# The Tectonic Evolution of the Scotia Sea Region from the Cretaceous until today 1

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# The Tectonic Evolution of the Scotia Sea Region from the Cretaceous until today

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**Key Points:**

- New tectonic reconstruction based on qualitative comparison endmember reconstructions
- The Central Scotia Sea consists of fragments Cretaceous and Cenozoic oceanic crust
- A shallow gateway at Drake Passage potentially existed already during the Eocene

**Abstract**

The interplay between regional tectonics and the development of a major ocean gateway between the Pacific and the Atlantic Ocean has resulted in numerous paleogeographic reconstruction studies that describe the Cenozoic tectonic history of the Scotia Sea region. Despite the multitude of published tectonic reconstructions and the variety of geological and geophysical data available from the Scotia Sea, the geological history remains ambiguous. We present a comparative paleogeographic analysis of previously published tectonic reconstructions to identify agreements and conflicts between these reconstructions and we propose an alternative model to explain the Cenozoic evolution of the Scotia Sea region. The paleogeographic comparison shows that most reconstructions agree on the tectonic evolution of the South Scotia Ridge and the East Scotia Ridge. Major differences between the reconstructions are the role of the westward subducting plate below the South American Plate, and the age and origin of the Central Scotia Sea (CSS). Tectonic reconstructions assume that the CSS is either a part of a Cenozoic back-arc basin, or a captured piece of Cretaceous oceanic crust. We propose a new alternative tectonic reconstruction that brings these two prevailing hypotheses elegantly together. In our model, we identified new geographical units consisting of thinned continental or Cretaceous oceanic fragments that originate from the Paleo Pacific – Weddell Sea gateway from high-resolution bathymetry. These fragments are now part of the CSS and have been affected by early back-arc tectonic activity of the South Sandwich subduction zone, leading locally to the formation of Cenozoic-aged crust in the CSS.

## 1. Introduction

The Eocene-Oligocene global cooling event occurred as a response to a decrease in atmospheric carbon dioxide ($CO_2$) levels (Anagnostou et al., 2016; Pearson et al., 2009) and the onset of the Antarctic Circumpolar Current (ACC, Sauermilch et al., 2021). The effect of both mechanisms on the Eocene-Oligocene cooling event have been investigated thoroughly, with a dramatic cooling of the surface waters recorded once the AAC formed deep-water currents (>300 m), demonstrating that tectonic changes, which allowed the ACC to form, are of major importance for the Eocene-Oligocene cooling event (Sauermilch et al., 2021). These tectonic changes involved the complex continental break-up of Southern Gondwanaland during the Cenozoic, which led to the complete separation of the Antarctic continent and marked the onset of the oceanic water current encircling Antarctica (ACC, Barker et al., 2007; Eagles et al., 2006; Eagles and Jokat, 2014; Scher et al., 2015). The tectonic opening of both the Tasman Seaway, between the South Tasman Rise south of Tasmania and Antarctica, and Drake Passage (Fig. 1), between South America (SAM) and Antarctica (ANT), allowed the ACC to develop. The timing of the opening of the Tasman Seaway is quite well constrained at around 32 Ma (Lawver & Gahagan, 2003), based on seafloor magnetic anomalies and foraminifera in IODP drill cores (Bijl et al., 2013). This is unlike the opening of Drake Passage and the formation of the Scotia Sea, for which the exact timing remains hotly debated, mostly because of the region’s complex tectonic evolution (Barker, 2001; Lawver & Gahagan, 2003; Livermore et al., 2007) and its remote location, which resulted in scattered and incomplete datasets. Nevertheless, various authors have suggested that the opening of Drake Passage played a key-role in the onset of the ACC (Dalziel et al., 2013b; Kennett et al., 1977; Livermore et al., 2007; Whitworth, 1983).

The tectonic evolution of the Scotia region has been investigated in various studies over the past decades (Barker, 1972; Barker, 2001; Dalziel, 1983; Dalziel et al., 2013, 2021; Eagles, 2000; Eagles et al., 2006; Eagles & Jokat, 2014; Lagemaat et al., 2021; Livermore et al., 2007; Maldonado et al., 2014; Nerlich et al., 2013; Pérez et al., 2016; Pérez et al., 2017; Pérez et al., 2019; Schellart et al., 2023; Vérard et al., 2012; De Wit, 1977). These studies do not provide a unanimous view on the tectonic evolution of the Scotia region, and consequently, they dedicate a different origin and evolution to the major structures in this area, i.e. the South Sandwich subduction zone, the adjacent crustal fragments, Drake Passage and the Central Scotia Sea (CSS, Fig. 1). The most striking differences between publications are the age and origin of the CSS. At first the CSS was thought to be a back-arc basin that opened during the Cenozoic (Barker, 1970). Several years later, De Wit (1977) proposed that the CSS originated from a Cretaceous back-arc basin. Later still, Livermore et al. (1994) suggested that the CSS could have been the oldest piece of crust found in the Scotia arc, that might pre-date the opening of Drake Passage. This idea (Livermore et al., 1994) was adopted by

(Eagles, 2010b) and reworked into a plate tectonic reconstruction (Eagles & Jokat, 2014). Both end-members, the Cenozoic back-arc basin and the captured piece of Cretaceous crust, are still being used in plate-tectonic reconstructions of the Scotia Sea (Dalziel et al., 2013a; Eagles, 2016; van de Lagemaat et al., 2021) but no scientific consensus has yet been reached about the age and origin of the CSS.

The aim of this study is to test a more inclusive hypothesis about the age, origin and extent of the CSS, using observational constraints and published reconstructions. We evaluate the question whether the CSS region can consist of remnant pieces of Cretaceous oceanic crust that have experienced back-arc extension during the Cenozoic. We hypothesize that these crustal remnants originate from a gateway that once connected the Paleo Pacific Ocean and the Weddell Sea, the so- called Paleo Pacific-Weddell Sea (PPWS) gateway.

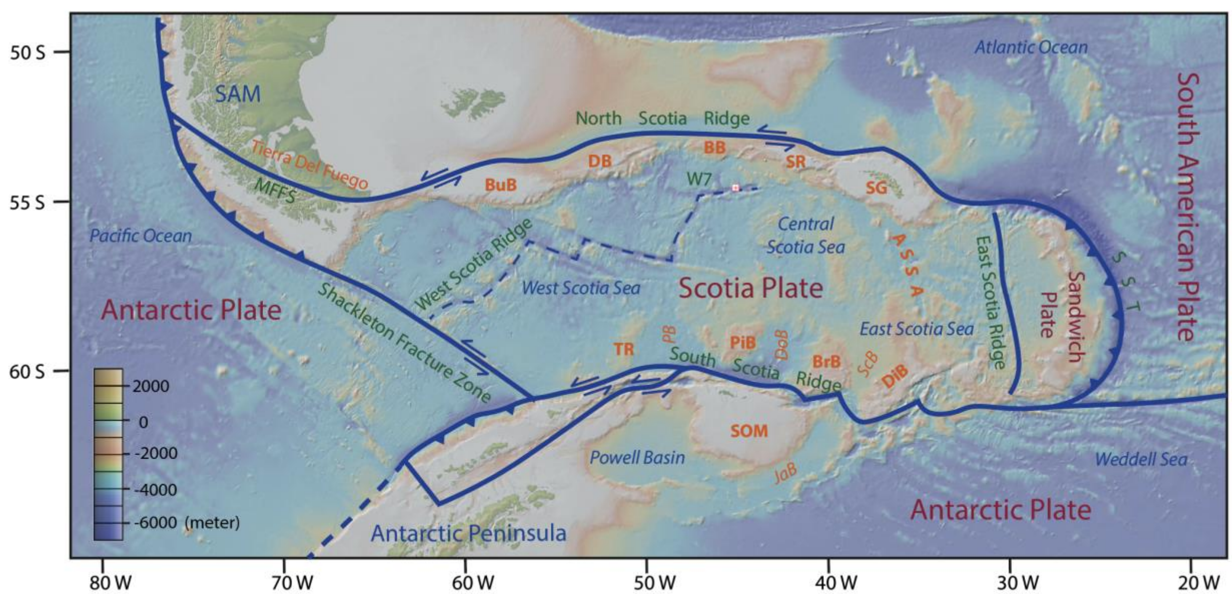


**Figure 1:** Bathymetric map of the Scotia Sea region (bathymetry obtained from GeoMapApp (Ryan et al., 2009)) and present-day tectonics (adapted from Riley et al., 2019). *Abbreviations of the bathymetric high and lows are given in orange. North Scotia Ridge (NSR): BuB-Burdwood Bank; DB-Davis Bank; BB-Bruce Bank; SR-Shag Rocks, SG-South Georgia. South Scotia Ridge (SSR): TR-Terror Rise; PB- Protector Basin; PiB-Pirie Bank; DoB-Dove Basin; BrB-Bruce Bank; ScB-Scan Basin; DIB-Discovery Bank; SOM-South Orkney Microcontinent; JaB-Jane Basin.*

## 2. Geological outline

The Scotia region consists of five plates (Fig. 1): the South American plate (SAM), the Antarctic plate (ANT), the Scotia plate (SCO), the South Shetland plate (SSh) and the Sandwich plate (Sa). The northern boundary of the Scotia plate (SCO-SAM), the North Scotia Ridge (NSR), is a left-lateral strike-slip fault (Smalley et al., 2007). The eastern boundary (SCO-SSa), the East Scotia Ridge (ESR) is an active spreading centre (Barker, 1972), whereas the southern to south-western boundary (SCO-ANT), consisting of the South Scotia Ridge (SSR) and the Shackleton Fracture zone (SFZ) classifies as a left-lateral strike-slip system (Fig. 1). The SSa, east of the SCO, is confined in the north and east (SSa-SAM) by the South Sandwich Trench (SST). Here, the South American plate subducts below the SSa. The southern plate boundary of the SSA (SSa-ANT) is a right-lateral strike-slip fault.

The Scotia plate formed throughout the Cenozoic and consists of a multitude of basins and elevated crustal fragments that define the present-day bathymetry. The largest basin, the West Scotia Sea in the west of the Scotia Plate, formed along the extinct spreading centre of the West Scotia Ridge (WSR, Fig. 1, Barker and Burrell, 1977). Several smaller basins and rises are located along the SSR. From west to east these are Protector Basin, Terror Rise, Dove Basin, Pirie Bank, Scan Basin, Discovery Bank and Jane Basin. The NSR is dominated by elongated East-West oriented banks and rises, including Burdwood Bank, Davis Bank, Barker Bank (previously referred to as 'Aurora Bank'), Shag Rocks and South Georgia. Numerous smaller faults (Cunningham et al., 1998) that accommodate the strike-slip movements along the ridge are present in and around the elevated banks. These banks are of Cretaceous age (Riley et al., 2019) or older (Tanner, 1982). Riley et al. (2019) also suggested Cretaceous ages for the adjacent seafloor, which is referred to as the W7 segment (Fig. 1). This is in contrast with the previous hypothesis that the W7 segment formed as a result of Cenozoic seafloor spreading along the WSR (Eagles et al., 2005).

Westward subduction of the South American plate below the Sandwich plate has resulted in the opening of the second largest basin of the Scotia plate, the East Scotia Sea, which initiated at least 15 Ma to 17 Ma along the ESR and continues spreading today (Eagles & Jokat, 2014; Larter et al., 2003). The South

Sandwich volcanic arc (Heezen & Johnson, 1965; Pearce et al., 2014) formed on the Sandwich plate in response to the subducting South American plate.

The central part of the Scotia plate is referred to as the Central Scotia Sea (CSS). Magnetic anomalies have been identified in the CSS (Barker, 1970), which suggests the presence of oceanic crust and former seafloor spreading. For the CSS the anomalies have proven difficult to interpret (Barker, 2001; Eagles, 2010b; Eagles & Jokat, 2014; Hill & Barker, 1980). There are two different schools of thoughts for the origin of this part of the Scotia plate, one assuming a Cretaceous age of the crust, the other assuming a Cenozoic age. The Cretaceous model assumes that the CSS is a captured piece of Cretaceous oceanic crust that could be a conjugate of the Weddell Sea (Dalziel et al., 2013; Eagles, 2010a, 2000; Eagles and Jokat, 2014). According to this model, no inactive spreading ridge, nor median valley is expected on this piece of oceanic crust. The Cenozoic model assumes that the CSS formed during the Cenozoic as a result of back-arc spreading due to westward subduction of the South American Plate beneath the Scotia plate (e.g. Barker, 2001; Hill and Barker, 1980; Livermore et al., 2007; van de Lagemaat et al., 2021; Nerlich et al., 2013; Vérard et al., 2012) According to this model, the age of the seafloor is relatively young, and an extinct spreading ridge is to be expected.

Remnants of a volcanic arc, named the Ancestral South Sandwich Arc (ASSA, Fig.1) are found on the eastern part of the CSS. This arc formed in response to the subduction of the South American plate during the early Oligocene - late Miocene (Pearce et al., 2014). The associated subduction zone extended from South Georgia towards the southernmost extent of Jane Bank (Pearce et al., 2014). The same subduction zone is suggested as driving force for back-arc spreading in the CSS in the young Cenozoic model (Barker, 2001; Hill & Barker, 1980; Livermore et al., 2007; Pearce et al., 2014; Pérez et al., 2014).

## 3. Methods

In this study, existing paleogeographic reconstructions have been compared using the open-source reconstruction software GPlates (Boyden et al., 2011). The reconstructions were remodelled in GPlates after georeferencing the published images and importing them in GPlates. We chose the reconstructions of Eagles and Jokat (2014) and Livermore et al. (2007) for the re-modelling and comparison (Fig. 2 and 3), because 1) they present two contrasting scenarios for the tectonic evolution of the CSS and 2) they were presented in such a way that allowed a quantitative comparison. Eagles and Jokat (2014) favour a Cretaceous CSS, while Livermore et al., (2007) present a Cenozoic age and origin of the CSS. The latter group of authors build further on reconstructions from older studies (Barker, 2001; Livermore et al., 2005). The published images of the two reconstructions were digitized with the thin-spline method of the open-source geographical information software QGIS (version 3.4, 2018), prior to loading into GPlates. The advantage of the GPlates software is that it allows the computation of the rotation poles of a set of pre-defined geological units according to geo-referenced figures of the existing studies. This makes it possible to quantitatively compare different tectonic reconstructions. In GPlates, rotations of so-called polygons are described in a rotation file. The polygons in this study are referred to as geological units (GUs). A GU represents a static crustal fragment. There are no general rules for defining these GUs, resulting in a variety of shapes of the same area in different reconstructions. For most GUs the difference in size between the different reconstructions is in the order of tens of kilometres. In some cases, however, the shapes vary greatly, for example the length of the GU representing Davis Bank defined by Lagemaat et al. (2021) at 10 Ma is almost half the size (200 km) of the same GU defined by (Barker, 2001) (380 km) at 10 Ma.

This study works with an independent set of GUs, to allow comparison between the different reconstructions (Fig. 4, red GUs). The shapes of these GUs were defined based on the bathymetry (DBM-BATDRAKE, Bohoyo et al., (2019), GEBCO 2014, Weatherall et al., (2015), South Sandwich Ridge, Leat et al., (2016), South Georgia, Hogg et al., (2016)), magnetic anomalies (Eagles et al., 2005), seismic profiles (Maldonado et al., 2006) and gravity anomalies (Sandwell et al., 2014.). After definition, the GUs were rotated according to the georeferenced images. This resulted in two different rotation files that mimic the rotations applied in Livermore et al. (2007) and Eagles and Jokat (2014). Rotations are relative to a fixed Antarctic Peninsula to be consistent with the reconstructions of Eagles and Jokat (2014) and Livermore et al. (2007).

The results of the comparison between these two distinct tectonic reconstructions highlight a significant number of uncertainties and disagreements in the evolution of the Scotia Sea region. The uncertainties, agreements and disagreements between the compared reconstructions (Eagles & Jokat, 2014; Livermore et al., 2007) and other existing reconstructions (e.g. Dalziel et al., 2013a; Pearce et al., 2014; Vérard et al., 2012) have been reinterpreted and visualized in a new tectonic reconstruction. Additional GUs were added to the new reconstruction to explain gaps between the existing reconstructions, and we discuss the potential origin of these additional GUs (Fig. 4, light grey GUs). The geometry of the GUs is defined following bathymetric features such as bathymetric highs and lineations. Shapes were adjusted to avoid under- and overlap of the GUs. The geometries of these GUs are not absolute. For the shapefile and the rotation file of the new reconstruction, see supplementary data.

## 4. Results

The results of the comparison of the paleogeographic reconstructions (Fig. 2 and 3) yield the major differences and similarities between the two end-member tectonic reconstructions for the Scotia Sea region. The most striking difference between the reconstructions is the assumption for the age and origin of the CSS. Eagles and Jokat (2014) present this part as a captured piece of oceanic crust that formed in the Cretaceous, which would later become the CSS, whereas Livermore et al. (2007) explain this part as the result of an east-west oriented spreading centre that existed during the Paleogene, which resulted in the formation of the CSS. All reconstructions (Fig. 2 and 3), including the ones not used for the GPlates comparison, agree on the general evolution of the SSR and the ESR although small differences exist. We will highlight the most striking similarities and differences between the reconstructions of Livermore et al. (2007)) and Eagles and Jokat (2014) at different time steps (Fig. 2 and 3). Where possible, comparisons are made with the other studies that are not included in our GPlates reconstructions.

**4.1 50 Ma- Configuration of the land bridge between South America and Antarctica**

During the Early Eocene (Fig. 2a and 2b), the South American continent and Antarctica were connected. This connection can be described as a land bridge, that later broke apart in multiple pieces that can be found on today's ocean floor of the Scotia Sea. During Early Eocene times this land bridge was confined by two subduction zones, one on the eastern side and one on its western side. Both Livermore et al. (2007) (Fig. 2a) and Eagles and Jokat (2014) (Fig. 2b) agree on this. The subduction zone on the eastern side of the land bridge has been interpreted by Eagles and Jokat (2014) to result from ongoing shortening along the Endurance Collision Zone (ECZ).

The most apparent difference between the reconstructions is the age and origin of the CSS. Eagles and Jokat (2014) argue that the CSS is of Cretaceous origin, thus their reconstruction includes a GU that represents this CSS. South Georgia, which they connect to the CSS, is not included in the land bridge in their reconstruction (Fig. 2b). The area in between the GUs of the land bridge, is referred to as Omond Land by Eagles and Jokat (2014). While Eagles and Jokat (2014) have space between the geological units that were part of the land bridge, the reconstruction of Livermore et al. (2007) could not be reproduced without overlap of the GUs that are part of the land bridge (Fig. 4b). This is not apparent in the reconstruction of Livermore et al. (2007) because their GUs are smaller than the GUs used for this study. The GUs could have been smaller in the geological past due to later stretching. Dalziel et al. (2013a, 2021) advocate that South Georgia was positioned close to the Southern Andes, in contrast with Livermore et al. (2007) and even more so with Eagles and Jokat (2014) while the origin of the CSS is proposed by Dalziel et al. (2013a) to be a Cretaceous conjugate of the Weddell Sea.

A last major difference at this time step is that the eastern margin of Tierra del Fuego is located ~150 km more towards the east in the reconstruction of Eagles and Jokat (2014) (Fig. 2b) compared to the reconstruction of Livermore et al. (2007) (Fig. 2a). The position of the GU of the South American plate in the reconstruction of Livermore et al. (2007) in our comparison cannot be compared to the reconstruction of Eagles and Jokat (2014) because the size of the South American plate is much smaller (app. 300km in length, measured from east to west) than the size of the GU that is being used by Eagles and Jokat (2014).

In our comparison we therefore only use parts of the continental margins of Tierra del Fuego and the South American plate that remain unchanged through time.

### 4.2 40 Ma- First signs of extension in the future Scotia Sea

Ongoing eastward retreat of the eastern subduction zone caused back-arc extension in the land bridge. Both Eagles and Jokat (2014) and Livermore et al. (2007) reconstruct an east-west oriented opening of Dove Basin, between Pirie Bank and Bruce Bank (Fig. 2c and 2d).

The location of the eastern margin of Tierra del Fuego is still 120 km apart between the different reconstructions, and thus Dove Basin is located at different latitudes and longitudes in both reconstructions. The extension in Dove Basin results in multiple sinistral strike-slip movements between the GUs. Livermore et al. (2007) do not report these faults (Fig. 2c). The Burdwood transform fault accommodates these strike-slip movements in the reconstruction by Eagles and Jokat (2014) (Fig. 2d).

In other reconstructions, the Scotia plate and the ASSA have already formed at this stage (Dalziel et al. 2013a, 2013b). In this case, the plate extends from 57W to 37W and is smaller than it is nowadays, because the WSR did not form yet (Dalziel et al. 2013a, 2013b). The CSS is displaced independently from South Georgia in Dalziel et al., (2013b). The Scotia plate and the ASSA are not present in the reconstructions of Eagles and Jokat (2014) and Livermore et al. (2007), although both Eagles and Jokat and Dalziel et al. (2013a, 2013b) report the presence of the CSS at this stage.

### 4.3 35 Ma- onset of the formation of the ASSA

The ongoing back-arc extension in the region caused sea-floor spreading between the crustal fragments that compose the SSR and the formation of Protector Basin (Fig. 3e and 3f). This has been reported in both Eagles and Jokat (2014)(Fig. 3f) and Livermore et al. (2007) (Fig. 3e). Livermore et al. (2007) treat the South American plate and Tierra del Fuego as one large GU, whereas Eagles et al., (2014) include an extending basin between Tierra del Fuego and the South American plate reported by Ghiglione et al. (2008), resulting in a widening of the underlap with 100km. However, they cannot distinguish how much of the underlap is the result of the errors expected from the rotations of the South American and Antarctic plates in their reconstructions.

Pearce et al. (2014) have published a schematic reconstruction that describes the evolution of the ASSA starting at 34 Ma. Pearce et al. (2014) suggest that subduction initiated at the ASSA around 34 Ma, along the eastern margin of the CSS, that was already present at this stage in their reconstruction. Remnants of the southern extend of the subducting slab below the ASSA have been observed in mantle tomography models (Beniest and Schellart, 2020). Galindo-Zaldívar et al., (2006) report Early Miocene ages for the opening of Protector basin, and a Late Oligocene to Early Miocene age for the opening of Dove basin (Galindo-Zaldívar et al., 2014). According to Pearce et al. (2014), the opening of Dove basin and Protector basin follow the initiation of the subduction zone, which is in line with the ages proposed by Galindo-Zaldívar et al. (2006, 2014). These openings are much younger than reported in Eagles and Jokat (2014) and Livermore et al., (2007).

**4.4 30 Ma- The ASSA and the possible onset of north-south oriented back arc spreading**

The most striking and controversial differences between the compared paleogeographic reconstructions become apparent around 30 Ma (Fig. 3a and 3b). Although all the compared reconstructions agree on the presence of a curved subduction zone at this stage, the influence of the subduction zone on the evolution of the back-arc basin is different. As a consequence of the high curvature of this subduction zone, Livermore et al. (2007) report the initiation of north-south oriented back-arc spreading, eventually leading to the formation of the CSS (Fig. 3a). They also provide evidence for north-south back-arc spreading in the form of east-west striking interpreted isochrons on the seafloor of the CSS, which was suggested by Barker (1970). Eagles and Jokat (2014) (Fig. 3b) have interpreted these anomalies as products of Cretaceous seafloor spreading. They therefore treat the CSS as a rigid crustal block.

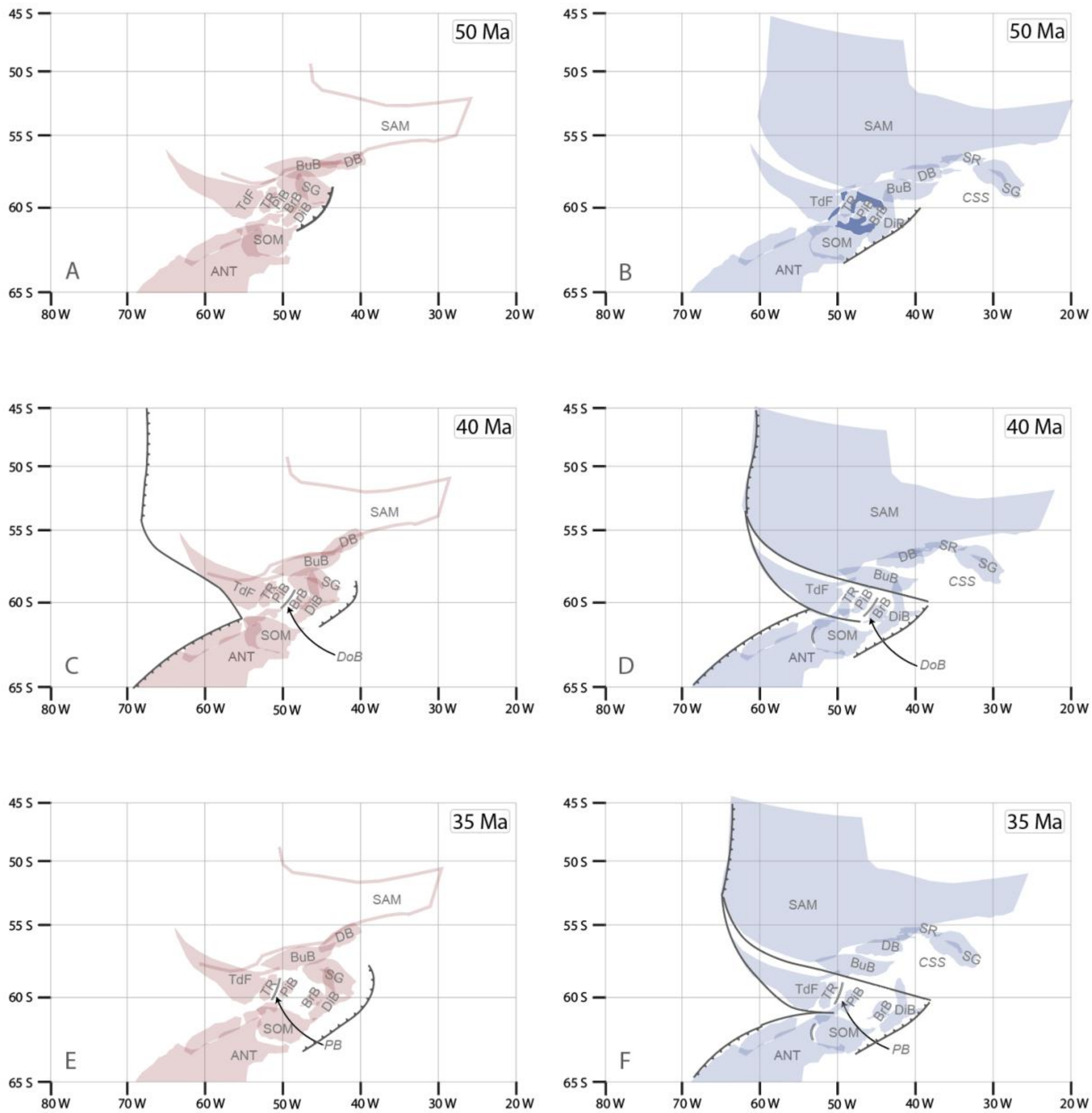


**Figure 2:** Comparison of the reconstructions (50 Ma – 35 Ma) of Livermore et al. (2007) in red (a, c, e) and the reconstruction of Eagles and Jokat (2014) in blue (b, d, f), shown with respect to a fixed Antarctica. *Abbreviations in grey are identical to those in figure 1. Subduction and major faults are indicated in black, sea floor spreading is indicated with two thin black lines when they were presented in the original studies. The dark blue area in figure 2b represents Omond Land.*

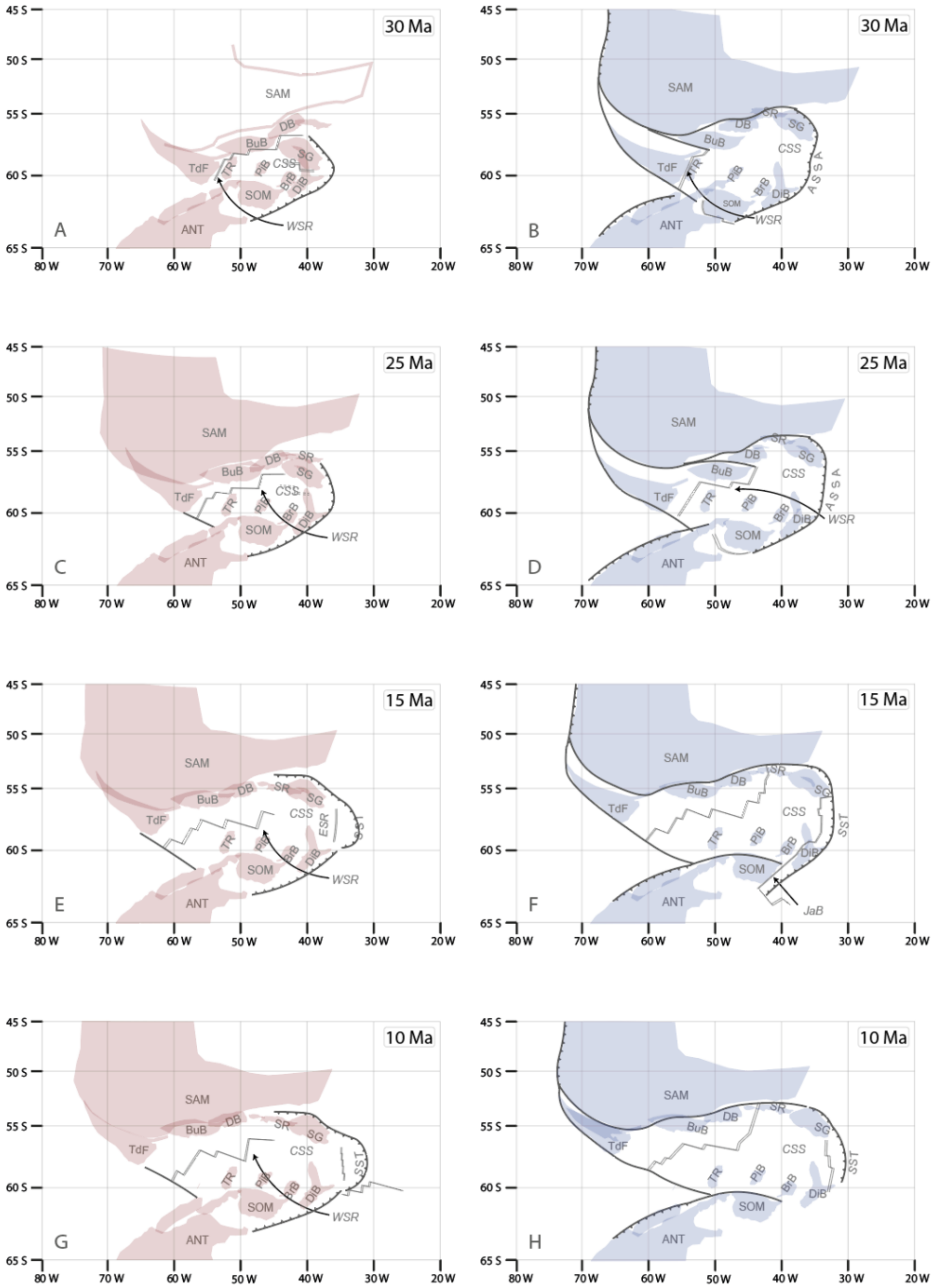


**Figure 3:** Comparison of the reconstructions (30 Ma – 10 Ma) of Livermore et al. (2007) in red (a, c, e, g) and the reconstruction of Eagles and Jokat (2014) in blue (b, d, f, h), shown with respect to a fixed Antarctica. *Abbreviations in grey are identical to those in figure 1. Subduction and major faults are indicated in black, sea floor spreading is indicated with two thin black lines when they were presented in the original studies.*

**4.5 25 Ma- Propagation of the WSR**

From 25 Ma onwards, the northward propagation of the WSR can be observed in the reconstructions of Eagles and Jokat (2014) (Fig. 3d) but is not apparent from the reconstructions of Livermore et al. (2007) (Fig. 3c). Seafloor spreading along the WSR has propagated in the reconstruction of Eagles and Jokat (2014) from the Shackleton Fracture zone towards the eastern side of Burdwood Bank (Fig. 3d). Towards the north, the WSR connects with the remnants of the Burdwood transform fault that runs through Tierra del Fuego. The WSR has not been connected with the NSR yet in the reconstruction of Eagles and Jokat (2014). Livermore et al. (2007) (Fig. 3c) do connect the northernmost transform fault of the WSR to South Georgia. The extent and width of extension in the WSR is smaller in Eagles et al. (2014) compared to Livermore et al. (2007), but the total size of the Scotia plate is larger in the reconstruction of Eagles and Jokat (2014). This results in a subduction zone that is located 150 km further eastward and a more easterly positioned ASSA and South Georgia. Neither the ASSA nor any volcanic activity are mentioned by Livermore et al. (2007). According to Pearce et al. (2014) the ASSA is active over the whole region at 25 Ma, which extends from the south-west corner of South Georgia to the south-east corner of JaB. Although the age, origin and geometry of the CSS are still different between the reconstruction of Pearce et al. (2014) and the reconstructions of Livermore et al. (2007) and Eagles and Jokat (2014), the shape of the subduction zone, the South Sandwich Trench (SST), is similar to that of Eagles and Jokat (2014).

Other reconstructions favouring a Cenozoic age for the CSS suggest different ages for the opening of this proposed back-arc basin, and/or do not explain how the propagation of the WSR towards the NSR along the margins of the CSS occurred, as this propagation is unclear in most other reconstructions. The CSS starts opening in a north-south direction shortly after 24 Ma in the reconstruction of Vérard et al. (2012). The CSS does not yet exist in the reconstruction of Nerlich et al. (2013) at 25 Ma but opens shortly after 21 Ma. South Georgia remains attached to Discovery Bank and Bruce Bank that do not split up either, which means that Scan Basin is not present in these reconstructions, even though Scan Basin does form in the reconstructions of Livermore et al. (2007) and Eagles and Jokat (2014) at this time step. A CSS that results from Cenozoic back-arc spreading requires a north-south trending transform boundary with the

WSS. This boundary is not present in the reconstructions of Barker et al. (2001) nor Livermore et al. (2007) although such a fault is expected. Nerlich et al. (2013) do not mention such a transform boundary but their figure that depicts the age of the Scotia region shows contrasting ages along this assumed transform boundary.

**4.6 15 Ma- Initiation of spreading along the East Scotia Ridge**

There are two major differences between the reconstructions of Eagles and Jokat (2014) and Livermore et al. (2007) at 15 Ma: the extent of the northernmost segment of the WSR, the W7 segment, and the extent of sea-floor spreading during the earliest stage of spreading along ESR (Fig. 3e and 3f). The W7 segment is reconstructed in Eagles and Jokat (2014) (Fig. 3f) but is not reported in Livermore et al. (2007) (Fig. 3e). The ESR comprises of a short ridge (app. 270 km long) striking app. N-S which is located west of the subduction zone in Livermore et al. (2007), while the spreading ridge extends from South Georgia towards Jane Basin in Eagles and Jokat (2014), with a total length of app. 900 km.

South Georgia is located 300 km towards the south-west in the reconstruction of Livermore et al. (2007) as a result of the ongoing opening of CSS. Spreading along the ESR starts soon after 20 Ma in the reconstruction of Livermore et al. (2007) (Fig. 3e). Eagles and Jokat (2014) (Fig. 3f) have proposed a similar onset for spreading at the ESR, starting at 17 Ma and the spreading ridge is connected with the spreading ridge in Jane Basin, in contrast to the reconstruction of Pearce et al. (2014), where spreading in Jane Basin already stopped before 20 Ma. Bohoyo et al., (2002) report a cessation of the spreading centre in JaB at 14.4 Ma. In the reconstruction of Eagles and Jokat (2014) (Fig. 3f) the spreading centre in Jane Basin is not interrupted when crossing the SSR and continues into Scan Basin. A small transform fault that cuts through Discovery Bank connects this spreading centre in Scan Basin with the ESR. The ESR ends in the reconstruction of Eagles and Jokat (2014) south of South Georgia with a second transform fault, that connects the ESR with the SST. In the model of Pearce et al. (2014) the cessation of spreading in Jane Basin is followed by a period of ongoing subduction of the South American plate. The spreading centre in Jane Basin is cut-off in the north by the SSR strike-slip zone, which merged with a major transform fault in the

Weddell Sea oceanic crust. North of this strike-slip fault, spreading continues west of Discovery Bank, in Scan Basin. The spreading continues towards the north. No reference frame has been provided in the reconstruction of Pearce et al. (2014), so the position of the ESR, relative to the other reconstructions, is unclear.

No signs of extension along the ESR are visible in the reconstructions of Vérard et al. (2012) at this time step. Nerlich et al. (2013) and Livermore et al. (2007) both did not publish a time slice that can be compared with the 15 Ma time slice. Our reconstruction allows a simulation of the paleo-location of the GUs for the reconstruction of the Livermore et al. (2007) (Fig. 3e), which suggests the ESR has developed significantly at 10 Ma, implying that the ESR has started to spread at 15 Ma, which coincides with the model of Barker (2001).

The WSR is still spreading at 15 Ma according to Livermore et al. (2007), but they do not show the final stage of WSR evolution. It is therefore unclear if the WSR has ever connected with the NSR in their reconstruction. The same applies to the reconstruction of Vérard et al. (2012). Eagles and Jokat (2014) do connect the WSR to the NSR, which exerts tension on the NSR west of Shag Rocks and thus the formation of the W7 segment.

### 4.7 10 Ma- Present day. End of spreading along the West Scotia Ridge and ongoing spreading along the East Scotia Ridge.

At this time slice, close to today's configuration, the compared reconstructions disagree significantly (Fig. 3g and 3h). The GUs in the youngest time slice of Livermore et al. (2007) (Fig. 3g) are very different from the reconstruction of Eagles and Jokat (2014) (Fig. 3h). This is most apparent from the position of the GU of South Georgia. To make the connection from 10 Ma to today's configuration the GUs of Livermore et al. (2007) had to be radially dispersed from their 10 Ma positions by rotating and expanding the GUs to their present-day location. In other words, South Georgia had to move around 250 kilometres towards the north-east, the GUs along the SSR towards the south and the SST had to move towards the east. Livermore et al. (2007) (Fig. 3g) propose that the SST has diverted from its previous location along the ASSA, resulting in a new arc. The SST has now become a N-S trending curved subduction zone, like its present-day shape. This is different in the reconstruction of Eagles and Jokat (2014) (Fig. 3h), where the ESR is actively spreading at 10 Ma, while the SST is still attached to the NSR strike-slip zone. At the 6 Ma timestep of the reconstruction of Eagles and Jokat (2014) this changes, when a new arc separated from the ASSA is clearly visible. Pearce et al. (2014) have modelled this separation of the two arcs between 12 Ma and 8 Ma. Dalziel et al. (2013a, 2013b) suggested the onset of spreading along the ESR at 10 Ma indicated with a few dashed lines. It is unclear if these dashed lines mark the start of the ESR or if they are a hint to the extension that might have pre-dated the sea-floor spreading (Dalziel et al., 2013a, 2013b). The development of the Shackleton Fracture Zone is thought to have caused an eastward asthenospheric mantle flow below the Scotia Sea region, which halted spreading at the WSR around 6 Ma (Martos et al., 2014b).

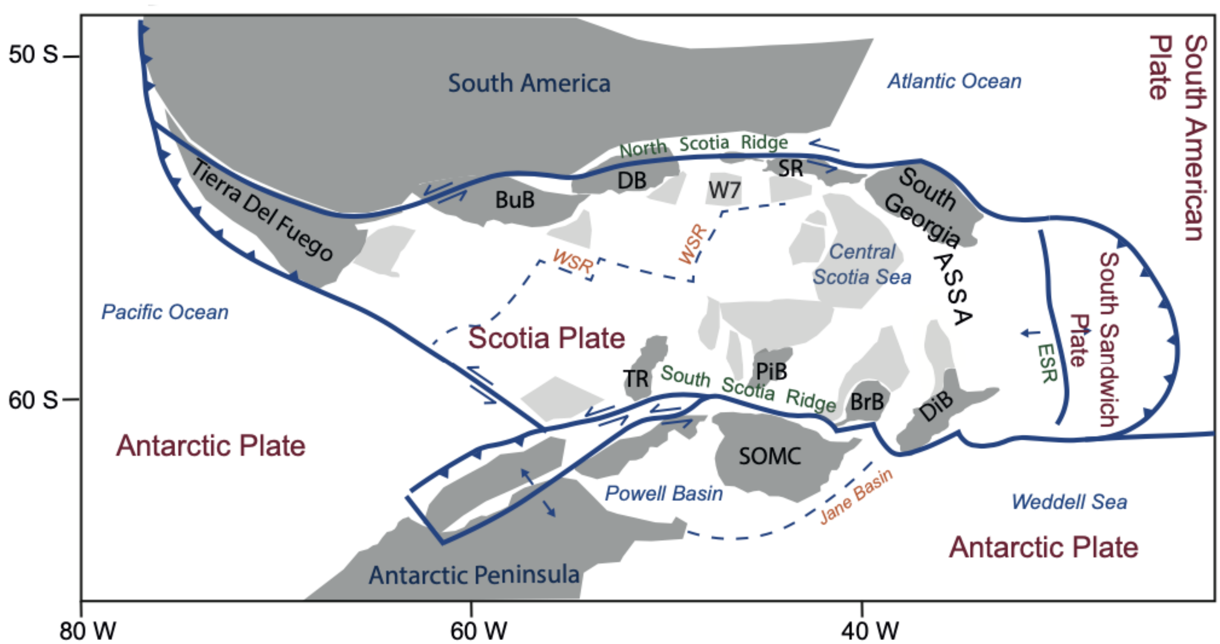


**Figure 4:** Geological units (GUs) according to their present-day position. The dark grey GUs are continental fragments and are the same as those used in figure 2 and figure 3. The light grey GUs are newly defined and interpreted to originate from PPWS. Abbreviations are identical to figure 1. The present-day tectonic structures are derived from Riley et al. (2019).

## 5. New Reconstruction

The comparison of reconstructions shows that there is still no agreement on the age and origin of the CSS. The two prevailing end-member solutions consider either a Cretaceous or Cenozoic age of the CSS. The origin of the CSS is considered either as the conjugate of the Weddell Sea or as a back-arc basin. To reach a consensus we present a new tectonic reconstruction including newly identified crustal fragments (see methods). In this reconstruction we bridge the two end-member models including both ages and origins of the CSS as proposed by Livermore et al. (2007) and Eagles and Jokat (2014) (Fig. 5). In our reconstruction, we assume that the CSS and the newly recognised oceanic crustal fragments (Fig. 4) originated in a branch of a gateway that connected the Paleo-Pacific Ocean with the Rocas Verdes Basin and the Weddell Sea (Fig. 6). We hereafter call this gateway the Paleo-Pacific Weddell Sea (PPWS) gateway. A continuous extensional system from the Rocas Verdes Basin to the Weddell Sea has already been proposed by several authors (Eagles, 2010a, 2016; Eagles & Eisermann, 2020; König & Jokat, 2006; Malkowski et al., 2016). Riley et al. (2019) identified Cretaceous crust along the west Scotia Ridge, the W7 segment. We follow their interpretations that this segment was part of the Cretaceous CSS as defined by Eagles and Jokat (2014). Despite the recognition of a continuous branch between the Rocas Verdes Basin and the Weddell Sea, there are no published reconstructions yet that advocate for a CSS containing both Cretaceous crust and Cenozoic crust. In our reconstruction, we include both the GUs that we used to compare the reconstructions of Eagles and Jokat (2014) and Livermore et al. (2007) and the GUs that were once located in an east-west oriented branch between the Weddell Sea and the Paleo-Pacific Ocean at 50 Ma (PPWS gateway Fig. 5a and Fig. 6).

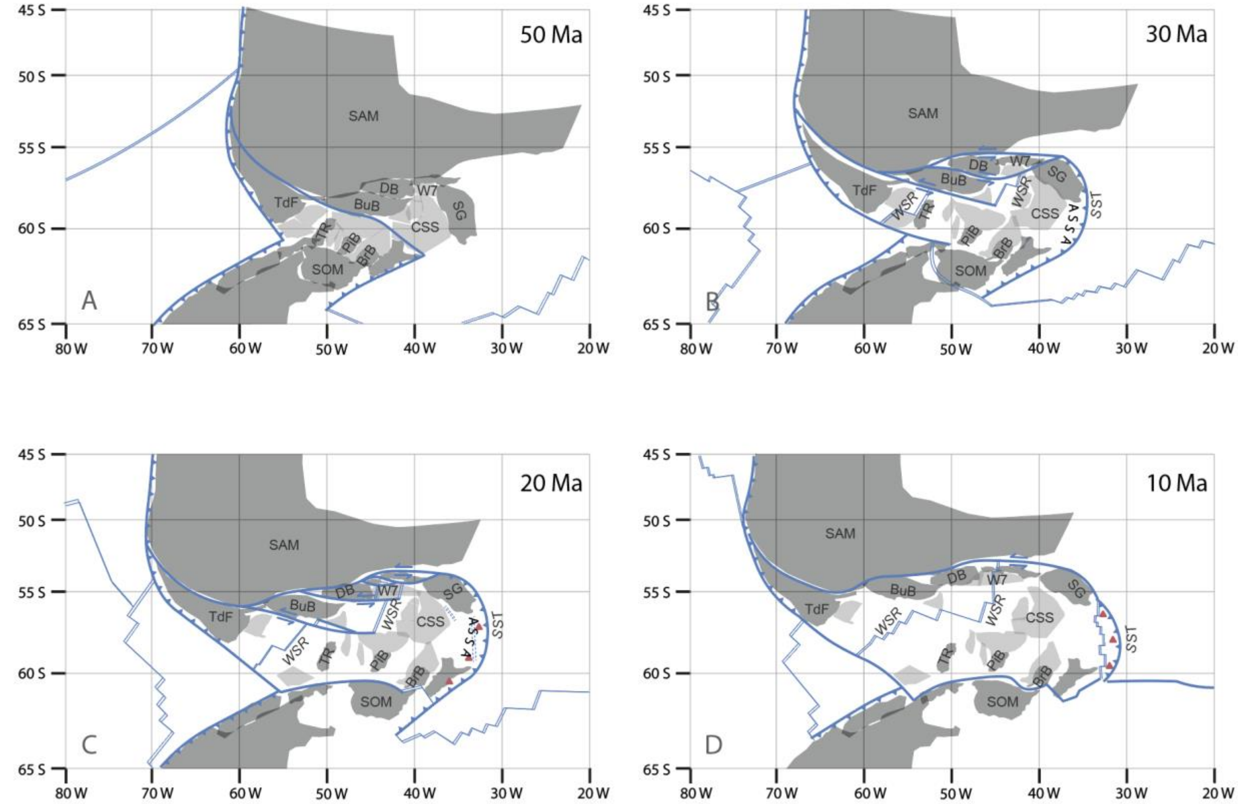


**Figure 5:** New tectonic reconstructions. a) 50 Ma: The Scotia Sea region illustrating the connection between South America and Antarctica including the paleo-position of the remnants of the PPWS. b) 30 Ma: Scotia Sea region at the start of the formation of the Central Scotia Sea back-arc basin. c) 20 Ma: wide-spread extension in the Scotia Sea region in response to the retreat of the SST. d) 10 Ma: wide-spread extension in the Scotia Sea region has ceased, and extension is now centred along the ESR. *Transparent light grey areas represent geological units originating from the PPWS. Subduction, sea floor spreading and major faults are indicated in blue. Volcanism is schematically illustrated with red triangles. Abbreviations are identical to figure 1. Plate boundaries are adapted from* Matthews et al.(2016) . *The dark grey colours indicate the same crustal blocks as presented in figures 2 and 3.*

### 5.1. 50 Ma:

In our model, at 50 Ma, a narrow gateway that connects the Paleo-Pacific Ocean and the Weddell Sea separates South America from Antarctica (Fig. 5a). The GUs originating from this branch are positioned in a seaway between the South American and Antarctic plates, which is different from all previous reconstructions. One could argue that the CSS in the reconstruction of Eagles and Jokat (2014) originates from this branch as well, but the CSS and South Georgia are positioned 350-400 km towards the east in their reconstruction, outside the land bridge. In our reconstruction South Georgia is located much closer to Burdwood Bank and Tierra del Fuego, which is more in agreement with the position proposed by Dalziel et al. (2021). The GUs that will later form the CCS comprise a smaller area in comparison to Eagles and Jokat (2014). We agree with Eagles and Jokat (2014) that there are still two subduction zones active, one on the eastern side and another on the western side of the South American - Antarctic connection during the early Cenozoic (Fig. 5a).

**5.2: 30 Ma:**

We adopt the commonly accepted curved geometry of the SST at 30 Ma (Fig. 5b). This subduction zone was fully developed, with the ASSA representing the active volcanic arc at 30 Ma (Pearce et al., 2014). Apart from the arc, this subducting plate at the ASSA caused stretching in the overriding plate, preluding the initiation of back arc spreading at the WSR. Crustal extension starts in the northern part of the future Scotia Plate, along with what will become the WSR, and close to the arc in the south that will become Jane Basin. The displacement in the north occurs along strike-slip faults.

**5.3: 20 Ma:**

At 20 Ma, back-arc spreading at the West Scotia Ridge is still ongoing with sea floor spreading along the WSR and propagation of the West Scotia Ridge towards the south, following Eagles and Jokat (2014). Several transform faults inside the West Scotia Sea accommodate east-west directed seafloor spreading. We follow Eagles and Jokat (2014) by initiating spreading at the ESR around 20 Ma (Fig. 5c)

In our reconstruction (Fig. 5c) the area in between the northern WSR and the ESR experiences extension, which results in stretching in the CSS domain and in South Georgia separating in an anti-clockwise rotation, away from the CSS. This results in a app. 100 km wide bathymetric low between South Georgia and the CSS as well as other areas where the Cretaceous pieces of crust actively thin, and potentially break apart, forming new oceanic crust at poorly developed spreading centres, of Cenozoic age in the CSS. Absence of dredge material to test if there is indeed thinned continental material at the base of these bathymetric lows, make it difficult to confirm this hypothesis. Beniest and Schellart, (2020) map small bits of continental crust in that domain that points to more felsic material than mafic, which they infer from the geophysical signature in the region. Refraction seismic data in this area would help to constrain the crustal structure towards the south-west of South Georgia, but such data are currently absent.

The ASSA is still active at 20 Ma and follows the curvature of the subducting slab (Pearce et al., 2014). The retreating slab continues to deform the Scotia Plate. Displacement along strike-slip faults in the NSR and basin opening along the SSR (Protector Basin, Dove Basin and Scan Basin) continues.

### 5.4 10 Ma: spreading along the East Scotia Ridge, formation of the Sandwich plate and eastward retreat of the SST

At 10 Ma, extension in the CSS domain starts to cease and continues to be accommodated along the ESR, causing growth of the Sandwich Plate (Fig. 5d). The strike-slip motion along the NSR and ESR continues. Activity at the ASSA stops around 10 Ma (Pearce et al., 2014) in response to the eastward retreat of the subduction zone that led to the formation of the East Scotia Sea back-arc basin and the South Sandwich volcanic arc.

## 6. Discussion

Our presented reconstruction is novel in three different ways: I) we ascribe a larger role to the connection between the Paleo-Pacific Ocean and the Weddell Sea (PPWS gateway, Fig. 6). II) with our reconstruction we recognize more pieces of Cretaceous seafloor that could be related to the PPWS gateway (Fig. 4). III) our reconstruction (Fig. 5) shows that previously published works, with opposing end-member hypotheses, are compatible when considering points I and II.

## 6.1 Paleo-Pacific - Weddell Sea (PPWS) gateway

The Weddell Sea and Rocas Verdes Basin both formed during the break-up of southern Gondwana (Eagles, 2010a; Jokat et al., 2003; König & Jokat, 2006; Ramos et al., 2020). The Rocas Verdes Basin was located either along the margin of the Paleo-Pacific Ocean (Bastias et al., 2021; Ghiglione, 2016; Schellart et al., 2023; Vérard et al., 2012) or cross-cutting Patagonia at the westernmost extent of the Magallanes - Fagnano Fault System (MFFS, Dalziel et al., 2013a; Dummann et al., 2020; Eagles, 2010a; Maffione et al., 2010; van de Lagemaat et al., 2021). During this initial break-up phase (app. 150 Ma, Bastias et al., 2021; Eagles, 2010a; van de Lagemaat et al., 2021), the Weddell Sea spreading centre was possibly connected through an oceanic gateway to the Paleo-Pacific Ocean (Fig. 6), as proposed by multiple authors (Bastias et al., 2021; Dummann et al., 2020; Eagles, 2010b; Ghiglione, 2016; Lagemaat et al., 2021; Vérard et al., 2012). The location and timing of this PPWS gateway is dynamic and starts initially in the Rocas Verdes Basin itself (Dalziel et al., 2013a; Dummann et al., 2020; Eagles, 2010a; van de Lagemaat et al., 2021) after which this branch is abandoned and continues in a proto-Drake Passage just south of mainland Patagonia, Argentina (Dalziel et al., 2013a; Dummann et al., 2020; Eagles, 2010a; Ghiglione, 2016; van de Lagemaat et al., 2021). Other authors (Eagles, 2010a; König & Jokat, 2006) propose that the PPWS gateways are rift- or spreading basins, which implies that the crustal structure would be thinned continental or oceanic crust.

In general, it is accepted that continental fragments from the Mesozoic continental parts of South America and Antarctica can be found along the margins of the Scotia Plate. Eagles (2010a), Dalziel et al. (2013a) and Eagles and Jokat (2014) report that parts of the CSS belonged to a more westerly, with respect to the PPWS gateway, located part of the Antarctic conjugate margin, and Riley et al. (2019) hypothesized ‘the existence of a previously unknown volcanic arc on an extension of the adjacent Cretaceous oceanic crust of the CSS’. Magnetic studies identified potential, roughly E-W oriented batholiths in the Central Scotia Sea (Martos et al., 2014). Other than those mentions, no remnants of oceanic or thinned continental crust originating from the PPWS have been reported in the Scotia domain. The recognition of PPWS remnants allowed us to reconstruct the tectonic history of the Scotia Sea domain more elegantly as we will discuss in the next section.

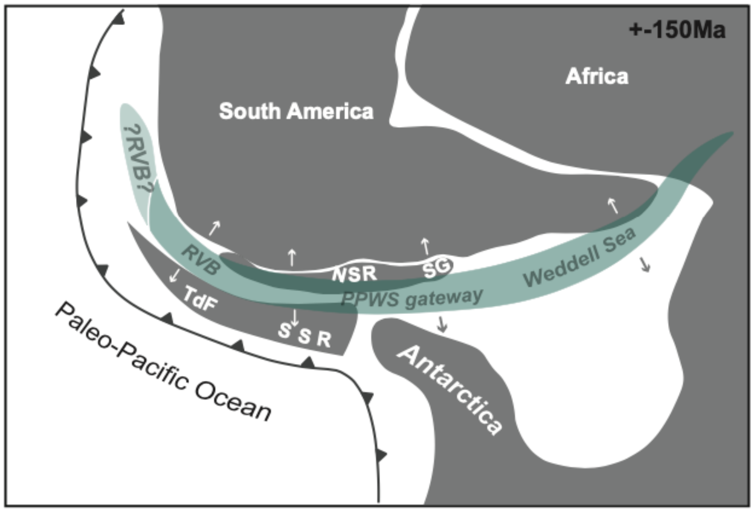


**Figure 6:** Schematic cartoon of the break-up of the southern margin of Gondwana at 150 Ma. Extension is centred in a zone that extends from the RVB through the PPWS gateway into the Weddell Sea and is indicated in green. Sea-floor spreading also occurred in the Weddell Sea but is not interpreted in this figure. Arrows indicate the direction of extension. Modified from (Eagles, 2010b).

### 6.2 Provenance of the Scotia Plate seafloor

Comparing the same-shaped geological units using the reconstruction of Livermore et al. (2007) and Eagles and Jokat (2014) revealed that Livermore et al. (2007) (Fig. 2 and 3), who chose an Oligocene age for the CSS, have a lot of overlap between the GUs (Fig. 2a), whereas Eagles and Jokat (2014), who consider a Jurassic-Cretaceous age for the CSS, have too much space at 50 Ma in the central part of the land bridge (Fig. 2b). Livermore et al. (2007) give no explanation for their overlap, but we assume the intention was to simulate crustal thinning under extension. Eagles and Jokat (2014) recognise Omond-land (Fig. 2b), a former coastal plain that is now dismembered and scattered over the Scotia Plate, to fill in the gap in their reconstruction.

To overcome the overlap in Livermore et al. (2007) and the underlap in Eagles and Jokat (2014), we have interpreted the dark grey areas of the Scotia plate (Fig. 4) as remnants of crust originating from the PPWS that got separated during the formation of the Scotia Plate (Fig. 6). Today, these dismembered crustal fragments can be found scattered over the Scotia Plate (Fig. 4), a result of the ongoing back-arc extension since the early Oligocene. This solution gives room for both ideas, where the CSS may consist of older (Cretaceous) crustal material (Dalziel et al., 2013a; Dalziel et al., 2013b; De Wit, 1977; Eagles, 2010a; Eagles and Jokat, 2014), younger crustal material (Barker, 2001; Livermore et al., 2007; Nerlich et al., 2013; Vérard et al., 2012) that formed during an Oligocene-Miocene extension phase and batholith that reside in the crust of the CSS (Martos et al., 2014) around which extension was accomodated. In addition, our solution also explains the Cretaceous ages of dredged rock samples reported by Riley et al. (2019) without generating large amounts of overlap or gaps between GUs as experienced by Livermore et al. (2007) and Eagles and Jokat (2014).

We acknowledge that our GUs, which represent continental crust and remain rigid during our reconstructed 50 myr, likely underwent some (diffuse) deformation during this time span. The amount of data from this region, which is currently sparse due to a limited number of drilled and dredged samples (see review Beniest and Schellart, 2020), with the most recent expedition IODP 382 carried out in 2019 (Pérez et al., 2021), should increase to confirm the presence and lateral extent of remnant fragments of the PPWS gateway. The only reconstruction that is suitable for a detailed comparison, that is also reconstructed with a GU that resembles a captured piece of (Cretaceous/oceanic crust) is that of Eagles and Jokat (2014). Other than that, no GUs with an origin related to something like the PPWS gateway have previously been recognized. Therefore, different sizes and shapes are possible, depending on the configuration of these newly identified GUs at 50 Ma.

### 6.3 Implications for the onset of the Antarctic Circumpolar Current

In our reconstruction, we assume that the crustal nature of the newly identified GUs are of oceanic origin and were most likely submerged at 50 Ma. This opens up the possibility for a, potentially shallow, Eocene-age paleo-gateway between the between the Pacific Ocean and the Atlantic Ocean around 50 Ma, which would pre-date the deeper ocean currents that are known to be present after the opening of Drake Passage (Maldonado et al., 2003; Martos et al., 2013).

To mitigate this challenge of identifying potential remnants of the PPWS gateway and possible earlier gateways between the Pacific and the Atlantic oceans, more data are required. These data may consist of dredged samples that specifically target the CSS, but it also includes high resolution reflection seismic data on the CSS. Until today, most of the reflection seismic data has been acquired and interpreted in the basins along the SSR (Civile et al., 2012; García et al., 2016; Kavoun & Vinnikovskaya, 1994; Lindeque et al., 2013; Maldonado et al., 1998; Maldonado et al., 2015; Vanneste et al., 2002), which has revealed important constraints on the tectonic movement of crustal blocks along the SSR. The CSS, and specifically the region around South Georgia, remains to be investigated. Apart from reflection seismic data, refraction seismic data would be particularly useful across the CSS, because this type of data allows the analysis of the crustal structure based on seismic velocities, which are quite specific for both felsic and mafic rocks.

## 7. Conclusion

The paleogeographic comparisons and remodelling of published reconstructions of the tectonic evolution of the Scotia region highlight important similarities and striking differences. A reinterpretation of these reconstructions in combination with bathymetric and magnetic anomaly data implies that pieces of Cretaceous crust are scattered throughout the CSS and along the margins of the NSR and SSR as a result of Cenozoic back-arc extension.

To compare existing models, we redefined GUs and remodelled existing reconstructions describing the Cenozoic evolution of the Scotia region. This comparison shows that major differences between the reconstructions exist in the age, origin and extend of the CSS and the role of the subducting SAM plate.

We propose a hybrid tectonic model, challenging the idea of a purely Cretaceous or Cenozoic age crust of the CSS. We also identify more regions that are potentially made of Cretaceous oceanic crust or stretched continental crust along the margins of the CSS and along the NSR and SSR. The areas containing such crust originate from crustal extension and seafloor spreading in the PPWS, which formed during the first phase of rifting and break-up of southern Gondwanaland. Most of the expansion of the CSS back-arc basin occurred during the Oligocene and Miocene in response to westward subduction of the South American plate under the Scotia plate. To verify this reconstruction, more geological and geophysical data about the age and lithology of the remnants of the PPWS gateway should be acquired, for example by dredging the sea floor of those areas or acquiring reflection and/or refraction seismic data.

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## 9. Open Research

No new data were generated or used during this project.

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