Chapter 4
Tectonic reconstructions of the Southernmost Andes and the Scotia Sea during the opening of the Drake Passage

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Abstract Study of the tectonic development of the Scotia Sea region started with basic lithological and structural studies of outcrop geology in Tierra del Fuego and the Antarctic Peninsula. To 19th and early 20th century geologists, the results of these studies suggested the presence of a submerged orocline running around the margins of the Scotia Sea. Subsequent increases in detailed knowledge about the fragmentary outcrop geology from islands distributed around the margins of the Scotia Sea, and later their interpretation in light of the plate tectonic paradigm, led to large modifications in the hypothesis such that by the present day the concept of oroclinal bending in the region persists only in vestigial form. Of the early comparative lithostratigraphic work in the region, only the likenesses between Jurassic—Cretaceous basin floor and fill sequences in South Georgia and Tierra del Fuego are regarded as strong enough to be useful in plate kinematic reconstruction by permitting the interpretation of those regions' contiguity in mid-Mesozoic times. Marine and satellite geophysical data sets reveal features of the remaining, submerged, 98% of the Scotia

Sea region between the outcrops. These data enable a more detailed and quantitative approach to the region's plate kinematics. In contrast to long-used interpretations of the outcrop geology, these data do not prescribe the proximity of South Georgia to Tierra del Fuego in any past period. It is, however, possible to reinterpret the geology of those two regions in terms of the plate kinematic history that the seafloor has preserved.

Keywords Southernmost Andes - Scotia Sea - Scotia Ridge - Antarctica - Antarctic Peninsula - Drake Passage

1 Introduction

The Scotia Sea is the name given to the area of the Southern Ocean lying to the east of Drake Passage, the strait that separates Tierra del Fuego from the Antarctic Peninsula (Fig. 1). It is named after the ship *S.Y. Scotia* that brought W.S. Bruce's Scottish National Antarctic Expedition to the region in 1902-1904, but has been known to western scientists, including the young Charles Darwin, since the early 19th century. Since that time, Drake Passage and the Scotia Sea have been suggested to play important roles for processes as diverse as migration, colonisation and evolution of the land fauna of South America and Australia (e.g. Reguero and Marenssi 2010), evolution and migration of volcanic vent-specific fauna between the Pacific and Atlantic oceans (Roterman et al. 2013), whale and penguin evolution (Fordyce 2003; Hospitaleche et al. 2013), and the flow of asthenospheric rocks from beneath the Pacific plates to beneath those of the Atlantic (Helffrich et al. 2002; Müller 2008; Nerlich et al. 2013). Most famously, however, an open Drake Passage is frequently referred to as a necessary pre-requisite for, or even a driver of, the onset of the Antarctic

Circumpolar Current and the attendant permanent glaciation of Antarctica in Neogene times (Kennett 1977; Toggweiler and Bjornsson 2000).

All these processes are active and changeable on geological time-scales, making the question of the first completion of Drake Passage pertinent to understanding them better. The passage exists as a result of oblique separation of the South American and Antarctic plates, which in turn caused the local development and relative motion of a number of smaller, shorter-lived plates, whose remnants constitute the floor of the Scotia Sea and its margins. The main archives of the motions of these plates are the exposed rocks dotted around the Scotia Sea margins, and the patterns of fracture zones and magnetic reversal isochrons in the floor of the Scotia Sea itself. This chapter reviews what can be interpreted of the plate tectonic history of the region by using these resources.

2 Comparative Tectonostratigraphy

Similarities between the Southernmost Andes and the mountain ranges of the Antarctic Peninsula have been sought and presented since the early 19th century. Arctowski (1885) first proposed that the similarities are the result of oroclinal folding on a grand scale, and that the rocks of the Andes continue into the peninsula via Shag Rocks and South Georgia on the North Scotia Ridge, the South Sandwich islands, the South Orkney islands on the South Scotia Ridge, and the South Shetland islands. These rocks and islands are all remote and their emergent parts encompass less than 2% of the Scotia Sea (Fig. 1). Less still is accessible outcrop.

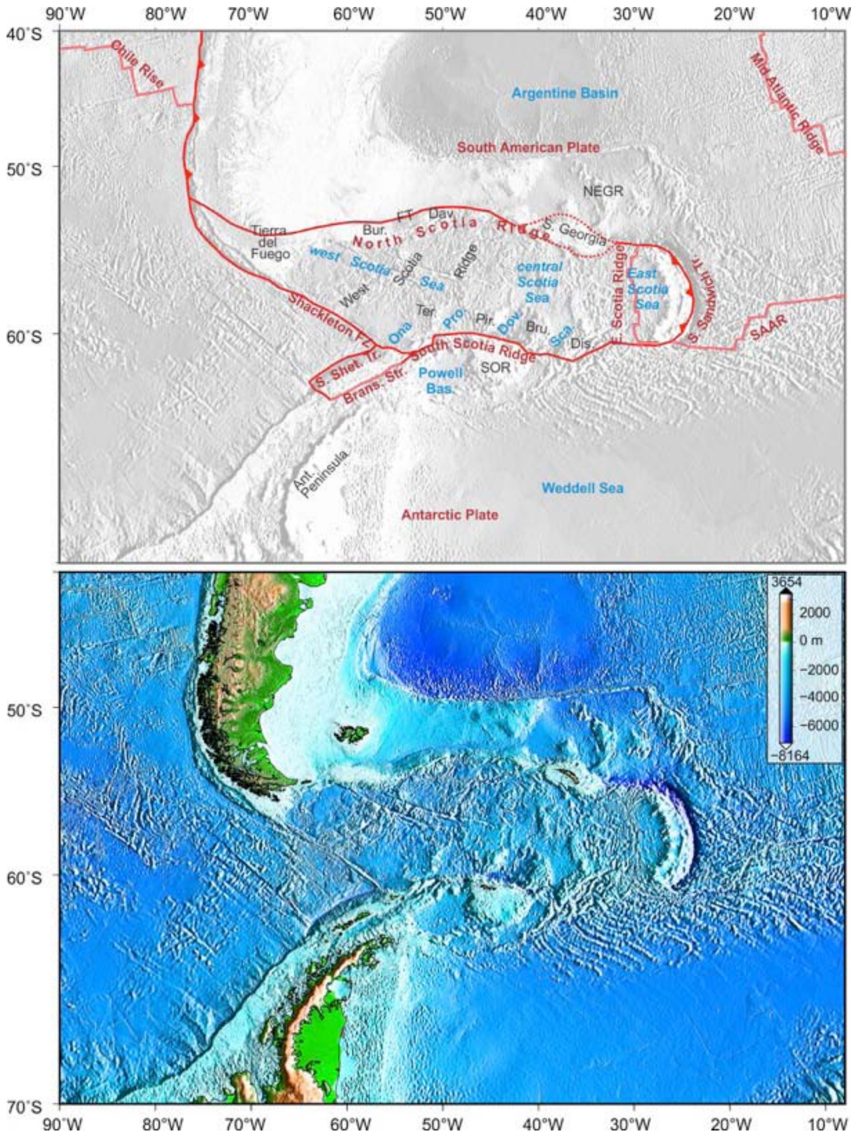

Fig. 1 Overview of the Scotia Sea region in bathymetric data (SRTM 15 PLUS; Becker et al. 2009). **Top** Red lines – present-day plate boundaries (modified from Bird 2003). Red labels: presently-active tectonic features. Blue labels: basins and basin regions. Black labels: extinct tectonic features and bathymetric highs. Brans. Str: Bransfield Strait; Bru: Bruce Bank; Bur: Burdwood Bank; Dav: Davis Bank; Dis: Discovery Bank; Dov: Dove Basin; FT: Falkland Trough; NEGR: Northeast Georgia Rise; Pir: Pirie Bank; Pro: Protector Basin; Sca: Scan Basin; SOR: South

Orkney Microcontinent; S. Sandwich Tr.: South Sandwich Trench; S. Shet. Tr.: South Shetland Trench; Ter: Terror Rise. **Bottom** color background image without references

The idea of a tremendous Scotian orocline remained popular through the first part of the 20th century as visits to these outcrops confirmed the presence of Mesozoic rock assemblages like those of the Southernmost Andes and Antarctic Peninsula (Pirie 1905; Suess 1909; Tilley 1935; Trendall 1953, 1959). The topic of oroclinal bending in the region has remained the subject of intense debate among structural geologists and paleomagnetists to this day (e.g. Cunningham 1993; Maffione et al. 2010, 2015; Maffione 2016).

By the second half of the twentieth century, the explanatory power of plate tectonics, along with improved sampling and dating techniques, brought the opportunity to assess details of the similarities of exposed rocks around the Scotia Sea's margins. The tectonostratigraphy of the Antarctic Peninsula and Tierra del Fuego came to be differentiated on the basis of differences in lithology, rock age and metamorphism. By then, close comparisons between the rocks of the South Orkney islands and those of South Georgia or the South Shetland islands were no longer supported by observations. Where correlations for the South Orkney islands are still suggested, these are with upper Paleozoic and lower Mesozoic rocks of the Antarctic Peninsula and the Southern Patagonian Andes north of Tierra del Fuego. These correlations are interpreted in terms of a shared history of subduction during that period, prompting suggestions of geographic proximity (Barron et al. 1978; Calderón et al. 2007, 2016; Hervé et al. 2003, 2005).

The most celebrated set of affinities in the region, however, are those between the Upper Jurassic and Lower Cretaceous rocks of Tierra del Fuego and South Georgia, which today occupy locations 1600 km apart at opposing ends of the boundary between the Scotia and South American plates (Fig. 1). These affinities are seen in the age and source of deposition of turbidites, and interpreted for the timing and setting of their deformation. The inset in Fig. 2 summarises the often-reported 'grain for grain' comparability of the Aptian-Albian Sandebugten and Cumberland Bay Formations of South Georgia to the Yahgán Formation of central Tierra del Fuego (Dalziel et al. 1975; Winn 1978). Both sequences consist of turbidites of andesitic debris overlain by more quartz-rich turbidites sourced by erosion of rhyolitic rocks to the north. Carter et al. (2014) presented U-Pb dating work on zircon grains that confirm how the three formations share similar Mesozoic sources. Furthermore, both turbiditic sequences are bounded to the south by ophiolitic complexes of Early Cretaceous age. The rocks are folded on similar wavelengths and the axes have similar orientations, which has been interpreted to indicate a common deformational setting at some period. This period has usually been put in mid-Cretaceous times, because various lines of evidence from the Yahgán rocks and elsewhere in Tierra del Fuego suggest that a protracted period of basin closure started in the period before 86 Ma (Klepeis et al. 2010). Less prescriptively, Rb-Sr analyses on minerals from a biotite schist (84 Ma; Curtis et al. 2010) and K-Ar whole-rock dating (135—51 Ma with best fits for 92—81 Ma; Thomson et al. 1982) record the timing of greenschist-facies metamorphism around the same time near the Cooper Bay shear zone in southeastern South Georgia. At other locations on the island, widespread prehnite occurrence and zircon- and apatite-based thermal histories show that granites were intruded at ~100 Ma, that the neighbouring Cumberland Bay and Sandebugten Formations were subsequently buried at shallow-to-moderate depths, and that rapid uplift occurred starting in Eocene times (Clayton, 1982; Carter et al. 2014).

These correlations are strong enough to support the notion of South Georgia having occupied a location immediately to the east of Isla Navarino and Tierra del Fuego in Early Cretaceous times (Dalziel et al. 1971). According to this idea, the Yahgán, Cumberland Bay and Sandebugten Formations were deposited at that time side-by-side in a basin floored by oceanic crust, the so-called Rocas Verdes Marginal Basin (Fig. 3) (see Calderón et al. 2016; González Guillot 2016). Later, both sets of rocks experienced orogenesis as the basin closed, which is usually attributed to an acceleration in the rate of seafloor spreading in the South Atlantic that increased the vigour of collision between the plates of the paleo-Pacific ocean and South America (Dalziel 1986; Curtis et al. 2010). Since significant lateral translation of South Georgia is required for South Georgia to have subsequently reached its present-day position on the North Scotia Ridge, the orocline concept had to be modified to accommodate the idea of its limbs' fragmentation (Dalziel et al. 1971; Fig. 2a-c).

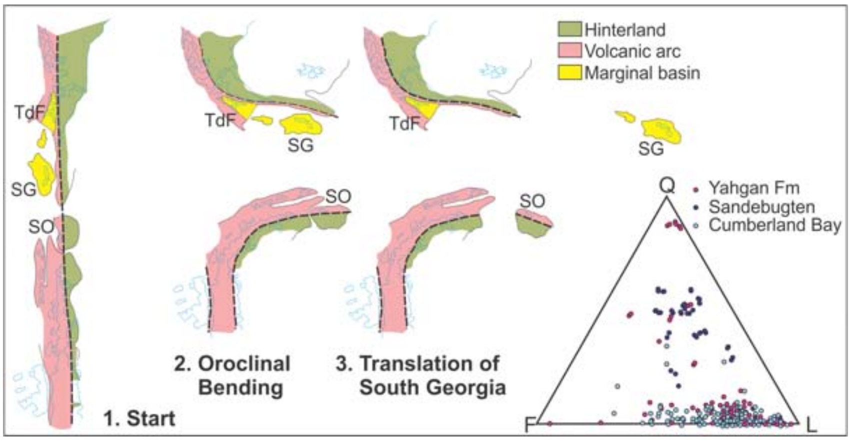

Fig. 2 Survival of the late-19th century orocline concept into the plate tectonic age and its modification by **a** segregation of the limbs into three elements related to subduction (volcanic arc, back-arc marginal basin, and hinterland) and **b** bend-

ing and **c** post-bending translation of continental fragments (South Georgia; SG) and the South Orkney microcontinent (SO) away from Tierra del Fuego (TdF) (redrawn from Dalziel et al. 1971). Bottom right: Quartz-feldspar-lithics plots demonstrate the comparability of sedimentary rocks on South Georgia (Cumberland Bay and Sandebugten Formations) to those of similar age on Tierra del Fuego (Yahgán Formation). From Dalziel et al. (1975) and Winn (1978)

Fig. 3 summarises the power of tectonostratigraphic correlations for regional reconstructions of the Scotia Sea. Available correlations can clearly support a wide range of such reconstructions. The similarities of South Georgia and Tierra del Fuego constitute essentially a single correlation point, permitting a wide angular range of possible locations for South America with respect to the Antarctic peninsula. Dalziel (1983) notes that, without additional information from plate kinematic studies of the basins forming the Scotia Sea floor, there would be little reason to prefer any of these possibilities over the others. The next section reviews studies of this kind and their results, which have been developed since the late 1960s.

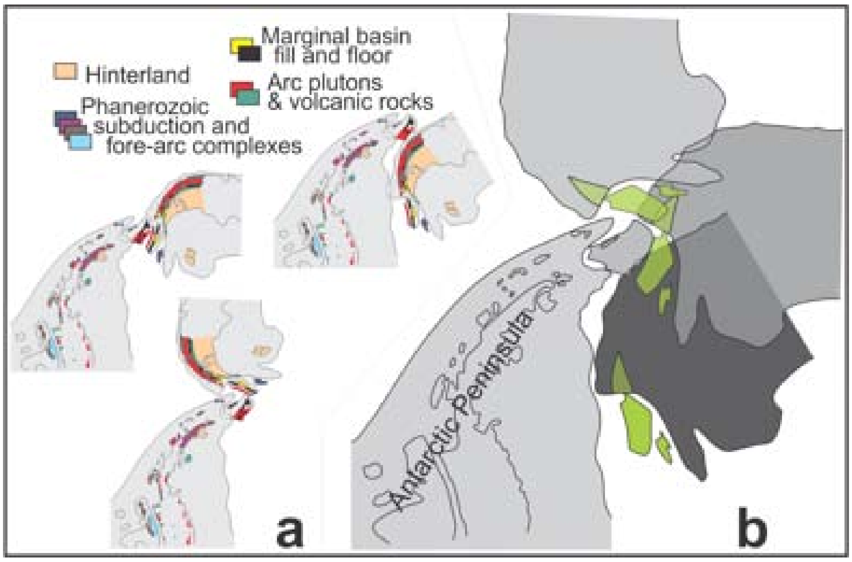

Fig. 3 a Three regional reconstructions that can be built on the basis of tectonostratigraphic correlations between outcrop geology in and around the Scotia Sea. Redrawn from Dalziel (1983). **b** Without other sources of constraint than the sedimentological similarities between the Cumberland Bay, Sandebugten and Yahgán Formations of South Georgia and the Rocas Verdes basin (green), the three reconstructions must be seen as equally likely, and thus of limited value for reconstructing the opening of the Scotia Sea

3 Basin Restoration

The recognition of magnetic anomaly isochrons over the seafloor in the Scotia Sea accompanied publication of the first magnetic reversal timescales in the late 1960s and early 1970s (Barker 1970; 1972). Using those timescales, a number of oceanic crustal provinces were identified on the basis of variable anomaly orientations and tentatively dated to periods over the last 40 Ma (Fig. 4). These provinces were identified as the products of episodes of plate divergence that had given rise to the creation of oceanic crust by volcanism. Taking advantage of the tenets of plate tectonics, that the interiors of plates are rigid and that deformation occurs only at the boundaries between pairs of plates, it is possible to reconstruct the development of the seafloor by reuniting the magnetic isochrons pairs. The newly-identified isochrons showed that the majority of the Scotia Sea floor had developed by east-west or ESE-WNW directed plate divergence episodes. Restoring the plate divergence that had led to their formation allowed for a compact cusp-like restoration of the basins' bounding blocks (Fig. 4b, c). The main exception to this pattern was an area in the central Scotia Sea that appeared to have opened by north-south directed divergence. This province made it conceivable to restore South Georgia via two phases of plate motion, one oriented north-south and one ESE-WNW, to a position close, but not directly adjacent, to the continental margin SE of Tierra del Fuego (Barker and Griffiths 1972). A variety of smaller continental blocks were depicted, from the margins of the closed basins, tightly packed into the spaces around and between South Georgia and Tierra del Fuego (Fig. 4b).

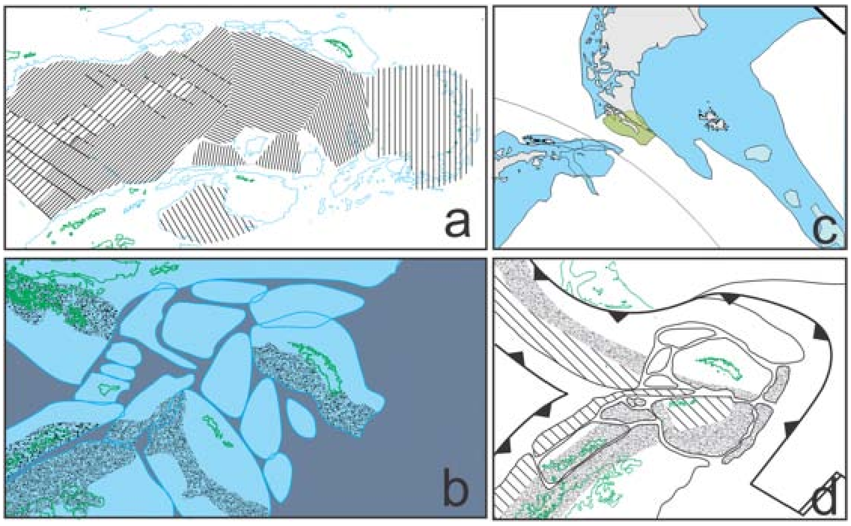

Fig. 4 a Magnetic anomaly provinces as interpreted from magnetic anomalies over the floor of the Scotia Sea by Barker (1970, 1972). The orientation of the hatching indicates the strike of the magnetic anomalies. Close hatching dated as 'post-Cretaceous' and wide hatching as <10 Myr old seafloor. **b** Plate kinematic reconstruction produced on a flat map by removing the oceanic crustal provinces between shallower, presumed continental, areas of crust. Stipple: areas of intense magnetic anomalies. Note that a close placement of South Georgia to Tierra del Fuego, as prescribed by sedimentological comparisons, is not a simple result of closing the oceanic basins of the Scotia Sea. **a** and **b** both redrawn from Barker and Griffiths (1972). **c** 50 Ma sphere-based plate reconstruction adapted from Lawver et al. (2003), with emphasis on fidelity to tectonostratigraphic comparisons between South Georgia (green) and Tierra del Fuego. Note that this reconstruction, despite its numerical precision, ignores much of the detail addressed by Barker and Griffiths (1972). **d** Flat-map reconstruction with all basins closed, generating a cuspate connection and placing South Georgia and Tierra del Fuego in closer proximity than **b**. Stipple: areas with strong magnetic anomalies. Hatching: areas with weak magnetic anomalies. Redrawn with modifications from King and Barker (1988)

Fig. 4 gives a feeling for the sources of complexity in reconstructing the numerous continental and arc blocks of the Scotia Sea to one another by the removal of intervening oceanic basins. This complexity became clear after much effort was invested in characterizing the floor of the Scotia Sea in detail both magnetically and bathymetrically (e.g. Barker and Burrell 1977; Hill and Barker 1980; Barker et al. 1982, 1984). Hence, whilst conclusions about the locations and opening directions of the individual basins in the Scotia Sea remained largely unchanged after the early 1970s, ideas about the number and the shapes of the continental blocks bounding the numerous individual basins evolved considerably. Knowledge about the basins thus enabled the relative locations of the blocks to be reconstructed with confidence, although the short lengths of paleo-plate boundaries that the basins represent, mean inevitably that the reconstructions could not be of particularly high resolution.

Seismic reflection profiles were also added to the regional data set during this second phase of marine geophysical discovery, allowing detailed interpretations of the Scotia Sea's active and fossil plate boundaries to be made (e.g. King and Barker 1988; Maldonado et al. 2003; Kavoun and Vinnikovskaya 1994; Coren et al. 1997). A lack of well-tie locations has consistently made these data difficult to use for correlating the basin's fills and therefore their stratigraphic age. Despite this, seismic data collection allowed for numerous refinements to Barker and Griffiths (1982) reconstruction (Fig. 4b) and its placement in a plausible geodynamic context dominated by back-arc extension behind a migrating west-directed subduction zone that is today expressed by the South Sandwich Trench (Fig. 1).

Until this point, Scotia Sea reconstructions had all been built like jigsaw-puzzles using paper and scissors, or simply sketched directly onto paper. Both of these methods fail to account for the distortions inherent in projecting features of a spherical surface onto a flat sheet of paper. Some of the first computer-based map-projected reconstructions of the region were presented by the PLATES group at the University of Texas (Lawver et al. 1992; Lawver and Gahagan 1998). Although the PLATES treatment at this time did not explicitly account for all of the basins and bounding blocks of the Scotia Sea floor, the South Georgia microcontinent was shown moving in ways consistent with ideas developed, using marine geophysical data, on the basis of Barker and Griffiths (1972) interpretation of plate motions in the west and central Scotia Sea.

By the mid 1990s, therefore, near-consensus had been reached that both the tectonostratigraphic and basin-restoration approaches advocate pre-Scotia reconstructions featuring a compact Andean cusp at ~40 Ma built around a close placement of South Georgia to Tierra del Fuego (Fig. 4d). Around this time, processing of satellite altimeter data to give an idea of sea surface slope, and with it free-air gravity over the oceans, greatly increased detail in knowledge about the shapes of the basin floors (Livermore et al. 1994). This data set paved the way for plate kinematic reconstruction techniques whose aims were to minimize and quantify uncertainties in basin restorations, and allow their full integration into map-projected plate kinematic reconstructions (Eagles 2000, 2004; Eagles et al. 2005). Using the results of these techniques to build reconstructions of gridded data sets allowed for new constraints, implicit in the rules of plate tectonics, to play a role in reconstructing the Scotia Sea. The most important of these constraints are those that concern plate rigidity and plate boundary continuity. The most relevant consequence was the recognition that the central Scotia Sea was unlikely to house both halves of a Cenozoic-aged basin. Multiple lines of evidence instead suggested that the basin formed during Cretaceous north-south directed plate divergence (Eagles 2000, 2010b; Dalziel et al. 2013a). This, in turn, removed the principal supporting interpretation of the mid-90s consensus, as it implied South Georgia could not have reached its present location by a combination of ESE-WNW plate divergence in the southern Scotia Sea and north-south directed divergence in the central Scotia Sea.

By today, therefore the largest remaining controversy in reconstruction of the Scotia Sea concerns whether or not the tectonostratigraphic correlations between South Georgia and Tierra del Fuego should continue to prescribe their geographical contiguity for any time in the past. The PLATES group continues to generate reconstructions that assume it should (e.g. Dalziel et al. 2013b), whilst acknowledging the lack of evidence for eastwards translation of South Georgia that is required of doing so. In contrast to this, the following pages present a plate tectonic history of the Scotia Sea in reverse stratigraphic order from 6 Ma until 50 Ma that has been derived with stricter adherence to the seafloor tectonic record. In detail, it is based on the plate kinematic model of Eagles and Jokat (2014) and illustrated by a set of reconstructions of Sandwell et al's (2014) gravity anomaly grid. A later section will reconsider the strength of testimony from South Georgia's tectonostratigraphy in the context of some pre-50 Ma reconstructions of the region.

4 Development of the Scotia Sea

6 Ma

The Scotia Sea has probably existed in its current plate tectonic form since around 6 Ma, when the mid-ocean ridge in the western part of the Scotia Sea ceased to operate. The two plates that had been diverging on its northwestern and southeastern flanks amalgamated to form the modern Scotia Plate (Fig. 5). This instituted a long and complex transcurrent plate boundary between the Scotia and South American plates along the North

Scotia Ridge, and a similarly-long and complex transcurrent plate boundary along the South Scotia Ridge that separates the Scotia and Antarctic plates. The South Scotia Ridge is characterised by a handful of deep basins that seem to form at releasing bends on the plate boundary (Galindo-Zaldívar et al. 1996). At the eastern end of the Scotia Plate, a divergent plate boundary is working by seafloor spreading to generate the oceanic floor of a small back-arc basin called the East Scotia Sea (Fig. 1). The eastern half of the basin is floored by the small Sandwich plate, whose eastern margin is a convergent margin at which part of the South American plate is being subducted towards the west beneath the Scotia Sea (Figs. 1 and 5). At the western end of the Scotia Sea, a SE-trending segment of the Scotia Plate's margin runs along the Shackleton fracture zone, separating it from the small oceanic Phoenix plate. At the Shackleton fracture zone, part of this plate has experienced flexural uplift owing to a very slight component of plate convergence at its margin with the plates in the west Scotia Sea (Livermore et al. 2004). Other parts of the Phoenix Plate at this time are undergoing subduction at a short segment of its margin, in the southeast, which sees it thrust beneath the Antarctic plate at the South Shetland islands. The opposing segments of the Phoenix Plate's margin, also shared with the Antarctic plate, are divergent and experiencing seafloor spreading. This unusually-simple plate kinematic setting has seen the Phoenix plate used as a laboratory for studying plate driving forces. These studies have repeatedly shown that slab pull seems to have played an important role in its motion with respect to the Antarctic plate (Larter and Barker 1991; Eagles 2004; Eagles and Scott 2014).

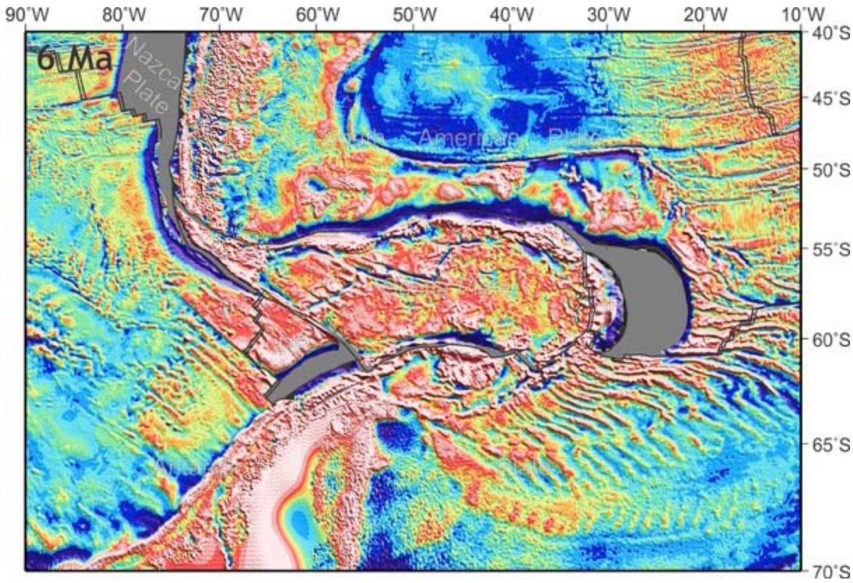

Fig. 5 Reconstruction of gridded free-air gravity anomalies (Sandwell et al. 2014) at 6 Ma, using rotations from Eagles and Jokat (2014). ESR: East Scotia Ridge; SFZ: Shackleton fracture zone.

10 Ma

The reconstruction in Fig. 6 illustrates the situation shortly before the extinction of the West Scotia Ridge, when the floor of the West Scotia Sea was subdivided into sections carried on the Magallanes and Central Scotia Plates (Fig. 6) (Eagles et al. (2005). A small 15 km underlap suggests that slow sinistral transpression has been accommodated along the North Scotia Ridge since the time of this reconstruction. The spreading rate on the West Scotia Ridge is quite slow (~10 km/Myr half rate) at this time (Eagles et al. 2005). This is reflected in the rough seafloor fabric close the flanks of the present-day extinct ridge (Fig. 1). Dalziel et al. (2013a) and Pearce et al. (2014) relate intraplate volcanism in the Central Scotia Plate to low-angle subduction of part of the Northeast Georgia Rise large igneous province beneath the Scotia Sea. This subduction occurs at the South

Sandwich Trench, the eastern boundary of a young and small Sandwich plate (Fig. 6).

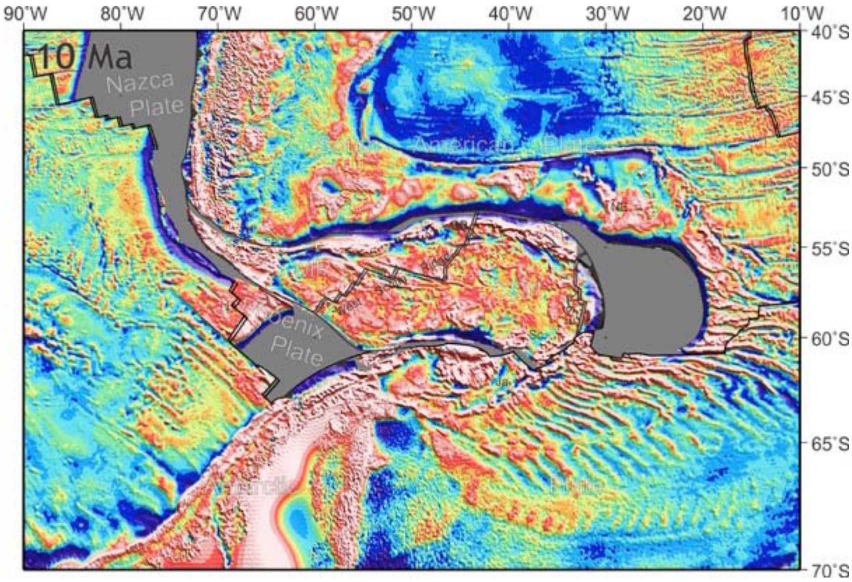

Fig. 6 Reconstruction of gridded free-air gravity anomalies (Sandwell et al. 2014) at 10 Ma, using rotations from Eagles and Jokat (2014). BB: Aurora (Barker) Bank; CSP: Central Scotia Plate; MP: Magallanes Plate; Sc.: Scan Basin, Ja.: Jane Basin; NE: NE Georgia Rise

17 Ma

The 17 Ma period (Fig. 7) marks two important aspects of the evolution of the West Scotia Sea, which developed shortly before it reached almost its full volume. The first is the onset of a period of slow spreading rates. The second is that the West Scotia Ridge has propagated northwards to reach the Barker/Aurora Bank, reaching its full length. Eagles and Jokat (2014) estimated that this occurred close to 18.5 Ma, based on magnetic anomalies crossing the bank, which may therefore consist largely of sediments resting on oceanic crust. The subsequent plate divergence at this latitude led to development of a gap in the North Scotia Ridge that today allows deep water of the Antarctic Circumpolar Current to cross out of the Scotia Sea and into the South Atlantic. Tectonically, the rest of the North Scotia Ridge acts in much the same way as in the 10 Ma reconstruction. A narrow underlap depicted across the South Scotia Ridge is consistent with interpretations of light transpressional strain made from seismic reflection profiles across it (Galindo-Zaldívar et al. 1996; Kavoun and Vinnikovskaya 1994; Lodolo et al. 2010).

A very small Sandwich Plate is shown in the East Scotia Sea, based on Vanneste and Larter (2002) interpretation of isochron 5C on the western flank of the East Scotia Ridge. Those authors suggested that the absence of a conjugate 5C on the Sandwich Plate is a consequence of subduction erosion – mechanical removal of crustal material from the leading edge of the overriding plate and its delivery into the mantle by the subducting plate. This earliest Sandwich Plate is shown with a longer north-south extent than at later times, which Eagles and Jokat (2014) attributed to opening of the Scan and Jane basins behind a longer ancestral trench. Barker et al. (1982, 1984) show how this trench may have deactivated as segments of the South American-Antarctic Ridge in the Weddell Sea collided with it in Miocene times. Eagles et al. (2005) noted that the initiation of this young Sandwich Plate meant that a lesser proportion of the eastwards migration of the trench would need to be accommodated at the West Scotia Ridge, consistent with its deceleration at this time.

The description of Scotia Sea tectonics at 17 Ma given above can be challenged based on alternative interpretations of basin ages given in the literature. These interpretations concern the Protector, Scan and Jane Basins and the central Scotia Sea. Lawver et al. (2001) suggested, on the basis of heat flow determinations from sediment temperature gradients, that Jane Basin may have opened far earlier than shown here, in the period

32—25 Ma. This would allow for the basin to have played an important role in early deep water circulation through Drake Passage. Although the interpretation requires the basin fill to be dominated by clay, which could be considered unusual for a back-arc basin, its adoption in Fig. 7 would not strongly alter the overall plate kinematic scenario depicted.

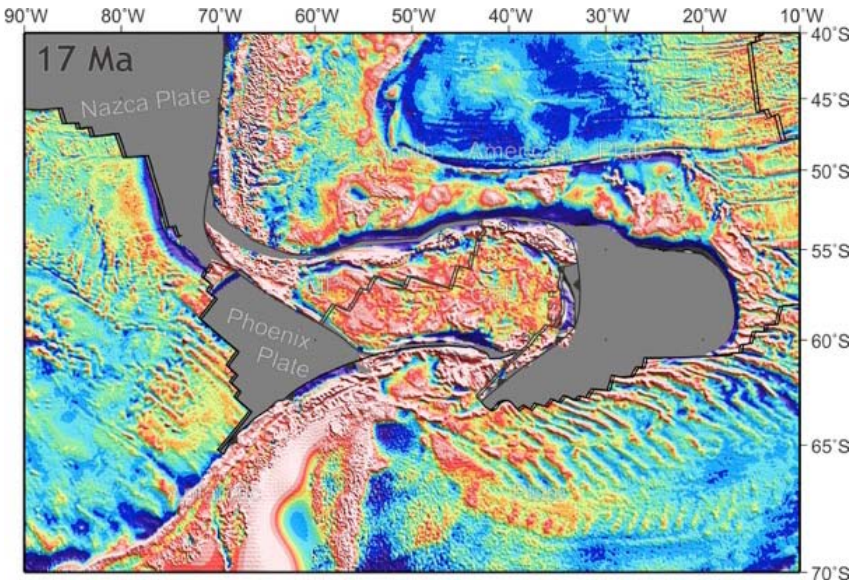

Fig. 7 Reconstruction of gridded free-air gravity anomalies (Sandwell et al. 2014) at 17 Ma, using rotations from Eagles and Jokat (2014). Da: Davis Bank; SG: South Georgia; SR: Shag Rocks

This is not the case for Protector Basin and the central Scotia Sea, both of which Fig. 7 shows as open and passive at 17 Ma. Hill and Barker (1980) suggested in contrast that both Protector Basin and the central Scotia Sea were opening by seafloor spreading at 17 Ma. Maldonado et al. (2003) and Galindo-Zaldívar et al. (2006) have reproduced the magnetic anomaly models that these young interpretations are based on, and depicted them in kinematic sketches. Fig. 8 portrays what these interpretations would mean for plate boundaries within the Scotia Sea at 17 Ma. The thick black lines depict those parts of the plate boundaries that have been identified and suggested as active at 17 Ma. The dashed red lines depict additional tectonic features that would be required to maintain a closed circuit of plate boundaries around rigid plates within the Scotia Sea. Dashed black lines depict the magnetic bights that would be expected at the junction of the spreading centres in the central and east Scotia Seas. Evidence for these extinct plate boundaries and magnetic bight has not yet been found.

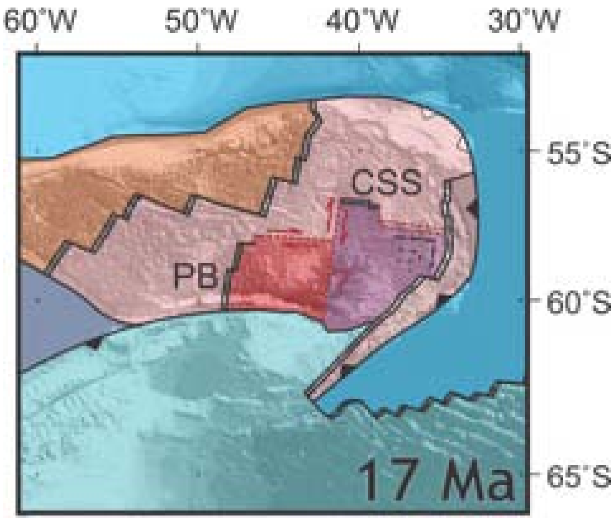

Fig 8 Unsubstantiated plate tectonic complexity of a Scotia Sea with active mid-ocean ridges in the central Scotia Sea (CSS) and Protector Basin (PB) at 17 Ma. Red shading: plates within the Scotia Sea. Blue shading: plates in the surrounding circuits. Red and black dashed lines: implied plate boundary segments and magnetic bights for which no evidence is known. Background shows the 17 Ma bathymetric reconstruction of Eagles and Jokat (2014)

20 Ma

Fig. 9 illustrates the tectonics of the Scotia Sea at 20 Ma. In contrast to the situation at 17 Ma, the back-arc basin in the eastern part of the Scotia Sea has yet to form and, concomitantly, the West Scotia Ridge is spreading more rapidly. The West Scotia Ridge is also shorter; its northern end lies somewhere east of Davis Bank. Just north of this, the reconstruction underlap on continental crust at the North Scotia Ridge is broader than that shown for 17 Ma. This implies ~75 km of shortening on the Scotia—South America plate boundary in the intervening period. Eagles and Jokat (2014) showed that the magnitude of this shortening is smaller than the uncertainties involved in constructing the plate circuit that depicts it. The occurrence of this convergence, however, is more confidently implied by the presence of a seemingly young accretionary prism at the southern edges of Burdwood and Davis banks, and of Miocene transpression in Tierra del Fuego and along northern Burdwood Bank (Bry et al. 2004; Cunningham et al. 1995; Klepeis and Austin, 1997; Kraemer 2003). The South Scotia Ridge, in contrast, is depicted much as in the later reconstructions, implying its history since Miocene times has been one of very slow sinistral transpression. As such, this reconstruction shows a period very early in the evolution of the Scotia Sea with northern and southern boundaries similar to today's.

Further in the west, Fig. 7 shows the possibility that a segment of the Phoenix–Nazca plate boundary was subducted beneath Cape Horn. Ongoing divergence of the surface portions of the two plates would have seen a space open within the mantle between their subducted parts. Breitsprecher and Thorkelsen (2009) and Eagles et al. (2009) have suggested that decompression melting of mantle rocks rising through this so-called slab window produced melts that are represented by minor occurrences of alkali basalts in Tierra del Fuego (Puig et al. 1984). Eagles and Jokat (2014) suggested that the loss of this ridge in subduction may have presented a new barrier to the dispersal of vent-specific Kiwaid crabs, whose Pacific and Atlantic lineages are reckoned to have diverged in the period 25.9–13.4 Ma (Roterman et al. 2013).

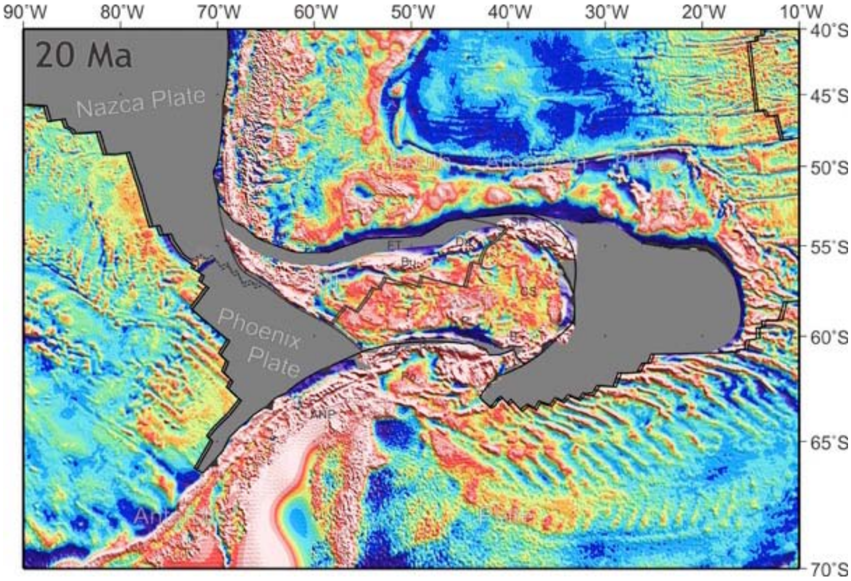

Fig. 9 Reconstruction of gridded free-air gravity anomalies (Sandwell et al. 2014) at 20 Ma, using rotations from Eagles and Jokat (2014). ANP: Antarctic Peninsula; B: Bruce Bank; Bu.: Burdwood Bank; CS: Central Scotia Sea; FT: Falkland Trough; P: Pirie Bank; Po.: Powell Basin; SSR: South Scotia Ridge; T: Terror Rise

As in the 17 Ma reconstruction, there are alternative interpretations of some of the smaller basins in the Scotia Sea that could alter the picture of plate tectonics in the Scotia Sea at 20 Ma. As well as the central Scotia Sea, whose interpretation as a Miocene back arc basin (Hill and Barker 1980) would affect the 20 Ma reconstruction in much the same way as the 17 Ma reconstruction, there is also the suggestion that the Scan and Dove basins may have been active at 20 Ma (Galindo-Zaldívar et al. 2014). Fig.

10 shows the implication of these ages for the plate tectonic setting in the Scotia Sea at 20 Ma. The red dashed lines show plate boundaries for which good evidence is missing. Most conspicuous among these is a mid-ocean ridge in Scan Basin. The sketch shows one of the best-known puzzles concerning Hill and Barker's (1980) back-arc interpretation for the central Scotia Sea: why should a back-arc basin behind an east-migrating trench have opened by north-south extension?

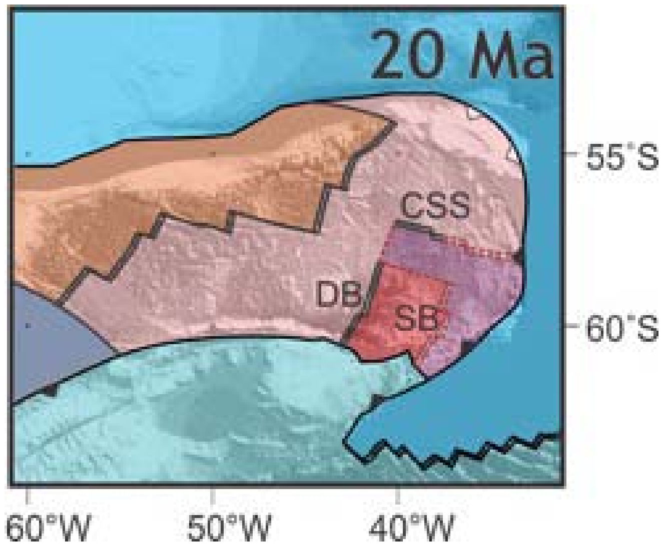

Fig. 10 Unsubstantiated plate tectonic complexity of a Scotia Sea with active mid-ocean ridges in the central Scotia Sea (CSS), Dove Basin (DB), and Scan Basin (SB) at 20 Ma. Red shading: plates within the Scotia Sea. Blue shading: plates in the surrounding circuits. Red and black dashed lines: implied plate boundary segments and magnetic bights for which no evidence is known. Background shows the 17 Ma bathymetric reconstruction of Eagles and Jokat (2014)

26 Ma

26 Ma was part of a transitional period in the development of the Scotia Sea (Fig. 11). Although seafloor spreading was underway on the young West Scotia Ridge, its flanking magnetic isochrons suggested it had yet to

propagate any further north than the eastern margin of Burdwood Bank. Dredging work has returned evidence for volcanism near what was the northern end of the ridge at 29 Ma (Dalziel et al. 2013a; Pearce et al. 2014). Dalziel et al. (2013a) suggest that this volcanism was related to subduction of South American lithosphere beneath the Scotia Sea, on the basis of the geochemical signature of the dredged rocks. Eagles and Jokat (2014) noted that this would require a very shallow angle (10–20°) slab, based on the distance to the trench in the reconstruction. They suggested alternatively that the source of the dredged rocks may be immature lower crust re-melted by the addition of mantle melts during extension related to the northward propagation of the West Scotia Ridge, noting the analogy to the region's older Chon Aike large igneous province (Pankhurst and Rapela 1995).

Regardless of its role in this melting, it seems that the divergent Magallanes—Central Scotia plate boundary reached far enough north that parts of the North Scotia Ridge could have adopted a role as the northern margin of the Scotia Sea, acting as it did later as two separate plate boundaries between the South American plate and the Magallanes and Central Scotia plates. The reconstruction underlap on the Magallanes-South America segment implies continuous slow convergence in the period 26—20 Ma, albeit below the statistical resolution of the plate circuit Eagles and Jokat (2014) built. Further south, in contrast to later times, the southern margin of the Scotia Sea did not run along the South Scotia Ridge but instead through a small oceanic basin off the northern end of the Antarctic Peninsula; Powell Basin. There is a consensus that seafloor spreading in Powell Basin was an Oligocene and earliest Miocene process (King and Barker 1988; Lawver et al. 1994; Coren et al. 1997; Eagles and Livermore 2002). The southern boundary's location may have switched in response to early Miocene collision of segments of the South American–Antarctic Ridge with the eastern convergent plate boundary of the South Orkney Microcontinent, beyond Powell Basin's eastern flank (Barker 1995; Barker et al. 1982, 1984; Hamilton 1989). The approach and eventual collision of the ridge may have reduced subduction-related driving forces that contributed to the basin's opening.

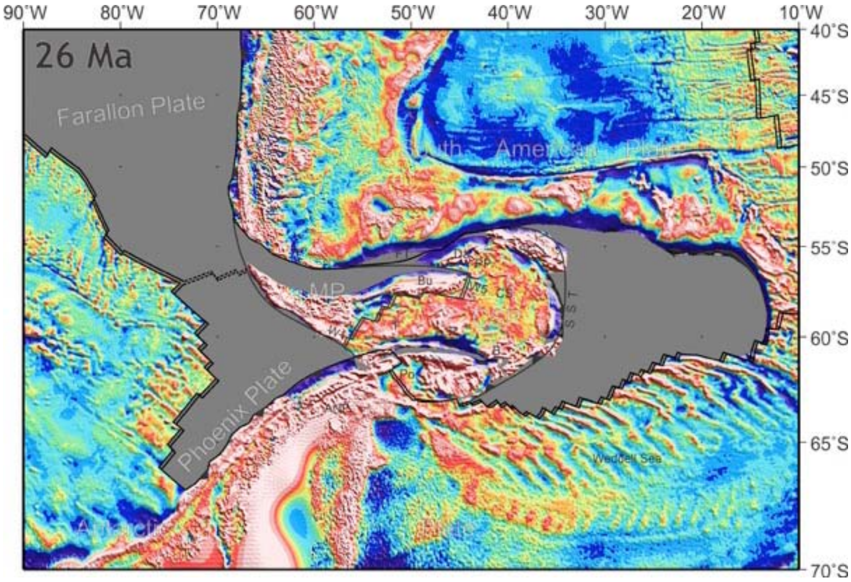

Fig. 11 Reconstruction of gridded free-air gravity anomalies (Sandwell et al. 2014) at 26 Ma, using rotations from Eagles and Jokat (2014). PP: magmatic Pirie Province of Dalziel et al. (2013); SST: South Sandwich Trench; W1, W5: numbered spreading corridors of the west Scotia Sea (Eagles et al. 2005)

30 Ma

30 Ma (Fig. 12) marks what has been presented as an important epoch in the development of the Scotia Sea. This period has returned the oldest interpretable evidence for active subduction of South American lithosphere beneath the central Scotia Sea, in the form of calc-alkaline volcanic rocks dredged from a rotated fault block in the modern fore-arc (Barker, 1995;

Livermore et al. 1994). Eagles and Jokat (2014) suggested this could be interpreted to mean that the South Sandwich Trench had, for the first time, reached as far north as South Georgia, where it bent into an east-west orientation to take up the very earliest transcurrent plate motions on the eastern North Scotia Ridge. The reconstruction shows no back-arc basin immediately behind the trench at this time, although suggestions that Scan Basin may date from around this time, based on heat flow values modelled from sediment temperature gradient data (Barker et al. 2013), could be interpreted as such a feature. Further west, the reconstruction shows the young West Scotia Ridge reaching only as far north as Isla de los Estados, where its motion is taken up on an oblique transform fault running NW into Tierra del Fuego. Here, this transform meets the east-trending transform fault that runs through or near South Georgia to the trench. Together with the young divergent plate boundary in Powell Basin, these plate boundaries enabled Eagles and Jokat (2014) to interpret this period as the one in which the central Scotia Sea first came to be encircled by plate boundaries, setting in place the core of the modern Scotia Plate.

The shape of the reconstruction misfit occupied by this plate boundary in Tierra del Fuego is largely unchanged in the 26 Ma reconstruction, suggesting at least the possibility that there were periods of no relative movement between the Magallanes and South American plates during the early development of the Scotia Sea.

The West Scotia Ridge in this reconstruction is the very oldest that Eagles and Jokat (2014) show. Following Livermore et al. (2005), they noted that a tight fit between the eastern and western margins of the west Scotia Sea (at Terror Rise and Tierra del Fuego) dated to this time when using a spreading rate before chron 8 that was the same as immediately afterwards. They further noted that this is the same time that Eagles et al.

(2006) determined for the end of seafloor spreading in Protector Basin on the opposing side of Terror Rise, suggesting simple abandonment of one mid-ocean ridge had occurred in favour of another.

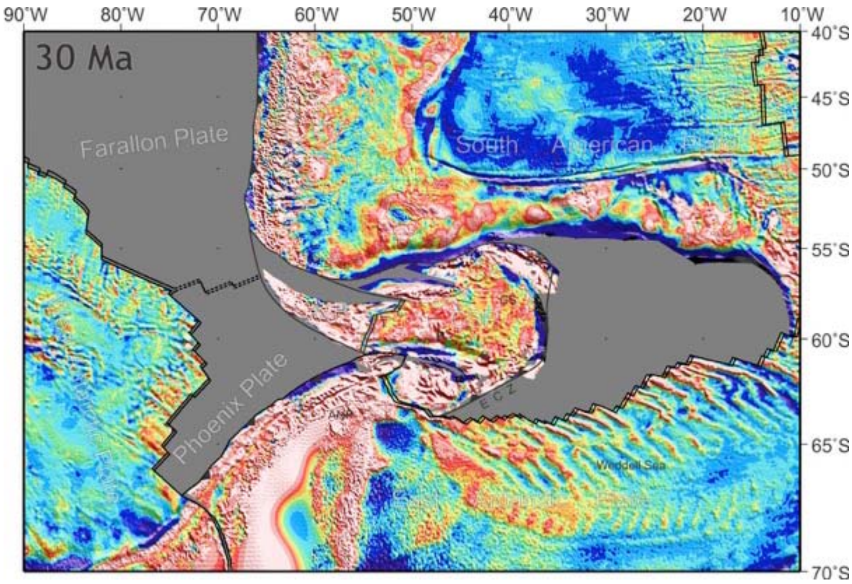

Fig. 12 Reconstruction of gridded free-air gravity anomalies (Sandwell et al. 2014) at 30 Ma, using rotations from Eagles and Jokat (2014). ECZ: Endurance Collision Zone (Ghidella et al. 2002)

Direct evidence for this earliest phase of spreading on the West Scotia Ridge is difficult to interpret, however, and is the subject of moderate controversy because the time frame lies very close to the end-Eocene build up of ice on Antarctica, which has been linked to the onset of the Antarctic Circumpolar Current, which in turn has been suggested as a simple consequence the opening of the Drake Passage (Kennett 1977; DeConto and Pollard 2003). Fig. 13 summarises this evidence, which comes from magnetic anomaly profiles crossing the southernmost corridors of seafloor spreading in the West Scotia Sea, directly adjacent to the Shackleton fracture zone.

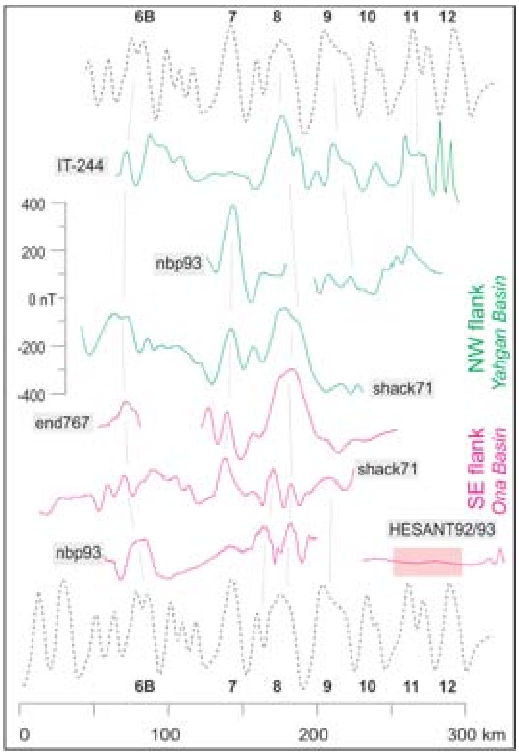

Fig. 13 Magnetic anomaly wiggles in the southwesternmost spreading corridors of the west Scotia Sea. Old end of profiles towards the right. Green lines show profiles from the NW flank, pink lines the SE flank. Dashed profiles are synthetic magnetic anomalies generated for a source layer 1 km thick lying at 4.5 km depth, labelled with chron number. Pink box shows the portion of the HESANT92/93 profiles in which reversal isochrons 11 and 12 were modelled at very small amplitudes by Maldonado et al. (2014)

The profiles, three for each flank in these corridors, show that anomaly isochrons younger than and including 8 are interpretable in many locations, although by no means are they ubiquitously so. Three of the profiles supply hints that isochron 9 may be present in these corridors. Beyond this, two profiles confined to the northwestern half of the corridors have been interpreted to reveal isochrons 10 and 11 (Lodolo et al. 2006), although it should be noted that the waveforms are far from coherent between them. Chron 12 has recently been interpreted from the southeastern flank in magnetic profiles crossing the Ona Basin, close to the continental shelf north of Elephant Island (Maldonado et al. 2014). Plotted at the same scale as the profiles in which the younger magnetic isochrons were identified, it is clear however that this interpretation requires an oceanic crust with an order of magnitude smaller magnetic susceptibility than anywhere else in the west Scotia Sea. It seems then that the oldest likely oceanic crust preserved in the west Scotia Sea dates from chron 11 (~30 Ma; Gradstein et al. 2012), as in the reconstruction. Whether this crust was developed on an organised linear mid-ocean ridge, as depicted, or in a more transitional setting like that described as 'chaotic seafloor spreading' by Barker and Burrell (1977), remains unclear with current data.

33 Ma

All of the Oligocene or younger reconstructions shown so far have featured one or more plate boundary segments along the North Scotia Ridge. The 33 Ma reconstruction in Fig. 14 represents a step further back towards an embryonic Scotia Sea by being the youngest to lack such a plate boundary. At this time, the reconstruction shows the young South Sandwich Trench reaching only as far north as Discovery Bank, although dating of available samples only confirm the bank as a site of subduction-related volcanism as far back as 20-12 Ma (Barker et al. 1982).

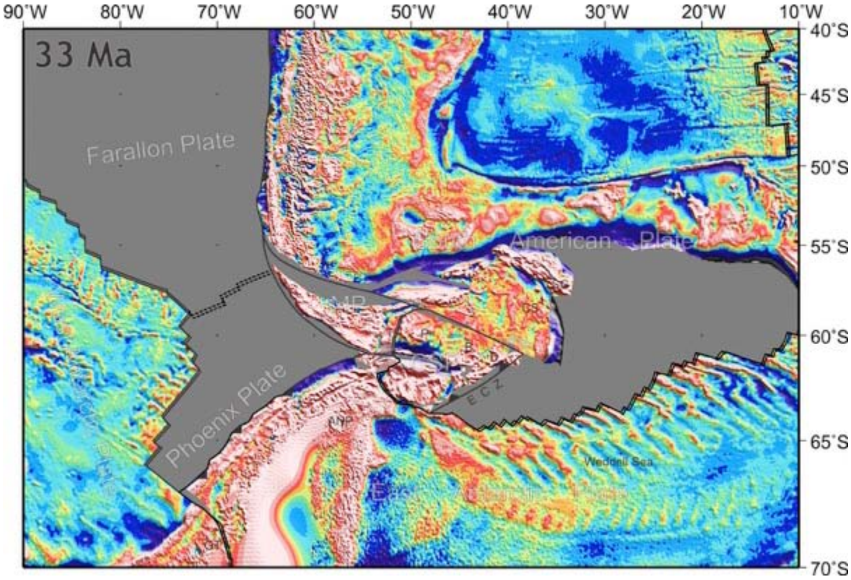

Fig. 14 Reconstruction of gridded free-air gravity anomalies (Sandwell et al. 2014) at 33 Ma, using rotations from Eagles and Jokat (2014). D: Discovery Bank

At the northern edge of Discovery Bank, the reconstruction shows the paleo-subduction zone bending abruptly into an east-west orientation much like its present-day manifestation does to run along the North Scotia Ridge near South Georgia. Both of these features are examples of so-called tear faults (Fig. 15). Eagles and Jokat (2014) termed the 33 Ma tear fault the Burdwood transform fault. Other than the gravity lineations along the northern edges of Bruce and Pirie banks, and the southern edge of Burdwood Bank, there is little direct evidence for the remnants this fault, although it should be noted that the area is buried by thick sediments (Perez et al. 2014) and the plate circuit, as constructed, suggests the cross-axial component of these movements may have been slight. The 30.2 Ma basement heat flow estimate at the northern edge of Scan Basin might be interpreted, instead of in terms of basin age, as the time of cessation of the fault's movement. This aside, there is stronger evidence for other plate boundaries further south in the form of the continental extensional basins bordering Powell Basin (King and Barker, 1988) and the short mid-ocean ridge in Protector Basin (Eagles et al. 2006). The reconstruction shows these boundaries, along with the Burdwood transform fault, as defining the body of an independently-moving small overriding arc plate at the ancestral South Sandwich Trench.

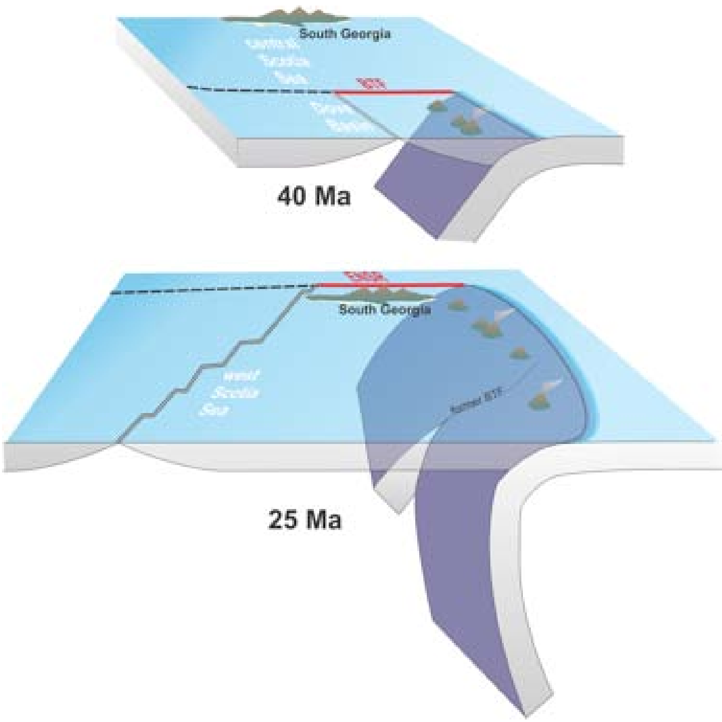

Fig. 15 successive locations of tear faults in the Scotia Sea following northwards propagation of the ancestral South Sandwich Trench. BTF: Burdwood tear fault; ENSR: eastern North Scotia Ridge

With the Burdwood transform fault running along part of its southern edge, the central Scotia Sea and South Georgia are shown as features embedded within the body of the South American Plate. To the west, the length of plate boundary running through continental South America is much shorter than in all the younger reconstructions; it is confined to Tierra del Fuego where a smaller underlap than in the next-younger (30 Ma) reconstruction can be interpreted in terms of a phase of plate divergence. As for Eagles and Jokat (2014) reconstructions at all other times, the amount of divergence shown on this particular boundary is unlikely to be greater than the uncertainties in the various elements of the plate circuit might combine to show, whereas the evidence for continental extension in the Sloggett Basin of southeastern Tierra del Fuego (Ghiglione et al. 2008), is not.

41 Ma

The general configuration at 41 Ma (Fig. 16) is in most aspects a shortened version of that at 33 Ma, suggesting a simple evolution from one to the other by ongoing action of the plate boundaries. The only large difference is in the location of the western, divergent boundary of the arc plate, whose northern reaches pass along a mid-ocean ridge in Dove Basin, rather than Protector Basin. The Burdwood transform fault is somewhat shorter because the Protector Basin was yet to open. These configurations for Protector and Dove Basin allow the Scotia Sea to be depicted as a relatively simple system of two plates behind the ancestral South Sandwich Trench at any time between 42 and 30 Ma. One of these plates is the overriding plate at the trench, and probably featured a volcanic arc at its eastern edge. The plate behind the arc plate bears Tierra del Fuego and moves only slowly, if at all, with respect to the South American plate. As before, the resolution of the plate circuit is too coarse to be able to define this motion as statistically relevant, but interpretations of active shortening in Tierra del Fuego in middle Eocene times seem to confirm that convergence did occur (Ghiglione and Ramos 2005; Gombosi et al. 2009; see Ghiglione 2016 for a review).

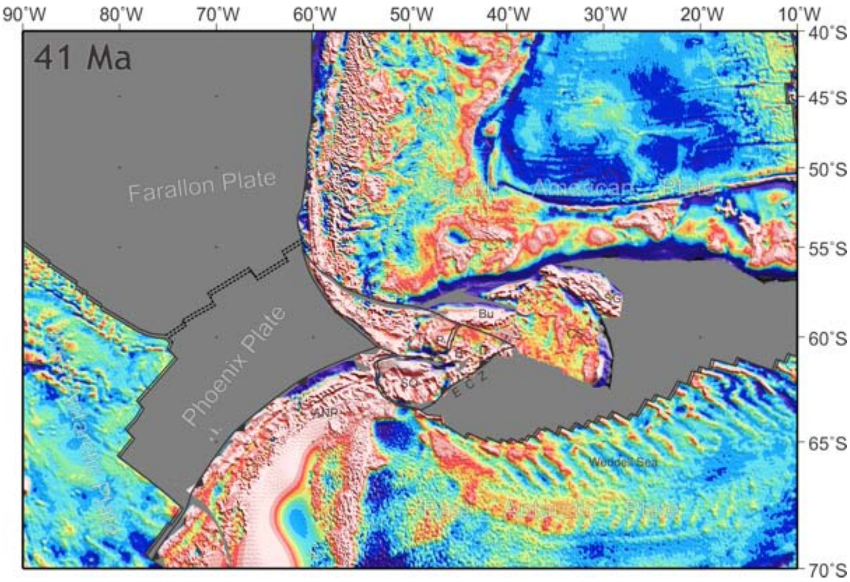

Fig. 16 Reconstruction of gridded free-air gravity anomalies (Sandwell et al. 2014) at 41 Ma, using rotations from Eagles and Jokat (2014). SO: South Orkney Microcontinent.

Eagles and Jokat (2014) calculated that the arc plate was moving rather more slowly with respect to Antarctica than with respect to South America in this period, and noted that this slow motion did not give rise to oceanic growth, but rather to continental extension, as expressed in the eruption of alkali basalts and the formation of grabens around and across the South Orkney Microcontinent (Barber et al. 1991; King and Barker 1988).

50 Ma

The onset of independent motions of small plates in the Scotia Sea began with continental crustal extension over the South Orkney Microcontinent and of Pirie and Bruce banks, which gave way eventually to seafloor spreading in the Powell and Dove basins. Fig. 17 shows the region before any of these motions had started, at around 50 Ma but neither it, nor that in Eagles and Jokat (2014), attempts to undo any of the continental extension. Eagles and Livermore's (2002) reconstruction of Powell Basin gives an idea of how such a reconstruction might appear around the South Scotia Ridge. Beyond this, the reconstruction can be directly compared to the tectonostratigraphic and flat-map reconstructions of Figs. 3 and 4. The clearest difference between them is in the area south of Burdwood Bank, where Pirie and Bruce banks and Terror Rise lie as a result of reconstructing the growth of the west Scotia Sea, Protector and Dove basins. The dredged stratigraphy and magnetic anomalies of these blocks match comfortably those of Tierra del Fuego (Eagles et al. 2006; Schenke and Udintsev 2009; Udintsev et al. 2012). South Georgia, on the other hand, lies south of Maurice Ewing Bank at the eastern end of the Falkland Plateau, a few hundred kilometres west of its current location. As the previous reconstructions have shown, there is no preserved evidence anywhere in the seafloor of the Scotia Sea for its translation from a location further west, in spite of the widely-reported tectonostratigraphic arguments for such.

Ghiglione et al. (2008) detail observations in geophysical and outcrop data for South American–Antarctic early Eocene plate divergence in Tierra del Fuego further north, which Livermore et al. (2005) had modelled as being slow, north-south directed, and coming to an end soon after 50 Ma. Prior to this, the eastern margin of Omond Land, the continental mass formed of contiguous South Orkney Microcontinent, Terror Rise, Pirie, Bruce and Discovery banks, had evolved from a transform fault into a continent–ocean collision zone as the azimuth of South American—Antarctic plate motions rotated from NE-SW to NW-SE in Maastrichtian through Paleogene times (Barker et al. 1991; Eagles 2010b). It was this so-called Endurance collision zone (Ghidella et al. 2002) that evolved to become the ancestral South Sandwich subduction zone, which slowly propagated northwards and migrated eastwards, as seen from Antarctica, throughout Cenozoic times. The 50 Ma reconstruction shows the tear fault, the Burdwood transform fault, at the northern end of this collision zone. At this time, the fault's shortness and orientation allow it to act as a simple transcurrent fault between the South American and Antarctic plates. In this way, relative motions of the Endurance collision zone/South Sandwich Trench, and the South American and Antarctic plates at 50 Ma are accommodated by plate boundary-scale processes on a single fault. As previous sections have shown, the subsequent plate tectonic history of the Scotia Sea can be seen as the history of this fault's lengthening and elaboration to accommodate changes in those relative motions by plate-scale processes instead.

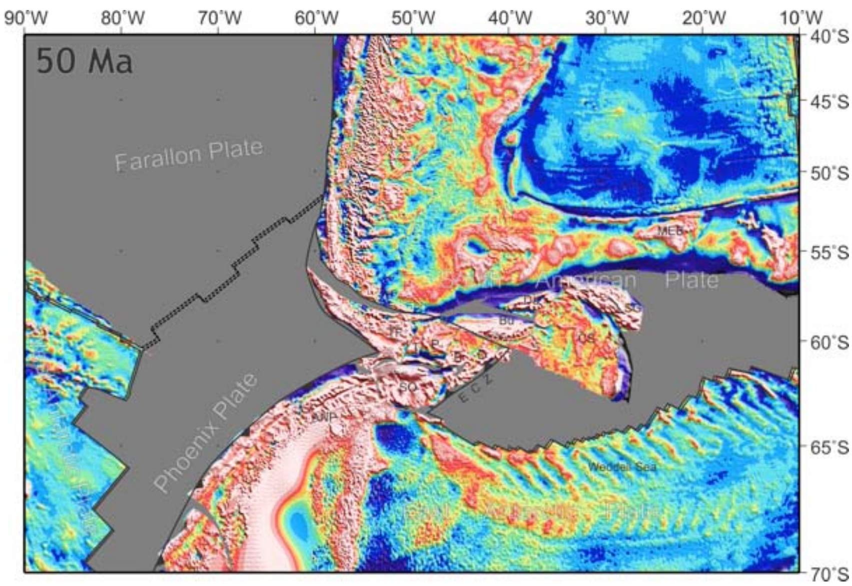

Fig. 17 Reconstruction of gridded free-air gravity anomalies (Sandwell et al. 2014) at 6 Ma, using rotations from Eagles and Jokat (2014). MEB: Maurice Ewing Bank; TF: Tierra del Fuego

5 Pre-Scotia Sea times

Unlike the reconstructions shown so far, Sandwell et al.'s (2014) gravity data for the 125 Ma reconstruction in Fig. 18 have been filtered to remove long wavelengths, probably related to very large-scale convection-related structures in the mantle, so that the remaining anomaly field matches across the mid-ocean ridge in the South Atlantic. This eases visualisation of the tectonic fabric, which tends to occur on shorter wavelengths. The reconstruction is developed by rotating the 50 Ma configuration of the Scotia Sea as if it had been embedded within the South American plate in the period 125—50 Ma. Doing this requires the assumption that the Burdwood transform fault had been newly inaugurated at 50 Ma, and that at earlier times the South American-Antarctic plate boundary lay further south, in the Weddell Sea, as suggested by magnetic seafloor spreading anomalies there (Livermore and Woollett 1993; Livermore and Hunter 1996; Livermore et al. 2005). The reconstruction shows a pair of extended continental margins that formed in the divergence of west and east Gondwana, and areas of Mesozoic oceanic crust that accreted to them in the central Scotia Sea (Eagles 2010a) and Weddell Sea (Livermore and Hunter 1996).

Further west, the reconstruction shows Graham Land and other parts of the Antarctic Peninsula as if they had been embedded within the South American plate for a period ending at 103 Ma, the time of the Palmer Land Event, a Cretaceous collisional episode interpreted from sparse outcrop data in southern parts of the peninsula (Vaughan et al. 2012). At face value, the reconstruction overlap highlighted by semi-transparent fill is incompatible with this interpretation, but it might be explained by some combination of post-Cretaceous extension of the South Orkney Microcontinent and crustal growth at the convergent margin by arc production. Despite this, the placement should still be viewed as speculative; not only does it rely on disputed tectonostratigraphic correlations between the South Orkney islands and rocks further north in the Patagonian Andes, but also the very occurrence of a Palmer Land Event has recently been called into question (Burton-Johnson and Riley 2015).

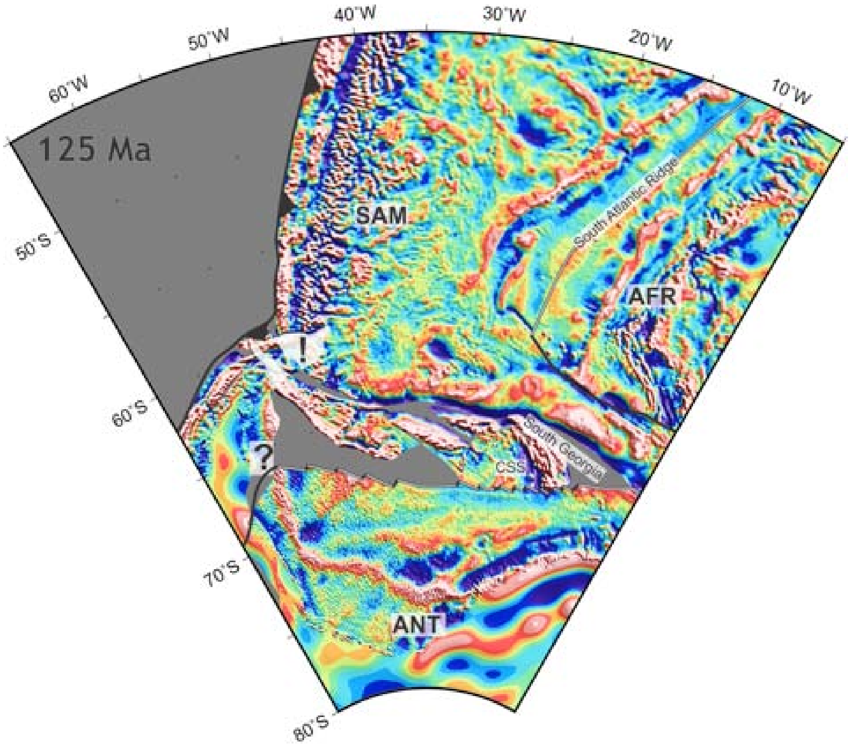

Fig. 18 125 Ma reconstruction. AFR: African plate; ANT: Antarctic plate; SAM: South American plate. ?: Precursor plate boundary to Palmer Land Shear Zone of Vaughan et al.(2012); "!": overlap between South Orkney Microcontinent and convergent margin of Gondwana. CSS: central Scotia Sea

Fig. 18 also shows where, at 125 Ma, the Yahgán, Cumberland Bay and Sandebugten Formations would have been deposited at widely separated sites in Tierra del Fuego and South Georgia. By this, it is evident that the plate kinematic history given so far fails to reconcile with the long-suspected geographic proximity of South Georgia and Tierra del Fuego in Aptian-Albian times. Faced with this, Eagles (2010b) attempted to reinterpret the similarities between South Georgia and Tierra del Fuego in terms of an Early Cretaceous plate boundary configuration from which the 125 Ma setting shown above might have evolved. His scheme presented South Georgia as part of the South American conjugate to the extended continental margin in the southern Weddell Sea. He suggested that breakup-related volcanism at this margin was distinguished geochemically because of its occurrence in lithosphere that had previously experienced an unusual combination of processes including metasomatism during flat-slab subduction and the arrival of a mantle plume (Pankhurst and Rapela 1995; Pankhurst et al. 2000). The Chon Aike large igneous province represents this volcanism in outcrop and subcrop at sites spread throughout Patagonia and the Antarctic Peninsula (Pankhurst et al. 2000). This volcanic province probably extends from the Deseado Massif in Patagonia offshore towards the Rio Chico high, and from there to the North Scotia Ridge and Falkland Plateau (Baristeas et al. 2013). It occurs in association with sites of crustal extension, and is characterized by bimodal andesitic—rhyolitic volcanism; as reflected in the petrographic detrital composition of Yahgán, Cumberland Bay and Sandebugten Formations. Detrital zircon U-Pb ages from Sandebugten Formation of South Georgia Island includes a strong 171 Ma peak (Carter et al. 2014) corresponding to the V2 Jurassic volcanic stage of the Chon Aike province where it crops out in the Deseado Massif (Pankhurst et al. 2000).

Fig. 19 summarises this new tectonostratigraphic interpretation and compares it to that of Dalziel et al. (1971). Both have been annotated with proposed locations for the sources of the South Georgia´s sequences. Neither scenario requires any of the Cumberland Bay or Sandebugten Formations' sediments to have been sourced from the Falkland Islands, despite Carter et al.'s (2014) attempt to distinguish between them on the basis of the absence of Proterozoic 'Gondwanan interior' zircons from South Georgia. If anything, it is the active margin location that is more difficult to reconcile with this absence, given the paleocurrent directions shown. Seen in this context, the sedimentological similarities between the Yahgán, Cumberland Bay, and Sandebugten Formations need not be prescriptive of geographical proximity.

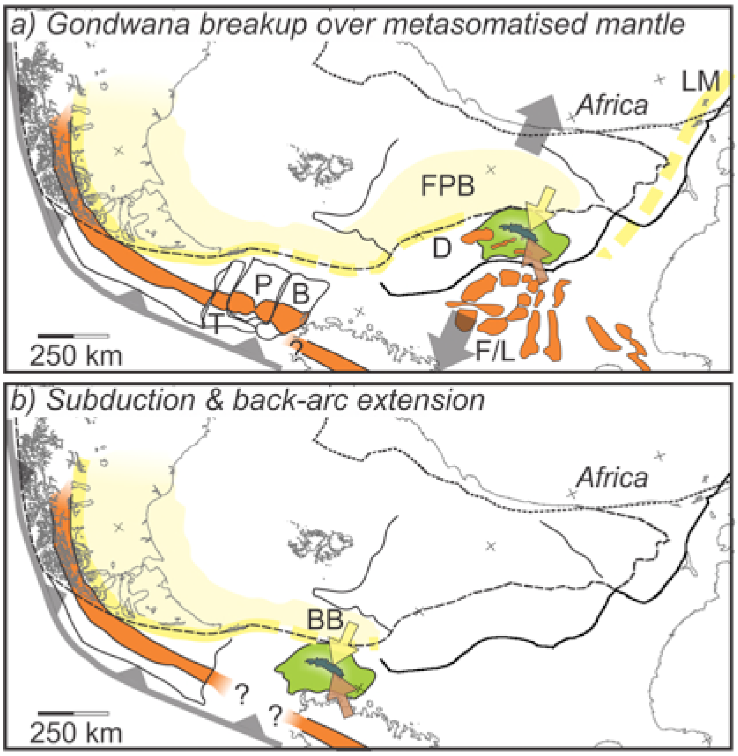

Fig. 19 Alternative contexts for deposition of the Yahgán, Cumberland Bay and Sandebugten Formations. The basemap, redrawn from Dalziel et al. (1975), depicts a time early in the Cretaceous. Bright yellow lines: outcrop or suspected outcrop (dashed) of silicic volcanic rocks of the Chon Aike large igneous province. Orange: interpreted locations of andesitic volcanic rocks. BB: Burdwood Bank; TPB: 'batholith' magnetic anomalies of Terror Rise, Pirie Bank, and Bruce Bank. D: Davis Bank dredge sample (Pandey et al. 2010); LM: Lebombo monocline rhyolites; F/L: Filchner and 'Lozenge' magnetic anomalies of Ferris et al. (2000); FPB: Falkland Plateau Basin. Yellow and orange arrows: paleocurrent directions determined for later deposition of Sandebugten and Cumberland Bay formation rocks. Grey arrows: orientation of Gondwana breakup-related plate divergence

The other claimed strong correlation between South Georgia and Tierra del Fuego is in the timing of tectonism that occurred to close the Rocas Verdes and 'Cumberland Bay' basins. In both locations, this event is dated to 86-84 Ma, or beforehand. This requires a plate boundary location for both basins at that time. Fig. 20 shows a reconstruction for 84 Ma that enables interpretation of the locations of plate boundaries in the region. This reconstruction is well constrained because of the ease of identifying magnetic reversal isochron 34y; statistical reconstructions for this isochron using three pairs of plates or three plates simultaneously have repeatedly demonstrated that a fourth plate did not exist in the Weddell Sea at this time (Nankivell, 1996; Eagles and Vaughan, 2009). There are no indications from structural geology or paleomagnetic work that the Antarctic Peninsula at this time was anything other than fixed with respect to the interior of Antarctica, just as it is today (Vaughan et al. 2012; Grunow 1993). The plate boundaries shown are thus necessary and sufficient for all current plate kinematic and paleomagnetic constraints. Within these constraints of these boundaries, the N-S trending path sketched through the Rocas Verdes Basin can explain the basin's shortening along a segment of the Antarctic-South American plate boundary. The main faults and folds of South Georgia, in contrast, suggest a plate boundary segment oriented

ESE. This orientation could not have acted in a convergent sense in either of the locations suggested for South Georgia.The evidence for Rb-Sr system closure in South Georgia's schists, and the K-Ar dating of its biotites' growth, are therefore very difficult to relate to Andean orogenesis at ~84 Ma without invoking extra plates whose motion would be otherwise unattested. An alternative setting, consistent with the thermal history presented by Carter et al. (2014) and with the location of the highest metamorphic grades in the closest proximity to the exposed basement and oceanic complexes in the SE of the island, may simply be deep burial of sediments in a basin situated on a young, warm, continental margin.

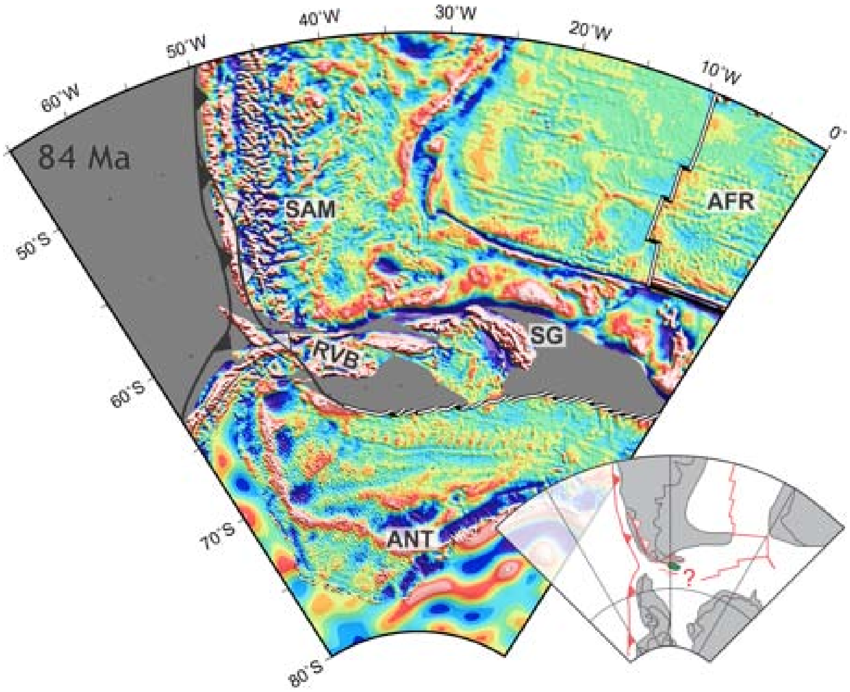

Fig. 20 The South Atlantic at 84 Ma, around the time of inversion of the Rocas Verdes Basin (RVB) and of the 'Cumberland Bay' basin in South Georgia (SG). At this time, the region was evolving by divergence of three large plates, South America (SAM), Africa (AFR) and Antarctica (ANT) beneath which plates of the

paleo-Pacific margin were subducting from the west. The Antarctic Peninsula was not moving with respect to the interior of Antarctica. Neither of the locations implied by reconstruction of the seafloor in the Scotia Sea (shown) or by comparitive tectonostratigraphy places South Georgia near the Pacific margin, or indeed any plate margin, that might be invoked to explain the deformation proposed from dating of Rb-Sr closure in biotite and titanite minerals at this time. Inset: non-closure (?) of plate boundaries with 'Rocas Verdes' location of South Georgia, redrawn and adapted from Curtis et al. (2010)

6 Summary

This chapter has revisited and summarised nearly 200 years of thinking on the tectonic history of the Scotia Sea region, which started from basic and fragmentary information on outcrop geology in Tierra del Fuego and the Antarctic Peninsula. The first century and a half of this work was dominated by increasing knowledge and understanding of the intervening outcrops, dotted amongst islands around the periphery of the Scotia Sea. By the time of the plate tectonic revolution, much was known in detail about contrasts and correlations between these outcrops, and little of the early conviction that an orocline of uniform Andean composition snaked continuously around the Scotia Sea could be sustained. Only a set of strong likenesses between the Jurassic oceanic basement rocks, and Aptian-Albian basin fills of South Georgia and Tierra del Fuego, and interpretations of their shared experience of orogenesis later in the Cretaceous remained. Since the second half of the twentieth century, new data sets offering new chances to consider the Scotia Sea's growth became available from marine and satellite geophysical techniques that revealed the bathymetric, gravimetric and magnetic structure of the 98% of the Scotia Sea that had previously lain hidden beneath the sea surface between its islands. Until now, these data have proved impossible to interpret in any way that enables the likenesses between the late Jurassic and Cretaceous rocks of South Georgia and Tierra del Fuego to be explained in terms of their contiguity at any time in the past. An alternative tectonostratigraphy that is consistent with the plate kinematic history interpretable from the seafloor has been suggested, and is beginning to be tested. This task is of importance in more than just its own right, because it stands in the foreground of a set of interdisciplinary studies that all stand to benefit from a more precise and confident understanding of the tectonic and bathymetric development of the Scotia Sea.

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