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RESEARCH ARTICLE

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Crustal block origins of the South Scotia Ridge

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Abstract

The Cenozoic development of the Scotia Sea and opening of Drake Passage evolved in a complex tectonic setting with sea-floor spreading accompanied by the dispersal of continental fragments and the creation of rifted oceanic basins. The post-Eocene tectonic setting of the Scotia Sea is relatively well established, but Late Mesozoic palaeolocations of many continental fragments prior to dispersal are largely unknown, with almost no geological control on the submerged banks. Detrital zircon analysis of dredged metasedimentary rocks of Bruce Bank from the South Scotia Ridge demonstrates a geological continuity with the South Orkney microcontinent (SOM) and also a clear geological affinity with the Trinity Peninsula Group metasedimentary rocks of the Antarctic Peninsula and components of the Cordillera Darwin Metamorphic Complex of Tierra del Fuego. Kinematic modelling indicates an Antarctic Plate origin for Bruce Bank and the SOM is the most plausible setting, prior to translation to the Scotia Plate during Scotia Sea opening.

1 | INTRODUCTION

Cenozoic opening of the Drake Passage, driven by growth of the Scotia Plate and westward subduction of the South American Plate, is widely seen as one of the major tectonic events that had a strong influence on the bathymetry and ocean dynamics linked to the formation of the Antarctic Circumpolar Current (ACC). Drake Passage opening led to crustal block dispersal forming the present-day North and South Scotia ridges (Figure 1) that influence the flows that define the modern ACC. The pre-translation position of the elevated banks and crustal blocks of the Scotia ridges are largely unknown, hindered by almost no geological control on the submerged banks of the Scotia Sea. As a consequence, the nature of early ocean pathways during Drake Passage opening are unknown and ocean models cannot use realistic constraints to identify any climate impacts from palaeogeographic changes (Sarkar et al., 2019; Toumoulin, Donnadieu, Batenburg, Poblete, & Dupont-Nivet, 2020).

Recent geological studies on the blocks that form the North Scotia Ridge have established connections to the Fuegian Andes (Dalziel, Macdonald, Stone, & Storey, 2021; Riley et al., 2019). However, the early development of the South Scotia Ridge (SSR), and how its geology relates to South America, the Antarctic Peninsula and the South Orkney microcontinent (SOM) remain unclear. Bruce and Pirie banks, which have received no prior geological investigation, are studied here using dredge sampling and detrital zircon geochronology to interpret their geological history. Our results and kinematic analysis in GPlates provide new constraints on the tectonic configuration that existed at the early stages of Drake Passage opening.

2 | GEOLOGICAL SETTING

The Scotia Plate is predominantly formed of Cenozoic oceanic crust created on the West Scotia Ridge and on the western flank of the

East Scotia Ridge (Figure 1), as well as a central zone, possibly consisting of Cretaceous oceanic crust (Eagles, 2010).

The formation of oceanic crust of the Scotia Plate initiated during the Late Eocene/Early Oligocene (Maldonado et al., 2014) and led to the severance of the land bridge and rifting and dispersal of continental fragments, combined with westward dipping subduction at the Weddell Sea front (Maldonado et al., 2014; Figure 1). It is the phase of tectonic activity during the latest Oligocene to latest Miocene that shaped the Scotia Sea that is recognizable today (Figure 1) with continental block dispersal along the North and South Scotia ridges and spreading along the segmented West Scotia Ridge (Eagles & Jokat, 2014).

The SSR is a fault-bounded array of mostly submerged continental fragments and discrete basins extending from the South Shetland Islands in the west to Herdman Bank in the east (Figure 2). The largest continental fragment of the SSR is the SOM, which is emergent at the South Orkney Islands (Figure 2) where the geology is dominated by an accretionary complex of metamorphosed Permian–Triassic sedimentary rocks (Flowerdew, Riley, & Haselwimmer, 2011; Figure 3). North of the SOM, the submerged continental fragments of the SSR are separated by steep-sided discrete troughs and basins (Figure 2). The basins and banks are bounded to the south by a sinistral transcurrent fault defining the boundary between the Scotia and Antarctic plates (Figure 1).

Several authors (e.g. Lodolo, Civile, Vuan, Tassone, & Geletti, 2010) have commented that the geology of the topographic highs from Terror Rise to Herdman Bank are largely unknown, although they are broadly thought to represent thinned continental crust based on seismic reflection profiles that are not characteristic of basaltic crust (Galindo-Zaldívar et al., 2002). However, at least parts of Discovery Bank and Jane Bank (Figure 2) have a significant magmatic component, which is linked to the Oligocene–Miocene (~30–10 Ma) development of the ancestral South Sandwich arc (ASSA; Pearce et al., 2014; Riley, Burton-Johnson, Leat, Hogan, & Halton, 2021). The topographic highs of Bruce and Pirie banks (Figure 2) will be explored here to investigate their relationship to the geological successions of the South Orkney Islands, the northern Antarctic Peninsula and Tierra del Fuego.

The pre-Eocene configuration of the crustal blocks of the SSR prior to Scotia Sea development and Drake Passage opening has been discussed by many workers (e.g. Dalziel, Lawver, Norton, & Gahagan, 2013), but their pre-translation configuration is hampered by uncertainty regarding their Palaeozoic–Mesozoic geological history. The broad consensus is that the SOM separated from the Antarctic Peninsula during Oligocene opening of Powell Basin (Eagles & Livermore, 2002), and that the SOM originated close to the tip of the Fuegian Andes (van de Lagemaat et al., 2021).

Statement of significance

The origin and dispersal of continental fragments that accompanied the opening of the Scotia Sea reflects the relative motions of the South American and Antarctic plates during the opening of Drake Passage and development of deep ocean gateways. We use geochronology and kinematic modelling to determine the tectonic setting of the Antarctic and South American plates from the mid Cretaceous to the present day.

3 | GEOLOGICAL SAMPLING

Geological samples were dredged at multiple sites from Bruce and Pirie banks during cruise DY088 on *RRS Discovery* (March–April 2018). Sample sites with steep topography (>25°) were selected to reduce the risk of sampling glacial dropstones, and to increase the likelihood of recovering in situ lithologies.

3.1 | Bruce bank

Five separate sites were dredged at Bruce Bank (Figure 2); at three sites (DR.223, DR.224, DR.226; Figure 2) the recovered samples are dominated (>70%) by a very fine-grained, pale grey/brown, poorly lithified sedimentary unit considered to represent more recent cover rocks. Alongside the poorly lithified units, coarse-grained, in situ sedimentary lithologies were also recovered and represent the bedrock beneath the more recent cover sediments. The other two dredge sites (DR.225 and DR.227; Figure 2) are

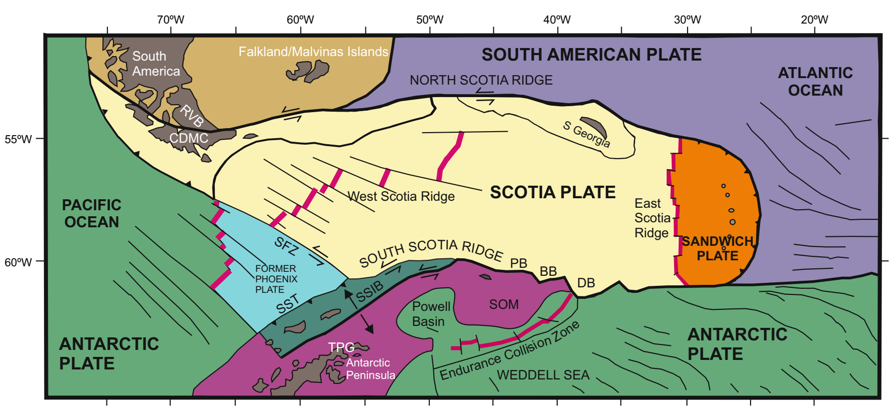


FIGURE 1 Tectonic setting of the Scotia Plate (Maldonado et al., 2006). BB, Bruce Bank; CDMC, Cordillera Darwin Metamorphic Complex; DB, Discovery Bank; PB, Pirie Bank; RVB, Rocas Verdes Basin; SFZ, Shackleton fracture zone; SOM, South Orkney microcontinent; SSIB, South Shetland Islands Block; SST, South Shetland trough.

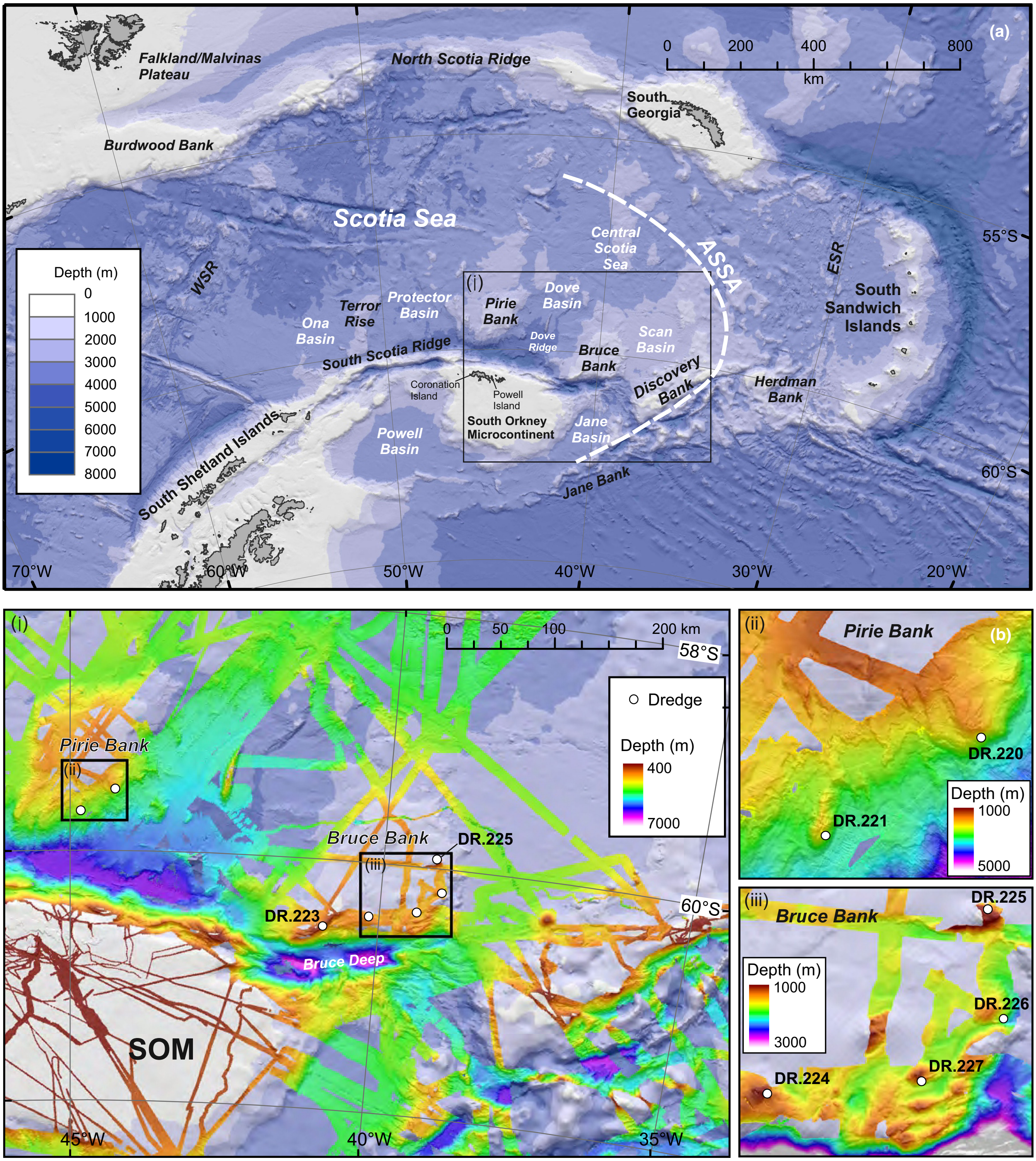


FIGURE 2 (a) Bathymetric map of the Scotia Sea. The position of the ancestral South Sandwich arc (ASSA) is from Pearce et al. (2014); (b) newly acquired bathymetric data and dredge sites. DR.223: 60.539°S, 040.884°W; DR.225: 59.927°S, 039.154°W.

dominated by mafic volcanic and intrusive rocks. Such an assemblage could represent a subvolcanic magmatic system, and lends support to the interpretation that the margins of Scan Basin (Figure 2) are characterized by widespread mafic intrusions and volcanic rocks (Pérez et al., 2019).

3.2 | Pirie bank

Two sites (DR.220 and DR.221; Figure 2) were selected for rock dredging from Pirie Bank. Both dredge sites yielded a significant return of low-grade metasedimentary rocks akin to the geology of

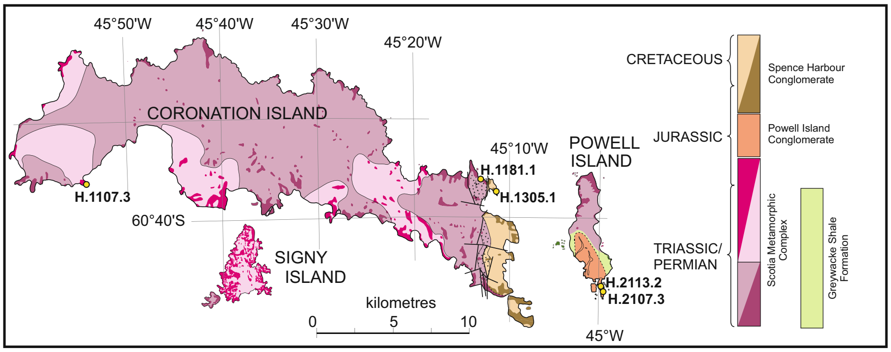


FIGURE 3 Geological map of the South Orkney Islands (Flowerdew et al., 2011). The location of the Permian–Cretaceous samples analysed for their detrital zircon populations (Figure 4) is shown.

Bruce Bank. The provenances of the metasedimentary lithologies are interpreted to be locally derived, given their angular morphology and fresh broken surfaces, implying that they have been sampled in situ.

4 | RESULTS

Although both Bruce Bank and Pirie Bank were dredged, only samples from Bruce Bank were suitable for detrital zircon geochronology analysis due to their coarser grain size.

4.1 | Detrital zircon geochronology (Bruce Bank)

Two sites from the southern and eastern flanks of Bruce Bank were selected for detrital zircon geochronology to investigate their provenance history. Site DR.223 from the southern margin of Bruce Bank is adjacent to the South Orkney plateau, while site DR.225 is slightly inboard of the eastern margin of Bruce Bank (Figure 2).

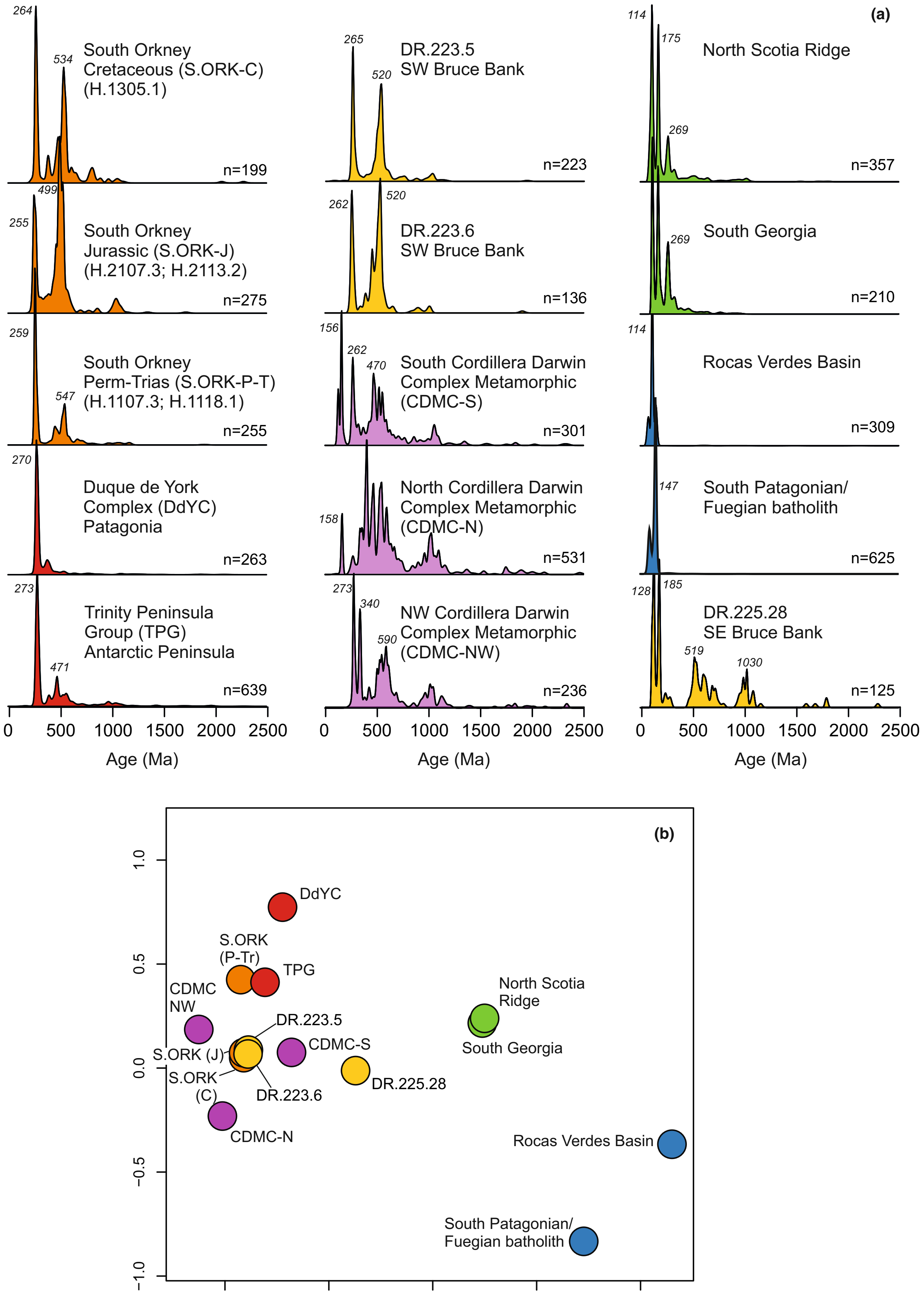
Two metasedimentary samples (DR.223.5 and DR.223.6) were investigated from site DR.223 and their detrital zircon age profiles (Figure 4a) overlap with Cretaceous, Jurassic and Permo-Triassic lithologies (Figure 4b) reported from the South Orkney Islands (Carter, Riley, Hillenbrand, & Rittner, 2017). Sample DR.223.5 is a sandstone and has two prominent age peaks (~265 Ma and ~ 520 Ma) and correlates almost exactly (Figure 4b) with the age profiles of Jurassic and Cretaceous (H.1305.1; H.2107.3; H.2113.2; Figure 3) lithologies from Coronation Island and Powell Island (Carter et al., 2017). Sample DR.223.6 has an almost identical age profile to DR.223.5, although the Permian age peak is marginally younger (~262 Ma) in DR.223.6. A strong correlation between Bruce Bank site DR.223 and Permo-Triassic lithologies from the SOM (H.1107.3; H.1118.1; Figure 3) and the Trinity Peninsula Group (TPG) metasedimentary rocks of the northern Antarctic Peninsula are also evident, as is the correlation to units of the Cordillera Darwin Metamorphic Complex (CDMC; Hervé et al., 2010) of Tierra del Fuego (Figure 4b). The detrital zircon ages from Bruce Bank site DR.223 suggest an Early Triassic maximum depositional age (~235 Ma; Vermeesch, 2021) for the metasedimentary units, akin to the Greywacke Shale Formation of the South Orkney Islands (Figure 3) and the youngest successions of the TPG.

Sample DR.225.28, a silty sandstone, from the eastern sector of Bruce Bank yields a different age profile to site DR.223 (Figure 4b). It is characterized by a Mesozoic age profile, with prominent peaks representing input from Mesozoic age sources (Figure 4a). Relative to site DR.223, the sandstone DR.225.28 also has a broad age spectra through the Neoproterozoic and a prominent Grenville-age peak (Figure 4a). Such an age profile is distinct to the lithologies reported from elsewhere in the region, with the closest correlation to components of the CDMC (Figure 4b).

4.2 | Recent sedimentary cover

At several dredge sites along the southern and eastern margins of Bruce Bank, sample recovery was dominated by a soft, fine-grained, pale grey/ silty sandstone. Two samples from dredge site DR.223 were examined to investigate their nannofossil population in an attempt to determine their sediment source and age of deposition (full details in the supplementary material). Samples DR.223.3 and DR.223.4 both yielded well-preserved Palaeogene calcareous nannofossils that strongly indicate an Eocene depositional age (45–40 Ma), with a taxa consistent with cold water deposition. Reworked Cretaceous nannofossils have also been identified and were likely to have been sourced from the SOM and eroded during Eocene inversion (Carter et al., 2017).

FIGURE 4 (a) Kernel density plots of detrital zircon ages from Bruce Bank (this study; Table S1), Trinity Peninsula Group, Duque de York Complex, South Orkney Islands, South Georgia, Fuegian Andes, CDMC (Carter, Curtis, & Schwanenthal, 2014; Hervé et al., 2010; Hervé, Pankhurst, Fanning, Calderón, & Yaxley, 2007; Klepeis et al., 2010) and North Scotia Ridge (Riley et al., 2019); (b) multidimensional scaling maps (Vermeesch, 2013) comparing the age spectra in dissimilar samples calculated using the Kolmogorov–Smirnov statistic. A MDS plot maps the degree of similarity between each sample, with any two points plotting closer if they are more similar. The axis scales are dimensionless and have no physical meaning. The data that support the findings of this study are available in the supplementary material of this article.


(a)
South Orkney Cretaceous (S.ORK-C) (H.1305.1)
n=199
South Orkney Jurassic (S.ORK-J) (H.2107.3; H.2113.2)
n=275
South Orkney Perm-Trias (S.ORK-P-T) (H.1107.3; H.1118.1)
n=255
Duque de York Complex (DdYC) Patagonia
n=263
Trinity Peninsula Group (TPG) Antarctic Peninsula
n=639
DR.223.5 SW Bruce Bank
n=223
DR.223.6 SW Bruce Bank
n=136
South Cordillera Darwin Complex Metamorphic (CDMC-S)
n=301
North Cordillera Darwin Complex Metamorphic (CDMC-N)
n=531
NW Cordillera Darwin Complex Metamorphic (CDMC-NW)
n=236
North Scotia Ridge
n=357
South Georgia
n=210
Rocas Verdes Basin
n=309
South Patagonian/ Fuegian batholith
n=625
DR.225.28 SE Bruce Bank
n=125
Age (Ma)
(b)
DdYC
S.ORK (P-Tr)
TPG
CDMC NW
DR.223.5
CDMC-S
S.ORK (J)
S.ORK (C)
DR.223.6
DR.225.28
CDMC-N
North Scotia Ridge
South Georgia
Rocas Verdes Basin
South Patagonian/ Fuegian batholith

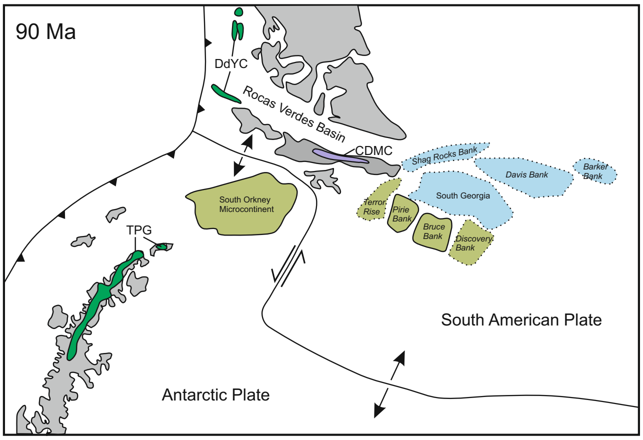


FIGURE 5 Putative palaeo-location of the crustal blocks of the North (blue) and South (olive green) Scotia ridges in the Late Cretaceous (90 Ma) relative to the Fuegian Andes of southern South America and the Antarctic Peninsula. Modified from the reconstructions of Dalziel et al. (2021) and van de Lagemaat et al. (2021). Present day positions of the crustal blocks are shown in Figure 1. Part of the outcrop extent of the Duque de York metasedimentary complex (DdYC) and Trinity Peninsula Group (TPG) are also shown (Castillo et al., 2015). The extent of the Cordillera Darwin metamorphic basement (CDMC) is from Hervé et al. (2010).

5 | DISCUSSION

The SSR is an array of submerged and subaerial crustal blocks that rifted from the Antarctic Peninsula and Fuegian Andes. The current configuration of crustal blocks and basins (Figure 2) is the result of spreading on the West Scotia Ridge, ridge-trench collisions at the SOM and Jane Bank, and extension and oceanic spreading forming basins between the blocks (Maldonado et al., 2014).

Several authors favour a close affinity between Bruce and Pirie banks with the Fuegian Andes (Eagles & Jokat, 2014), however, the crustal blocks have received almost no prior geological investigation (Lodolo et al., 2010). Dredged samples from Bruce and Pirie banks were selected for detrital zircon analysis to help understand the provenance history of the SSR, however, samples from Pirie Bank were mostly fine-grained mudstones and were unsuitable for detrital zircon analysis. Sandstone samples from Bruce Bank share a close affinity and likely continuation to the geology of the South Orkney Islands, with lithologies from Bruce Bank having detrital zircon age profiles (Figure 4) matching those of successions from Coronation and Powell islands (Figure 2). They also share a strong correlation to the TPG metasedimentary rocks of the northern Antarctic Peninsula, as well as components of the CDMC (Figure 4b). In contrast, one sample (DR.225.28) investigated from the eastern flank of Bruce Bank has a detrital zircon age profile distinct to the SOM lithologies, and is closest in age structure to the southern CDMC of Tierra del Fuego (Figure 4b).

The provenance of the Eocene Bruce Bank cover sediments is considered to be reworking of SOM Mesozoic sedimentary rocks. Apatite fission track data from the SOM (Carter et al., 2017) and the Fuegian Andes (Gombosi, Barbeau, & Garver, 2009) record Eocene inversion and rapid cooling at 45–40 Ma, which overlaps with rifting and extension during early opening of Powell Basin (Eagles & Jokat, 2014). This is coincident with a significant sediment provenance shift at ~39 Ma in the Magallanes foreland basin, interpreted as evidence of uplift of the CDMC (Barbeau et al., 2009).

5.1 | Tectonic implications

Most post-Eocene reconstructions (e.g. Eagles & Jokat, 2014) satisfy the geological criteria presented here, including a shared geological history between Bruce Bank and the SOM (Figure 4). However, Cretaceous and older reconstructions do not account for the geological continuity of Bruce Bank and the SOM; Cretaceous configurations show the SOM was adjacent to the northern tip of the Antarctic Peninsula, while Bruce Bank was located southeast of Tierra del Fuego (Figure 5).

To address this issue we present three GPlates-derived kinematic models for the development of the crustal blocks of the SSR (Figure 6), using the rotations for South America and Antarctica of van de Lagemaat et al. (2021), illustrating an Antarctic Plate (Figure 6a) and South American Plate (Figure 6c) origin for Bruce Bank. The pre-Oligocene core of Discovery Bank was separated from Bruce Bank by the Palaeogene Scan Basin, so we have interpreted a shared Mesozoic kinematic history. In addition, given the similarity in lithotypes from Bruce and Pirie banks, we also interpret a common geological history.

A South American Plate origin for the SOM (Figure 6c) would account for the geological overlap between southern Bruce Bank and the SOM as well as the correlation between Bruce Bank with components of the CDMC (Figure 4b). However, this tectonic setting would indicate a strong geological relationship between Bruce Bank and the SOM with components of the North Scotia Ridge and South Georgia, which is not supported in the detrital zircon age profiles (Figure 4). The data presented here and in Riley et al. (2019) clearly indicate a distinct provenance difference between the North and South Scotia ridges.

Therefore, an Antarctic Plate origin for Bruce Bank and the SOM (Figure 6a) is favoured, which would have required translation of the crust forming the banks of the SSR to the Scotia Plate during Eocene Scotia Sea opening. An Antarctic Plate origin for the Bruce Bank is also supported by the close correlation to the TPG of the Antarctic Peninsula. The close correlation between Bruce Bank and parts of the CDMC lends support to the interpretation of Hervé et al. (2010) that the CDMC may represent a crustal block with a distinct history to units elsewhere in Tierra del Fuego and may also have originated on the Antarctic Plate prior to translation to the Scotia Plate (Figure 6b).

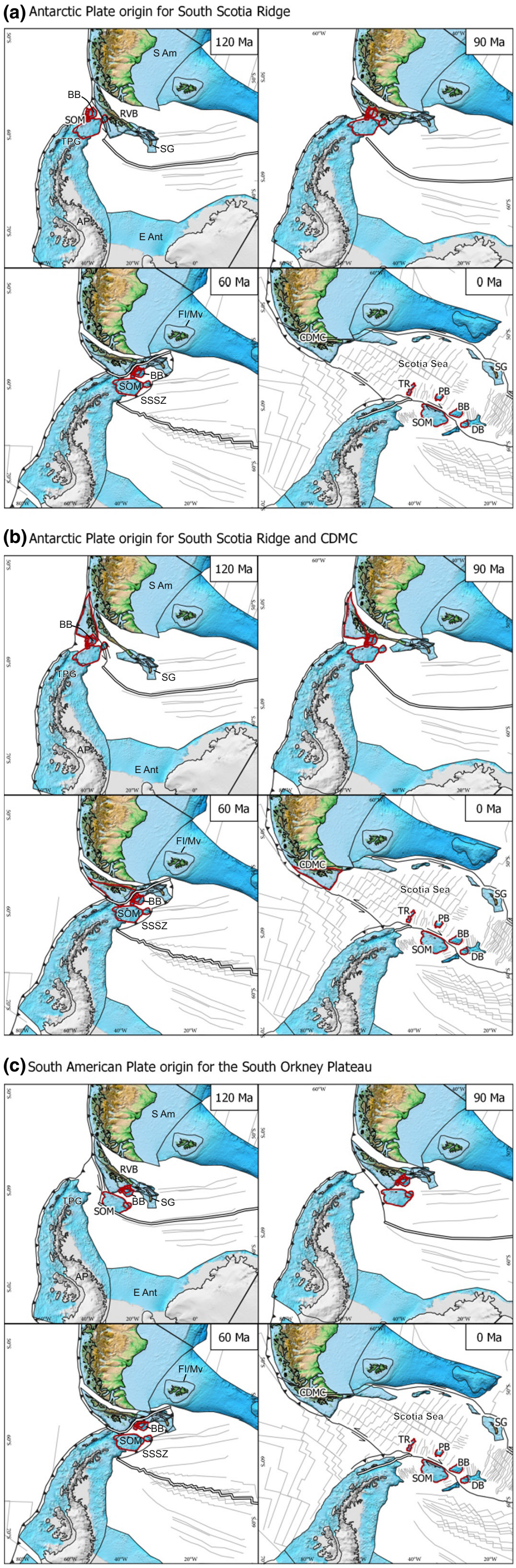


FIGURE 6 GPlates derived kinematic reconstructions of the Antarctic Peninsula–South America–Scotia Sea region from 120 Ma to the present (using the rotations of van de Lagemaat et al., 2021, constrained by the Antarctica–Africa–South America plate circuit). The lithological and zircon provenance data for Bruce Bank (BB) indicates a shared history with the South Orkney Microcontinent (SOM), northern Antarctic Peninsula (Trinity Peninsula Group—TPG) and the Cordillera Darwin metamorphic complex (CDMC). This requires either: (1) that the SOM, BB and potentially the CDMC originated on the Antarctic Plate (a and b), the latter including relative motion between the CDMC and Patagonia); or (2) that the SOM originated on the South American Plate (c), and was transferred to the Scotia Plate during opening of Drake Passage. AP, Antarctic Peninsula; DB, Discovery Bank; E Ant, East Antarctic Plate; FI/Mv, Falkland Islands/Malvinas block; S Am, South American Plate; PB, Pirie Bank; SG, South Georgia; SSSZ, proto-South Sandwich subduction zone; TR, Terror Ris. The GPlates files are available in the supplementary material.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Supporting Information

Appendix S2. Supporting Information

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