation to (probably) about 7 Ma (Fig. 3A–F). As yet, no evidence of this position (Cenozoic arc volcanism and normal faulting, for example) has been found in the onshore geology, or offshore. A possible explanation for this absence is extensive tectonic erosion (Lallemand, 1995), but it is unlikely that tectonic erosion would have removed all traces. It would be interesting to search for components of a palaeo-arc within the northern Scotia Sea and North Scotia Ridge, as well as along the southern margin. For example, it is possible that the two seamounts lying south of the South Georgia block, within the central Scotia Sea near 56°S 37°W, might have been part of an older island arc, and that the curve of the arc might have continued northwesternly to the rough elevated region at 54°S 40°W, on the southwestern corner of the South Georgia block. No sample of any of these features is available.
Fig. 5. A model to explain the origins of east-directed subduction and accompanying back-arc extension in the Scotia Sea region (revised from Barker and Lonsdale, 1991; Barker et al., 1991). (a) Opening of the Rocas Verdes back-arc basin, continuing southeastward as separation of the Antarctic Peninsula before South Atlantic opening, and with likely decoupling between the Antarctic Peninsula and East Antarctica. SAM–ANTP pole of opening is to the northwest. (b) Closure of the Rocas Verdes basin, possibly from faster westward motion of South America, leading to formation of the Magallanes fold-thrust belt in southernmost South America. SAM–AFR–ANT separations are well-established, and East Antarctica and the Antarctic Peninsula are probably by now a single plate. Pole of SAM–ANT motion is close to the South America–Antarctic Peninsula junction, leading to slow extension (slower westward) in the east and convergence in the Magallanes Basin to the northwest. The junction bends. (c) Continued motion as described in (b) bends the junction double. Whereas in the Magallanes fold–thrust belt to the north, convergence is limited by the presence of the South American continental foreland, farther south ocean floor is underthrust, presenting the opportunity for subduction to develop.

- Also remaining at the subducting margin, in these reconstructions, is the fragment of 31-Ma-old continental arc sampled by dredging the present fore-arc (Barker, 1995). Again, tectonic erosion of this fragment seems likely and, though inefficient compared with back-arc extension (Section 3.7), it may have removed a significant fraction of any continental material within the fore-arc over the past 30–40 Ma.

- The North Scotia Ridge extended steadily eastward, and migrated northward to produce the accretionary prism that now lies on its northern flank. There has to be a balance between such northward migration and events at the southeastern margin: essentially, there was excess spreading (over major plate separation) within the Scotia Sea at all times, that had to be accommodated by subduction either at the northern margin or in the southeast. The amount of extension that could be accommodated in the southeast is limited by the line of ridge crest subduction. For some periods, this balance is sufficiently understood to be able to constrain the reconstructions presented here, but it is capable of doing so completely, when all the ages of ocean floor in the Scotia Sea and collision ages in the northern Weddell Sea are determined.

- Eastward roll-back of the subduction hinge was a persistent feature of the past 40 Ma of Scotia Sea evolution, since the eastward component of back-arc extension was consistently faster than major plate motion. For much of this period, however, there was also northward roll-back of the subducted SAM oceanic lithosphere beneath the extending and northward-migrating North Scotia Ridge. Geometrically, roll-back cannot occur simultaneously in two divergent directions without tearing of the sinking slab and separation of the torn components. Today, only one section of lithospheric slab is subducting, the tear lies at the northern end of the South Sandwich trench, and tearing propagates eastward. In the past (before about 7 Ma) both the location of the tear and its direction of propagation would have been less certain.

- In all of the Scotia Sea region and its surroundings, the only place where a substantial accretionary prism survived or formed over the past 40 Ma was...
the North Scotia Ridge. Subduction elsewhere, at the Pacific margin, along the eastern and southern margins of the Scotia Sea or internally, appears to have preserved very little deformed sediment. This may be attributed in general terms to sediment availability. Along the North Scotia Ridge there was a South American terrigenous source in the west a more distal province of the Magallanes Basin), augmented in the east by biogenic sediments, as are found on the Falkland Plateau (Saito et al., 1974; Barker and Dalziel, 1976; Ciesielski et al., 1982) and, latterly, as produced close to the Polar Front and deposited in drifts along the Falkland Trough (Cunningham and Barker, 1996; Cunningham et al., 1998) where bottom current strength permits. Elsewhere, accretion may have been limited by the young age and intra-oceanic origin of subducted ocean floor, and the restricted extent of subduction in time and space.

5. Origins and causes of Scotia Sea evolution

To explain Scotia Sea evolution, it is necessary to explain why it began, and how it continues. The second of these has already been considered several times within this paper. The driving force is provided by subduction of South Atlantic ocean floor of the South American plate, which can continue only by tearing at its northern end, and roll-back of the subduction hinge. Collisions of ridge crest sections of the South American–Antarctic plate boundary with the trench have interrupted this process at intervals, causing changes in the mode of back-arc extension, but have not contributed to the primary drive. A key question remains, as to whether or not roll-back of the hinge of subduction is influenced by (driven by, enabled by, used by) shallow eastward flow in the sub-lithospheric mantle (Section 6).

The question of why east-directed subduction should have begun is interesting. It has been argued that, although subduction is easy to maintain (because there is an instability at the earth’s surface, the cold, oceanic lithospheric mantle being denser than the underlying, warmer asthenospheric mantle), it is difficult to initiate. A situation must develop in which oceanic lithosphere is underthrust as a result of forces originating elsewhere within a plate system. It has been suggested (Barker and Lonsdale, 1991; Barker et al., 1991 and Fig. 5) that, in the case of the Scotia Arc, the circumstance was the onset of convergence behind the leading (Pacific margin) edge of the South American plate, originating perhaps in an increase in its absolute westward motion coincident with an increase in the rate of South Atlantic opening in the mid-Cretaceous (Rabinowitz and LaBrecque, 1979; Dalziel, 1985). This convergence closed the Rocos Verdes back-arc basin and created the Magallanes Basin fold–thrust belt of Tierra del Fuego. The original position of the Antarctic Peninsula at the Gondwana margin is unknown, and there was probably movement between East Antarctica and the Antarctic Peninsula, but (latterly Jurassic) Rocos Verdes opening can be considered to have been connected to SAM–ANTP separation (Fig. 5a), forming the early Weddell Sea. The pole of opening would have been remote, and to the northwest. With the beginning of closure (and by then, East Antarctica and the Antarctic Peninsula had probably joined), the pole of SAM–ANT motion moved south, coming to lie close to southermost South America. Over a long time (Fig. 5b), the Antarctic plate rotated clockwise with respect to South America. Convergence continued in the Magallanes Basin and to the south (as far south as the pole of relative plate motion). However, whereas in the north the presence of a South American continental foreland acted to limit underthrusting, the availability of oceanic lithosphere in the south (on the northern flank of the SAM–ANT boundary, congruent to Weddell Sea floor) created the conditions necessary for subduction to begin. Eventually (presumably as the sinking South American oceanic lithosphere tore, south of the Falkland Plateau) the present regime of eastward roll-back and complementary back-arc extension was able to develop. The pole of SAM–ANT motion now lies much farther south.

This speculative model is borne out in essence by satellite altimetry-derived gravity images of ocean floor fabric in the Weddell Sea (McAdoo and Laxon, 1996), which show a southern zone in which older transform topography is oriented northeast (Re: Fig. 5a), then a younger zone of prominent northwest-oriented transform fabric to the north (Fig. 5b and c). SAM–ANT motion has passed through the sequence hypothesised in the model. The timing of the abrupt change in direction of SAM–ANT motion is not yet
known with confidence, and it remains to be seen if a particular change in major plate motion or boundary caused the other major model development: the onset of back-arc extension (see Section 6.4.). Also, the significance of other, shorter-lived episodes of regional tectonic activity remains to be assessed, for example the slowing down in SAM–ANT separation between 65 and 50 Ma (Livermore and Woollett, 1993), and two episodes of deformation of the southern margin of the Magallanes Basin during the Late Cretaceous and early Cenozoic (Kohn et al., 1995; Klepeis and Austin, 1997).

6. Consequences for mantle flow

6.1. Techniques: shear-wave splitting and geochemistry

As a result of the correlation made between shear-wave splitting (that is, velocity anisotropy), a preferred orientation of olivine crystals within the mantle and mantle strain, measurements are now being made of past and present mantle flow at comparatively high lateral resolution (for a review, see Savage, 1999). At present, many factors are uncertain: for example, the distinction between olivine orientation within the lithosphere (frozen in and reflecting flow during lithosphere formation) and within the underlying asthenosphere (reflecting more recent flow, and not necessarily the motion of the plate during formation), the nature of decay of sublithospheric mantle anisotropy, the meaning of anisotropy beneath continents (the existence of a tectosphere), and the effects of hotspots. In the Scotia Sea region, the measurement of shear wave splitting presents the opportunity of testing the hypothesis of Alvarez (1982) that the imbalance between mantle excess beneath a shrinking Pacific realm (largely surrounded by continents and rolling-back sinking slabs) and a dearth of mantle beneath an Atlantic–Indian realm (losing mantle to the expanding lithosphere) is compensated by shallow eastward mantle flow. Shear-wave splitting measurements off Peru and Chile (Russo and Silver, 1994) have suggested mantle flow parallel to the trench, thereby pointing to decoupling of asthenospheric flow from the lithosphere and the effectiveness of a subducting slab as a barrier to flow, both of which are requirements of the Alvarez hypothesis. If the Scotia Sea provides a gap in the hypothesised barriers of trench and continent, it may be a conduit for shallow flow, as Alvarez (1982) suggested. Shallow eastward mantle flow may have contributed to the eastward roll-back (in the mean hotspot reference frame) of the hinge of subduction. While it has been proposed that all back-arc extension happens as a result of remnant arc retreat and slab roll-back in an “absolute” reference frame (e.g. Chase, 1978), roll-back of the South Sandwich trench is fast, and only the New Hebrides trench is faster (Jarrard, 1986). There would be value in testing Alvarez’ hypothesis by direct measurement of shear waves beneath parts of the Scotia Sea.

The hypothesis may be tested also by geochemical means which (given suitable samples) allows the affinities of the sub-lithospheric mantle at a particular time and place to be assessed (e.g. Pyle et al., 1995). Sampling for geochemistry is limited often to the spreading centre by subsequent sedimentation, or to off-axis volcanism which may be sparse. Given the outcrop, however, dredge sampling is relatively simple. The analysis defines the affinities of underlying mantle at the time of melting.

Seismological studies are limited to existing fixed stations (usually on continents) or to ocean bottom seismometers. These latter may be sited anywhere, but are technically complex and expensive. The measurement is usually a reflection of cumulative mantle strain. Given their respective practical difficulties and different assumptions, the geochemical and seismometric methods should probably be considered complementary.

6.2. Scotia Sea evolution

For the Scotia Sea region, it is useful to examine tectonic evolution as a part of the design and interpretation of suitable experiments. Fig. 6 shows the paths taken (relative to a fixed South America) by several tectonic elements over the past 40 Ma, derived from the reconstructions described in Section 4. The use of South America as a reference frame is appropriate, in that the continent and the subducting lithosphere at its western edge appear to have formed a fixed barrier to mantle flow.
The flow lines, which end at the feature whose path they represent, are numbered, and each has seven nodes, representing the six reconstructions and the present day. Line 1, ending at D’Urville Island close to the northeastern end of the Antarctic Peninsula, is a reasonable representation of the separation of the major (SAM–ANT) plates. Line 2, ending on the seabed outcrop of 31-Ma-old calc-alkaline lavas in the present fore-arc, is probably the closest representation of the track of the proto-South Sandwich subduction zone, and shows how much faster than major plate motion has been the eastward growth of the Scotia Sea, at every stage. This is most probably correct also for the two reconstructions older than Anomaly 8, even though there is direct constraint only on major plate motion, not on Scotia Sea spreading rates. Eastward back-arc extension has averaged 2.7 times the rate of major plate separation over the past 40 Ma, and eastward roll-back of the subduction hinge has averaged 50 mm/a, not far short of its present rate and significantly faster than the likely “absolute” rate of westward motion of the South American plate (Gripp and Gordon, 1990). Line 3 ends at the eastern end of South Georgia: the motion of the South Georgia block was parallel to that of the trench (Line 2) until 20 Ma or later, while it lay close to the east-advancing trench; thereafter it diverged towards the northeast, still close to the subduction zone (until perhaps 7 Ma) but not subducting as rapidly. Lines 4 and 5 end at the southern margin of the Shag Rocks block and at the boundary between Burdwood and Davis Banks, respectively, and show progressively earlier and sharper changes in direction than Line 3: they serve to map the northward migration of the subduction zone of the North Scotia Ridge at two intermediate positions along its length. Line 6 ends on Cape Horn and shows the slow closure of the Magallanes Basin at the southeastern end of its onshore exposure in South America.

The main uncertainties in our understanding of regional tectonic evolution concern the ages of small, probably oceanic basins in the southern Scotia Sea, and the nature of the coupling between some spreading regimes. Given the plausibility and success of the reconstructions, these uncertainties may be relatively small. In terms of the flow lines of Fig. 6, they probably affect mainly the size of intermediate velocity vectors, particularly within lines 2, 3 and 4, but perhaps not their overall lengths or directions.
6.3. Consequences for seismological studies

It is not the purpose of this paper to propose locations for seismometers capable of recording shear waves in order to test a hypothesis of mantle flow. For one thing, practical considerations are important, such as signal-to-noise ratio at the seabed, raising questions of sediment thickness and bottom current strength and variability. Also, experiments may aim to examine more detailed aspects of mantle flow, such as distinguishing between older and younger flow, or between time extent of flow and speed of flow as influences on mantle velocity anisotropy, or mapping mantle flow in geographic detail. However, Fig. 6 suggests some potential constraints on measurement, that should be borne in mind.

There are three major initial assumptions, independent of the particular nature of tectonic evolution:

1. DEEP mantle flow is unknown, but both hotspot studies and seismological studies suggest that, globally, deep mantle motion is slow. Thus, if the Alvarez hypothesis holds, then measured anisotropy will result from a combination of frozen-in lithospheric and more recent or modern asthenospheric strain (that is, NOT from a third, independent lower mantle flow).

2. Again, if the Alvarez hypothesis holds, flow-related anisotropy will probably be greatest beneath lithosphere that has moved only slowly with respect to southernmost South America, and least beneath lithosphere that has moved east with the subduction zone because it has experienced less basal shear.

3. Assuming that measurement on oceanic lithosphere is desirable (because of its simpler structure than continental lithosphere, and freedom from a sub-lithospheric “TECTOSPHERE”), anisotropy beneath older ocean floor might be greater than beneath younger, as it would have experienced a longer period of decoupled sub-lithospheric flow, following the possibly complicated flow associated with initial formation.

In addition to these, it is clear from Fig. 6 that the North Scotia Ridge has moved northward as it has formed, contributing to different histories of sub-lithospheric mantle flow beneath the north and south of the present Scotia Sea. The zone of longest, most consistent oceanic back-arc extension and eastward sub-lithospheric flow most probably lies in the wake of South Georgia and the calc-alkaline forearc body (lines 3 and 2 of Fig. 6), beneath the southern rather than the northern Scotia Sea.

The effects of the unknown aspects of Scotia Sea tectonic evolution may be avoidable in at least the earlier stages of examination of mantle flow. The ages of formation of small ocean basins in the southern Central Scotia Sea are unknown, but it should be possible to select measurement sites elsewhere that have a sufficiently wide range of combinations of ocean floor age and motion, to test most hypotheses of mantle flow.

One additional point: in this paper, the region west of the Shackleton fracture zone has not been considered. Its history is of the formation of young ocean floor and of likely (but indeterminate) subduction of a Phoenix–Nazca spreading centre and Phoenix/Nazca/Antarctic triple junction, that would make measurements of shear-wave splitting difficult to interpret, even though it might overlie part of the zone of present-day east-directed mantle flow.

An early study of this kind (Müller, in press) shows much promise, but there is a need for improvement in the distribution of local recording stations (see also papers in Brancolini et al., in press).

6.4. Consequences for geochemical studies

The consequences of Scotia Sea evolution for geochemical studies of mantle flow are straightforward. An abandoned ridge crest extends for a considerable east–west distance through Drake Passage, and ocean floor in the northern Scotia Sea is unusually free from sediment as a result of scour by the vigorous ACC (see Section 7.1 below). Outcrop in the Central Scotia Sea is more sparse, but exists, certainly in the northern part, for the same reason (Barker and Lawver, 2000). A programme of ocean floor dredging could easily delineate the eastward extent of Pacific-origin mantle at about 10–7 Ma, in the northern part of the Scotia Sea, by sampling ocean floor close to the abandoned ridge crest. Ocean floor formed earlier is less accessible, and younger ocean floor may probably be sampled only in the East Scotia Sea. No such sampling programme has begun, but Pearce et al. (in press) show what can be done with the sparse existing sample distribution. They conclude that shallow mantle flow from the
Pacific was limited, once free connection to the Atlantic had been established, because of the contribution of Atlantic mantle hotspots, but the data distribution restricts what can be said. The geochemistry of the northern extremity of the East Scotia Sea back-arc spreading centre is interpreted by Leat et al. (2000) as indicating flow of South Atlantic (Bouvet-influenced) mantle around the edge of the subducting slab. This modifies but does not rule out the Alvarez (1982) hypothesis of shallow eastward mantle flow, and points to the potential value of geochemical studies to investigate this hypothesis further.

6.5. Feedback to tectonic evolution

There is a key uncertainty in Scotia Sea evolution, concerning the onset of trench roll-back, that might be determined through studies of mantle flow. It has been stated here (Section 3.1 and above) that, in essence, a causal connection between events in the SE Pacific and Scotia Sea evolution is unlikely. However, was there such a connection? Did subduction of the Phoenix–Farallon (Nazca) spreading centre (and of the Phoenix/Nazca/Antarctic triple junction) enable the onset of rapid eastward trench hinge roll-back, via disruption of the Pacific margin subduction zone so as to permit shallow eastward mantle flow? There is now insufficient ocean floor unsubducted in the SE Pacific to determine the times or locations of ridge crest subduction precisely, but it may be possible (perhaps by geochemical sampling) to erect a hypothesis of disruption and its consequences, that could be tested in broad terms.

7. Consequences for palaeocirculation

As already noted, there is considerable interest in the history of development of the Antarctic Circumpolar Current (ACC), mainly because of its presumed effect on north–south heat transport and consequent significance for the history of global climate (and Antarctic glaciation in particular). It is now well-established that the Scotia Sea region was the site of the final barrier to a complete circum-Antarctic deep water path (e.g. Barker and Burrell, 1977), and generally agreed that neither a complete shallow (continental shelf) path nor an incomplete deep-water path would have led to the creation of a large ACC.

For studies of the palaeoceanographic consequences of Scotia Sea evolution, the requirements are more detailed than in the case of mantle flow, and the unknowns potentially more significant. It is necessary to know about the entire pathway in order to study palaeocirculation, rather than merely about the character of a particular point. Pathways may be created and destroyed by horizontal motion (opening and closing gateways), or by vertical motion (lowering and raising sills). Horizontal plate motion is relatively fast, and can open and close substantial deep water pathways in a million years or so. Vertical motion in tectonics derives usually from convergence which can lead to rapid uplift (associated often with deformation), or from thermal effects which are relatively slow. In general terms, uplift is usually faster than subsidence, but horizontal motion can be more effective than either.

Here I try to identify tectonic changes that might have affected palaeocirculation and thus possibly palaeoclimate. Of course, the climatic effects of tectonic changes must be considered with caution. Present-day oceanography is incompletely understood, and it is most likely that the palaeoceanography of an earth without an ACC, or without an Antarctic ice sheet, would have been different. For example, without very cold poles, the north–south temperature gradients which create the westerly winds that largely drive the present ACC would have been reduced, and the oceanic thermohaline circulation, driven mainly at present by the density effects of ice-related processes at high-latitude margins, may have been much more sluggish, if it existed. When a deep circumpolar path was created, would there have been a delay before an ACC developed, and would a smaller ACC have disrupted north–south circulation as it does today? Conversely, a developing current such as the ACC may become limited other than by the size of the tectonically created gap, so that tectonic development beyond a certain stage would have a much lesser effect on circulation.

Also, of course, there are variants on the null hypothesis: that global climate was insensitive to development of the ACC. This hypothesis would remain, even were a synchronicity to be established that might suggest circulation cause for climatic effect. It would be necessary to examine such developments by means of numerical models, to assess the
possibility of a causal link. A particularly significant variant on the “null hypothesis” is one in which changes in the concentrations of atmospheric “greenhouse” gases such as CO₂ have been important. It is sometimes argued that such changes can alone explain global climatic change, or that they amplify other effects. Thus, although an earth with and without an ACC may be fundamentally different in its climate response, the amplitude of that difference may be crucially dependent on levels of atmospheric greenhouse gases, and the difference be revealed only by changes in such levels.

7.1. Present-day circulation

The present-day ocean circulation has two main components. The warm Circumpolar Deep Water (CDW) of the high-energy Antarctic Circumpolar Current (ACC) flows eastward through the Scotia Sea from the SE Pacific, and cold Weddell Sea Deep Water (WSDW) leaks northward into the Scotia Sea through gaps in the South Scotia Ridge and over shallow sills. These flows are shown schematically in Fig. 7A.

The ACC is wind-driven throughout its length, but over much of its path extends to the seabed. Total ACC transport has been estimated as 130 Sverdrup, relative to 2500 m depth (Whitworth and Peterson, 1985), which is large [1 Sv = 10⁶ m³/s]. In Fig. 7A the ACC covers a broad area, but much of the flow is considered to occur within narrow jets (e.g. Nowlin and Klinck, 1986; Peterson and Whitworth, 1989; Gille, 1994) coincident with two fronts, the Polar Front (PF) and SubAntarctic Front (SAF) that are continuous around the Antarctic. The fronts are well separated generally, but come together where flow is constricted by topography (as in Drake Passage). Having flowed eastward through northern Drake Passage, the ACC fronts veer north, partly as a result of earth rotation (Coriolis). Shallow flow crosses the North Scotia Ridge where seabed topography permits (Tectonic Map, 1985; Locarnini et al., 1993; Orsi et al., 1995), while a deeper component continues eastward within the Scotia Sea. Gaps in the North Scotia Ridge reach 1700 m near 35°W, 3000 m near 48°W (the “Shag Rocks Passage” of Zenk, 1981)—although it is some distance from Shag Rocks), to 3200 m in places over a 250 km distance east of South Georgia, and to around 2000 m between the volcanic South Sandwich Islands. The two fronts pass to either side of Maurice Ewing Bank (45–40°W) in the eastern Falkland Plateau, well north of the Central and East Scotia Sea (see for example Moore et al., 1997, 1999; Trathan et al., 2000) but, partly through meanders and eddies of the fronts and partly through more general eastward flow outside them, the ACC prevents or controls sedimentation across much of the Falkland Plateau (Saito et al., 1974; Barker and Dalziel, 1976; Ciesielski et al., 1982), North Scotia Ridge and northern Scotia Sea (Barker and Burrell, 1977; Cunningham et al., 1998; Pudsey and Howe, 1998; Barker and Lawver, 2000).

In addition, current meter moorings in the central Scotia Sea 1993–5 (Pudsey and Howe, in press), 50 m above the seabed in 4000 m and 3650 m water depth, show short periods of high velocity (reaching 50 cm/s and mainly north of east) and rapid bottom temperature change (up to ±0.2°C; see also Barker and Lawver, 2000) in areas that are well away from the two fronts.

The bulk of WSDW, and Weddell Sea Bottom Water (WSBW) which augments WSDW from beneath, flow clockwise around the Weddell Gyre, which extends from the Weddell Sea to about 30°E, south of the ACC. Flow around the gyre has been variously estimated at between 30 and 76 Sv (Gordon et al., 1981; Fahrbach et al., 1994; Schröder and Fahrbach, 1999). Cold, dense WSBW is produced mainly by interaction with the Antarctic ice sheet and by sea ice formation, within the southern and western Weddell Sea (Foster and Carmack, 1976; Foster and Middleton, 1980; Gordon, 1998). Some WSDW escapes north through gaps in the South Scotia Ridge (particularly that near 39°W which exceeds 3000 m: Tectonic Map, 1985) and over shallower sills, into the Scotia Sea (Nowlin and Zenk, 1988) and thence along the Pacific margin of West Antarctica (Camerlenghi et al., 1997). Some WSDW crossing the eastern South Scotia Ridge flows northeast across the East Scotia Sea (Locarnini et al., 1993) and joins the WSBW that has cut through deep gaps in the SAM–ANT plate boundary near 25°W and flowed north along the South Sandwich trench (Georgi, 1981) towards the Atlantic (Mantyla and Reid, 1983). This north-flowing WSDW is also considered to make an excursion
Fig. 7. (A) Schematic diagram of present-day ocean circulation in the Scotia Sea region, showing in orange the Antarctic Circumpolar Current (ACC) flowing eastward into the Scotia Sea from the southeast Pacific, then spreading north and northeast over the Falkland Trough and Falkland Plateau, across the elevated North Scotia Ridge. The ACC is shown as a broad current, but the fastest flow (scouring the sea floor and preventing sediment deposition in places) is along the northernmost Drake Passage, then across the North Scotia Ridge and Falkland Plateau. Red circles mark the mean position of the Polar Front (Moore et al., 1997). See text for details. Weddell Sea Deep Water (WSDW, shown in blue) escapes northward from the Weddell Gyre into the Scotia Sea, through gaps and over sills along the South Scotia Ridge. Some WSDW flows west along the South Scotia Ridge and South Shetland fore-arc into the southeast Pacific. Other WSDW flows north and northeast across the East Scotia Sea, beneath the ACC, to join WSDW and Weddell Sea Bottom Water (WSBW) that has flowed north along the South Sandwich trench. WSDW flows in a narrow westward loop along the Falkland Trough before continuing north into the Southwest Atlantic. Of these water masses, the main ACC transport (ca. 130 Sv) is far greater than any of the others. (B) The reconstruction of Fig. 3C (to Anomaly 6o, about 20 Ma) with superimposed the likely pathways for the same major currents as shown schematically in (A) above. The ACC cannot yet develop, if Aurora and Davis Banks were elevated parts of the North Scotia Ridge, despite the gap at the Shackleton Fracture Zone (SFZ). Note also that the mid-ocean ridge crest in the western Scotia Sea (Drake Passage) was more elevated than today, because spreading was then active, and was closer to the North Scotia Ridge, therefore more directly within the path of the ACC and a possible impediment to rapid flow. Also more elevated than today was the Antarctic–Phoenix–Farallon (Nazca) spreading system in the SE Pacific, although its precise location is poorly known. Northward flow of southern-origin bottom water (SOBW—not necessarily having the same properties as modern WSDW) is largely unaffected (other than by the absence of the ACC), but flow westward into the southeast Pacific is unlikely. “X” marks where SOBW-influenced sediment may be sampled closest to the SOBW source. For further discussion, see text.

westward along the Falkland Trough, north of the North Scotia Ridge, on the evidence of sediment drift formation and sediment waves (Cunningham and Barker, 1996). All of these flow paths are shown in Fig. 7A. The colder, denser WSDW and WSBW flow beneath the ACC wherever they cross (Falkland Trough, north of Maurice Ewing Bank and South Georgia, East Scotia Sea, South Sandwich Trench).
Locarnini et al. (1993) point to the far larger mixing area provided by a sub-horizontal boundary between CDW and WSDW within the East Scotia Sea (corresponding to the Weddell–Scotia Confluence of Gordon, 1971) than would be available at a sub-vertical front. The transport of WSDW and WSBW, northward towards the Atlantic and west into the SE Pacific, is small (estimated as 1–5 Sv) compared with that of the ACC.

7.2. Independent evidence of palaeocirculation

Clear, precise, incontrovertible evidence of the time of onset of either southern-origin bottom water (SOBW) or the ACC has not yet been obtained. Today, SOBW is represented by WSDW and WSBW; the term Antarctic Bottom Water (AABW) has now too disparate and contradictory a set of meanings within different communities, for precise and unambiguous use, and it is not used here. It is generally considered that widespread sedimentary hiatuses on the deep sea floor, together with an offset of oxygen isotopic ratio in benthic foraminifera (Shackleton and Kennett, 1975) and changes in deep-sea biota (Benson, 1975), signalled the onset of SOBW formation at the Eocene–Oligocene boundary. Modern WSBW formation involves both the segregation of dense brine during sea ice formation and supercooling at the base of cold ice shelves, at the Antarctic margin, but early SOBW formation need not have involved both of these processes, and the presence of ice shelves in the Oligocene is not implied (Barker et al., 1999). There is no convincing direct evidence of the age of onset of the ACC either, but speculation has placed it as early as the Eocene–Oligocene boundary (to coincide with, and have caused, the effects already described) and as late as Middle Miocene, to have caused the intensification of Antarctic glaciation observed at that time. The development of the ACC may also have helped stabilise Antarctic glaciation, by isolating the continent, reducing at the Antarctic margin the amplitude of climatic variation at lower latitudes.

The present-day sedimentary signatures of the ACC and SOBW provide markers that may (with caution) be sought in the past. Diffuse upwelling of WSDW within the Weddell Gyre encourages biogenic productivity (north of the zone of sea ice cover), but deep and bottom waters south of the ACC are corrosive to both siliceous and (particularly) calcareous skeletal debris. Calcareous production and preservation is dominant north of the Polar Front, and a siliceous ooze belt is found for some distance to the south (e.g. Goodell, 1973). Productivity is high within the photic zone of the ACC, but deep ACC flow is (at least intermittently) sufficiently strong to prevent deposition and to rework existing sediments over an axial zone that is enlarged by frontal meanders and eddies. Some of these sedimentary markers should be used with caution, because of the unknown nature of pre-ACC circulation and biogenic production. In particular, the elevated Falkland Plateau directly to the north may have been a source of upwelling and consequent productivity, that might resemble that associated now with the ACC and its related fronts. Also, comparison of Pacific and Atlantic biota that have a planktonic phase, while bearing on the existence of a shallow-water connection across a South American–Antarctic Peninsular isthmus, cannot be used to determine the age of a deep-water gap.

A strategy for determining the onset and development of the ACC from the sedimentary record would have to:

(a) avoid areas of very fast current flow, leading to high-energy deposition that might include hiatuses (which by erosion can extend beyond the period of their cause)

(b) examine sections lying on basement sufficiently old to have a hope of extending to the early Oligocene or earlier

(c) include a comparison of conditions north and south of the hypothesised palaeo-ACC axis, where the greatest differences should appear.

It is a general axiom of palaeoceanography that, other things being equal, a phenomenon is best studied proximally, so that its effects are less likely to be confused with those of other changes over the same period. In the case of the ACC, this is reinforced: where the ACC is unconfined, as where it crosses a major ocean basin, it may migrate north and south in response to short- and long-term climatic changes, which makes its examination more difficult. In the Scotia Sea region, ACC flow has always been confined by the constriction of Drake...
Passage and the western North Scotia Ridge, so that its variation is easier to examine.

7.3. Palaeocirculation and Scotia Sea evolution

Numerical models of palaeo-circulation have already considered the effects of developing a strong zonal circulation that affects bottom water production, by “opening Drake Passage” (e.g. Gill and Bryan, 1971; Mikolajewicz et al., 1993; Toggweiler and Samuels, 1995), but views differ of the effect upon meridional heat transport (thence global climate). Also, in taking these results into account we should perhaps bear in mind the numerical model grid, which at present is unavoidably coarse, unable to represent narrow topographic gaps, western boundary undercurrents or frontal streams within the ACC.

Given the nature of the present-day circulation (Fig. 7A) it is clear from Fig. 3A–F that the various deep pathways now occupied by both the ACC and WSD/BW have developed and evolved with time. It is convenient to address the lesser question first, of variations in the flow of SOBW. We see the persistence, over the past 40 Ma, of the extensional SAM–ANT boundary, and of an ancestor of the South Sandwich trench. Thus, for as long as there has been ice-related production of cold bottom water within the Weddell Sea (probably, for the past 34 Ma), there would have been something like a Weddell Gyre, with the SAM–ANT plate boundary influencing and possibly even defining its northern edge. Probably, with only short-offset transforms at that boundary before 20 Ma (Fig. 3C), and a much smaller Scotia Sea, the flow northward into the Atlantic would have been different. Without an ACC, it is possible that there would have been a smaller Weddell Sea reservoir, and a northward flow more closely related to production, less steady perhaps and at times more vigorous than today (Barker, 1992). Almost certainly, the most rapid northward flow would have travelled as a kind of western boundary current around a much broader Falkland Trough, between the Falkland Plateau and a shorter and more southerly North Scotia Ridge, on its way to the South Atlantic (Fig. 7B). Because of pack ice cover in the western Weddell Sea, and past subduction around the Scotia Sea, the location closest to the (southern Weddell Sea) source of SOBW where a sedimentary record of its evolution is preserved and accessible, is off the southeast corner of the Falkland Plateau, northwest of the present position of South Georgia (marked “X” in Fig. 7B).

The question of SOBW flow into the SE Pacific is uncertain. It seems likely that the South Scotia Ridge has become deeper (by thermal subsidence) and the number of gaps in it has increased, as it has become elongated with time and the active subduction zone has advanced eastward. Flow into the SE Pacific is therefore likely to have increased with time. Since even now it is small, it was probably never important (as leakage of the general Weddell Sea circulation). However, the possibility of a fortuitous but temporary arrangement of South Scotia Ridge components causing a short-lived but major leakage, that might have reduced flow into the South Atlantic, cannot be ruled out.

The major question concerns the development of deep pathways in the northern Scotia Sea, useful to the ACC. It is clear that, in the early stages of Scotia Sea development (Fig. 3F and E), the creation of a deep pathway was unlikely. Barker and Burrell (1977) argued that, following the onset of spreading in Drake Passage at about Anomaly 8 time (26.5 Ma: Fig. 3D), the ridges at the Shackleton Fracture Zone (SFZ) formed a barrier to deep water flow. The simplest assumption is that the ridges then had the same elevation above their surroundings as today, but would have been shallower because the entire area was shallower, being comparatively young. In support of the contention that these ridges existed at that time, Barker and Burrell (1977) cited the contrasting character of sedimentation on the northern and southern flanks of Drake Passage: thick, regular, well-bedded all the way down to ocean floor reaching Anomaly 8 age, in the lee of the southern SFZ ridge, compared with grossly uneven and obviously current-controlled throughout, overlying ocean floor of the same age in the north. If the long southern ridge had developed only after ACC onset, then a lower sediment sequence showing these unmistakable signs of ACC control would have been expected on the southern flank also. The ends of the SFZ ridges cleared at about 22 Ma. [Note that there is today a very narrow but deep gap at the southern end
of the southern SFZ ridge, that is used by the WSDW flow described by Nowlin and Zenk (1988). The sediments to the east show no sign of that gap having been present before 22 Ma, and it is possible that it developed only recently, as a result of Phoenix/Shetland/Scotia plate interaction after spreading ceased in Drake Passage. It is clear also from Fig. 3 that additional barriers to deep water flow existed in the early stages of Scotia Sea evolution: for example, the South Scotia Ridge would have prevented the flow through Powell Basin that was suggested by Lawver and Gahagan (1998).

Fig. 7B is a copy of Fig. 3C (Anomaly 6, 20 Ma) with possible current flow superimposed. It supports the contention of Barker and Burrell (1982) that, although the ends of the SFZ ridges had cleared, there may have been a barrier farther east as a result of a more compact arrangement of the North Scotia Ridge. In this reconstruction Aurora and Davis Banks overlap, and the deep gap now at 48°W does not exist. Farther to the east and south, the Central Scotia Sea has just begun to open, and the arc and remnant arc of the South Scotia Ridge (Jane Bank, Discovery Bank) form a much more compact elevation than now. It is conceivable that there could have been proto-ACC flow through this southern region, into the northern Weddell Sea, but if so it may have had to override (as now) any northward-leaking SOBW. The reconstructions to more recent times (Fig. 3B and A) show additional deep pathways for the ACC, with the creation of the gap in the North Scotia Ridge at 48°W by 16 Ma, and the development of an ocean floor gap east of South Georgia as the Central Scotia Sea opened, even before creation of the East Scotia Sea.

In considering the relevance of these developments, the nature of Aurora Bank and Davis Bank, along the North Scotia Ridge, assumes a particular importance. At present, as with all of the North Scotia Ridge, they comprise accretionary prism and “backstop”. However, the history of development of the accretionary prism and the nature of the backstop (shallow continental fragment or much deeper oceanic crust, possibly subduction-related volcano) are unknown. These are new uncertainties, more important in this context than the uncertainties in reconstruction already identified (coupling between adjacent spreading regimes and the age of small extensional basins in the southern Central Scotia Sea). Possibly, they may be addressed by marine geophysics, or by direct sampling.

An additional factor should be considered, that emerges from efforts over the years to develop useful numerical models of a wind-driven ACC. Early numerical models, having input a realistic wind stress, obtained transport estimates that were too high, and interaction with bottom topography was considered to be a major energy dissipation mechanism that could account for the difference. Of several numerical model schemes reviewed by Nowlin and Klinck (1986), all those touching on the question acknowledge the importance of shallow topography (see also Gille, 1997). It may therefore be significant that, in the past, the ocean floor topography of the Scotia Sea region would have been at least as rough as today’s, but shallower.

More specifically, (a) in the western “entrance” to Drake Passage (west of the SFZ) is an approximately north–south elevated zone down 66°W, an en echelon spreading centre that was abandoned 3–4 Ma ago. It was not described in Section 3, but most probably an active spreading centre lay directly west of the SFZ for the past 20 Ma at least. It cannot all be located precisely, but Fig. 7B shows an estimate of its location at 20 Ma, based on the surviving ocean floor record (Barker, 1982; Cande et al., 1982; Larter and Barker, 1991). While active, it would have been some 650 m shallower than today. Although more distant from Drake Passage than the ridge described below (b), it was fairly continuous across the current path, and may thus have been effective.

(b) In Drake Passage east of the SFZ now lies a spreading centre that was abandoned 6–9 Ma ago (Section 3.1. and (Figs. 2, 3C and 7B)). While active, its crest would have been some 900–1000 m shallower than at present, at least as rough and (Fig. 3A–C and particularly Fig. 7B) initially very much closer than today (or than (a) above) to the direct path of the ACC, along the northern part of the Scotia Sea towards the North Scotia Ridge.

The elevation and rough topography of these ridges (particularly the more easterly ridge, within the Scotia Sea) would have influenced early ACC transport, after a gap in the North Scotia Ridge had developed.
In summarising the relations between tectonic evolution and palaeocirculation, I conclude that, depending mainly on the nature of a part of the North Scotia Ridge, there may have been a delay in the creation of a deep-water pathway for exploitation by a wind-driven ACC, for a few Ma after the ends of the SFZ ridges had cleared, possibly until as late as 18 or 17 Ma. This is interesting, but the closest and most intuitive (also the most simplistic) connection between ACC development and palaeoclimate would link it to the deepening and stabilisation of Antarctic glaciation that only began at about 16 Ma. If this association is correct, then it is necessary to hypothesise an additional delay. The southward migration (with respect to the North Scotia Ridge) and slow subsidence of the spreading centre in the western Scotia Sea (Drake Passage), shown in Fig. 7B and described above, could have contributed to such a delay. However, the delay may have been in part non-tectonic—for example, either (for some reason) a tectonic pathway was not exploited immediately by the ACC, or a certain size or depth extent of ACC flow was necessary in order to disrupt meridional heat transport, or there was a delay between such disruption and the response of the ice sheet. Also of course, as already mentioned, changes in the concentrations of atmospheric greenhouse gases, or in other variables of tectonic or non-tectonic origin, may have been responsible for the mid-Miocene change in the level and stability of Antarctic glaciation, although recent estimates of atmospheric CO$_2$ (Pagani et al., 1999; Pearson and Palmer, 2000) show relatively low, invariant concentrations since the Oligocene.

It seems likely that direct sampling will be required, of the sedimentary record of palaeocirculation close to the principal tectonic causes of its variation, as an essential test of tectonic models and with the additional aim of determining any consequential climatic response.

8. Conclusions

This paper describes an exercise in understanding regional tectonic evolution since 40 Ma, that has involved a review and assessment of all the relevant information (present and past boundaries and movements of the major plates, Scotia Sea region crustal structure and age, Scotia Arc geology) and a series of reconstructions. The reconstructions provide information that contributes to a better understanding of past ocean circulation, and past and present mantle flow.

1. Data relevant to Scotia Arc evolution are sufficient to permit a series of six reconstructions that extend back to 40 Ma.

2. The reconstructions show that the Scotia Sea has developed by extension behind an east-migrating subduction zone ancestral to the present South Sandwich arc-trench system, driven by roll-back of the subduction hinge and affected by collisions of ridge crest sections of the SAM–ANT plate boundary with ancestors of the South Sandwich trench.

3. The reconstructions also show progressive closure of the Magallanes Basin, compatible with onshore geology, together with northward migration of the North Scotia Ridge, consequent subduction and formation of an accretionary prism. The reconstructed continental fragments form a continuous continental connection between southernmost South America and the Antarctic Peninsula at about 40 Ma.

4. The positions of the fragments at this connection are consistent with their known geology. They form a “fore-arc sandwich”, which is compatible with an origin for the east-migrating subduction (the driving force for Scotia Arc evolution) as a result of changes in major plate motion, involving southward migration of the pole of SAM–ANT motion through the past 150 Ma.

5. The reconstructions demonstrate persistent roll-back of the hinge of subduction, with respect to stable South America (average speed 50 mm/a) and almost certainly in absolute terms also, throughout the evolution of the Scotia Sea region. Back-arc extension exceeded major plate separation in the ratio 2.7:1 over the past 40 Ma, and the roll-back suggests the possibility of shallow eastward sub-lithospheric mantle flow. The reconstructions provide guidance as to how such flow might be detected by geochemical and seismological studies, and constrain their interpretation. Scotia Sea development (with respect to stable South America) has led to a difference in the likely history of such flow, between the northern and the southern parts of the Scotia Sea,
that should be borne in mind when locating recording stations and dredge sites.

(6) The reconstructions also suggest how deep-water pathways between Pacific and Atlantic might have developed within the period 22–17 Ma, that could have been used by an Antarctic Circumpolar Current (ACC). They point to uncertainties in structure and tectonic evolution of Davis Bank and Aurora Bank (parts of the North Scotia Ridge), that should be resolved in order to refine the timing of the creation of pathways. Ocean floor elevation and roughness in the Scotia Sea may have been important also. A strong link between tectonic evolution and ACC development is likely, but the changes in pathways suggested by regional tectonic evolution do not coincide in time with the major changes in regional or global climate that hypothetically would accompany ACC development. It may be necessary to consider additional, possibly non-tectonic causes of a delay in climate response.

Acknowledgements

This review has been written, after several years working mainly on other questions, partly as a useful way of getting back up to speed on the tectonic evolution of the Scotia Sea region and its consequences for mantle flow, palaeocirculation and palaeoclimate. Much remains to be done in this complicated region. I am grateful for constructive comments on the text from Andres Maldonado and an anonymous reviewer, and particularly pleased to acknowledge vigorous discussion with many friends and co-authors (not mutually exclusive categories) over the years, and continued financial support from the NERC.

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