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Cretaceous–Paleogene tectonic reconstructions of the South Scotia Ridge and implications for the initiation of subduction in the Scotia Sea

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Abstract: The Cenozoic development of the Scotia Sea and the opening of Drake Passage led to the dispersal of crustal blocks of the North and South Scotia ridges, which today have a strong influence on the pathway of the Antarctic circumpolar current. The pre-translation positions of the crustal fragments of the Scotia ridges are uncertain, with correlations to both the Antarctic and South American plates. We present direct geochronology results ($^{40}Ar/^{39}Ar$) from the Bruce and Jane banks of the South Scotia Ridge that yield Late Cretaceous–Paleogene ages, indicating a pre-translation magmatic history. The basaltic magmatism from Bruce Bank is calc-alkaline, akin to the Cenozoic magmatism of the South Orkney microcontinent and the South Shetland Islands, and agrees with pre-translation tectonic models that place the crustal blocks of the South Scotia Ridge adjacent to the northern Antarctic Peninsula arc. The intra-oceanic arc magmatism at Jane Bank is Late Cretaceous in age (97.2 ± 1.1 Ma) and is therefore inconsistent with models suggesting a Miocene origin as part of the ancestral South Sandwich arc. The development of westwards-directed subduction adjacent to Jane Bank is predicted in some tectonic models as a consequence of Late Cretaceous plate dynamics that developed prior to the Oligocene–Miocene ancestral arc.

Supplementary material: Full $^{40}Ar/^{39}Ar$ datasets and GPlates reconstruction files are available at https://doi.org/10.6084/m9.figshare.c.6639909

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The Cenozoic separation of the Antarctic Peninsula and South America, and the accompanying opening of Drake Passage, was driven by the creation of the Scotia plate and the westwards subduction of the South American plate. The growth of the Scotia plate led to crustal block dispersal along the North and South Scotia ridges (Fig. 1). Today, these ridges form prominent submarine topographic highs and have a strong influence on the pathway of the Antarctic circumpolar current. The pre-translation position of the elevated banks and crustal blocks of the Scotia ridges are the source of considerable debate (e.g. Dalziel *et al.* 2021; Riley *et al.* 2022; Schellart *et al.* 2023), with only limited geological control on the origin of the submerged banks.

Detrital zircon provenance analysis on the crustal blocks that form the North Scotia Ridge point to a geological affinity with the Fuegian Andes (e.g. Carter *et al.* 2014; Riley *et al.* 2019; Dalziel *et al.* 2021), whereas Riley *et al.* (2022) established connections between parts of the South Scotia Ridge and the Antarctic plate. We present here the first direct geochronology results for mafic magmatic rocks from Bruce Bank and Jane Bank of the South Scotia Ridge and examine potential correlations with the Antarctic plate, the timing of the onset of subduction in the Scotia Sea and post-translation magmatism.

Geological setting

The Scotia Sea is located between the Antarctic Peninsula and the South Atlantic Ocean and forms a key component of the circumpolar Southern Ocean. The Scotia Sea is bound by the submerged mountainous belts of the North and South Scotia ridges, which form extensive ridges up to 1500 km in length and extend from the Shackleton Fracture Zone in the west to the East Scotia Ridge in the east (Fig. 1). Prior to the development of the Scotia plate, the Magallanes and Central Scotia plates formed as a result of plate reorganization and later (Oligocene–Miocene) seafloor spreading on the West Scotia Ridge (Eagles and Jokat 2014; Maldonado *et al.* 2014) and also spreading on the East Scotia Ridge from *c.* 15 Ma to the present day (Larter *et al.* 2003). The central zone of the Scotia Sea is less well constrained and consists of oceanic crust and potentially extended continental crust of uncertain age (Eagles 2010). Proposed oceanic crustal ages for the central Scotia Sea range from 21 to 7 *Ma* (Barker 2001), Miocene (Vérard *et al.* 2012), Eocene to mid-Miocene (Beniest and Schellart 2020), Early Cretaceous (Dalziel *et al.* 2013*b*) and Late Jurassic to mid-Cretaceous (Eagles 2010; Riley *et al.* 2019).

The creation of the Scotia plate from the Late Paleogene to the Neogene developed alongside the westwards-directed subduction of the South American plate (Fig. 1). Subduction continues today at the South Sandwich Islands, which form an intra-oceanic island arc chain of volcanoes on the Sandwich plate (Fig. 1). Prior evidence for subduction of the South American plate beneath the Central Scotia plate during the Late Cenozoic has been identified in the central Scotia Sea, where Dalziel *et al.* (2013*a*) described a chain of eroded volcanoes that have been dated from the Oligocene to the Miocene. Dalziel *et al.* (2013*a*) interpreted the chain of eroded volcanoes as an ancestral island arc from the Late Cenozoic that predates the present-day South Sandwich island arc. The ancestral South Sandwich arc (ASSA; Fig. 2a) had a duration of at least 20 myr (*c.* 31–10 Ma; Dalziel *et al.* 2013*a*; Riley *et al.* 2021) and

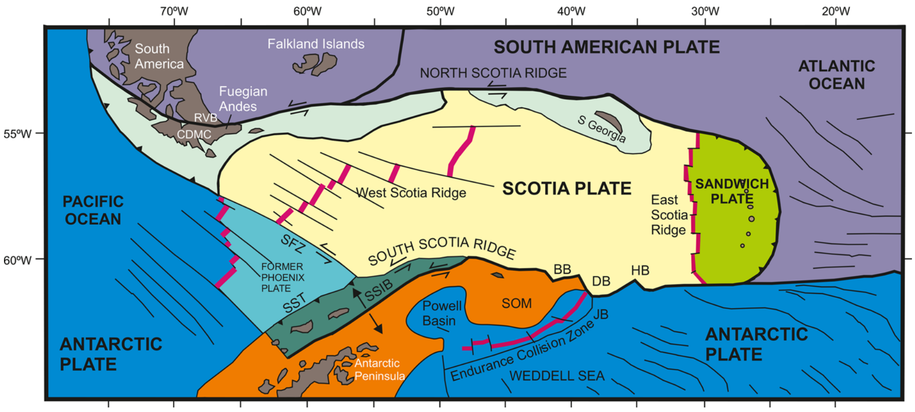

Fig. 1. Tectonic setting of the Scotia plate. BB, Bruce Bank; CDMC, Cordillera Darwin metamorphic complex; DB, Discovery Bank; HB, Herdman Bank; JB, Jane Bank; RVB, Rocas Verdes Basin; SFZ, Shackleton Fracture Zone; SOM, South Orkney microcontinent; SSIB, South Shetland Islands Block; SST, South Shetland Trough. Source: Maldonado *et al.* (2006).

has geochemical characteristics indicating an intra-oceanic island arc setting (Pearce *et al.* 2014; Riley *et al.* 2021).

Other studies have indicated a much longer geological history for the ASSA, with subduction of the Antarctic plate in the NW Weddell Sea (Fig. 1) potentially initiating during the Late Cretaceous (Eagles 2010; Vérard *et al.* 2012; van de Lagemaat *et al.* 2021) or Early Paleogene (Maldonado *et al.* 2014), but with no determined age to support an older history. The onset of subduction was interpreted to be the result of a shift in relative motion between the continental blocks of South America and the Antarctic Peninsula (Barker 2001; Eagles 2010; van de Lagemaat *et al.* 2021). This change in relative plate motion would have led to convergence at a plate boundary in the northwestern sector of the Weddell Sea (the Endurance Collision Zone; Fig. 1) during the mid-Cretaceous (Barker *et al.* 1991; van de Lagemaat *et al.* 2021), *leading to the early initiation of* subduction.

Schellart *et al.* (2023) proposed a different mechanism for the initiation of subduction in the Scotia Sea as a result of a subduction invasion polarity switch, with stresses from the long-lived eastwards-directed subduction beneath the Antarctic–South American margin leading to the initiation of westwards subduction, potentially in the mid-Cretaceous. The model suggests that compressive stresses develop in the overriding plate as a result of strong trenchwards basal drag induced by subduction-driven whole-mantle poloidal return flow.

A factor in understanding the mid-Cretaceous tectonics of the proto-Pacific margin prior to the development of the Scotia Sea is the closure of the Rocas Verdes back-arc basin (Fig. 1) at c. 100 Ma associated with underthrusting of the Rocas Verdes oceanic crust prior to sedimentation (Muller *et al.* 2021).

South Scotia Ridge

The South Scotia Ridge is a prominent east–west-trending array of submarine crustal fragments (the Terror, Pirie, Bruce, Discovery and Herdman banks) separated by steep-sided ocean basins (the Ona, Protector, Dove and Scan (Discovery) basins; Fig. 2) that extends from the Shackleton Fracture Zone in the west to the Sandwich plate in the east (Fig. 1). The South Scotia Ridge is cut by a sinistral transform fault that separates the Scotia and Antarctic plates (Fig. 1). Separate from the continental fragments of the South Scotia Ridge is the larger crustal block of the South Orkney microcontinent, which is exposed at its northern margin, forming the South Orkney Islands (Fig. 2). The South Orkney microcontinent was contiguous with the northern Antarctic Peninsula, but separated during the Late Eocene–Oligocene rifting that led to the development of the Powell Basin (Eagles and Livermore 2002), the Scan Basin (Eagles *et al.* 2006) and presumably other rifted basins of the South Scotia Ridge (Pérez *et al.* 2019). Its geology is predominantly Permian–Triassic turbidites forming part of an accretionary complex (Flowerdew *et al.* 2011; Riley *et al.* 2023).

The South Orkney Islands succession is cut by a suite of dykes that were provisionally dated as Early Cenozoic (referred to in King and Barker 1988) and were correlated to Cenozoic arc magmatism of the Antarctic Peninsula. Basaltic rocks with an arc composition have also been dredged (D.93, D.95, D.96; Fig. 2) from the western and eastern margins of the South Orkney microcontinent and have been dated in the interval 85–68 Ma (K–Ar whole-rock analysis; Barber *et al.* 1991), whereas basalts recovered from the southern margin of Powell Basin (D.64; Fig. 2) have been dated in the interval 49–47 Ma (Barber *et al.* 1991).

The geology of the crustal blocks of the South Scotia Ridge are largely unknown (e.g. Lodolo *et al.* 2010; Civile *et al.* 2012), but are generally considered to be thinned continental crust on the basis of seismic reflection profiles that are not characteristic of basaltic crust (Galindo-Zaldívar *et al.* 2002). Udintsev *et al.* (2012) reported dredged lithologies of paragneiss, granitoid and sedimentary rocks that they interpreted to be *in situ* and may correlate with the geology of the South Orkney Islands. The geology of the southern margin of Bruce Bank has been examined by Riley *et al.* (2022), who investigated the provenance of metasedimentary lithologies dredged from depths of *c.* 850 m. Detrital zircon geochronology of the metasedimentary units from Bruce Bank are consistent with a direct correlation to the Mesozoic successions of the South Orkney Islands and also share a geological affinity with the northern Antarctic Peninsula and components of the Cordillera Darwin metamorphic complex of Tierra del Fuego (Fig. 1).

To the east of Bruce Bank, Discovery Bank and the more southerly Jane Bank (Fig. 2a) are interpreted to have a geological history that is distinct from the crustal blocks further west. Parts of the Discovery and Jane banks are interpreted to preserve Oligocene–Miocene volcanism that developed in an intra-oceanic island arc setting and represent the southern sector of the ASSA (Barker *et al.* 1984; Pearce *et al.* 2014; Riley *et al.* 2021).

Several researchers have considered the Eocene configuration of the crustal blocks of the South Scotia Ridge prior to the development of the Scotia Sea and the opening of Drake Passage (e.g. King and Barker 1988; Vérard *et al.* 2012; Dalziel *et al.* 2013*b*, 2021; Eagles and Jokat 2014; Galindo-Zaldívar *et al.* 2014; Pérez *et al.* 2019; van de Lagemaat *et al.* 2021; Riley *et al.* 2022; Schellart *et al.* 2023). The broad consensus is that the continental fragments of the South Scotia Ridge, including the South Orkney microcontinent, originated close to the southern tip of the Fuegian Andes (Fig. 1) based on their Eocene palaeolocations. This was developed further by Riley *et al.* (2022), who used zircon age provenance combined with kinematic modelling to determine that the crustal blocks of the South Scotia Ridge had a close relationship with the Antarctic plate and the Cordillera Darwin metamorphic complex in the Late Mesozoic.

The topographic highs of the Bruce and Jane banks (Fig. 2a) are explored here to investigate their relationship with the geological successions of the South Orkney Islands, the other crustal blocks of the South Scotia Ridge and the northern Antarctic Peninsula/

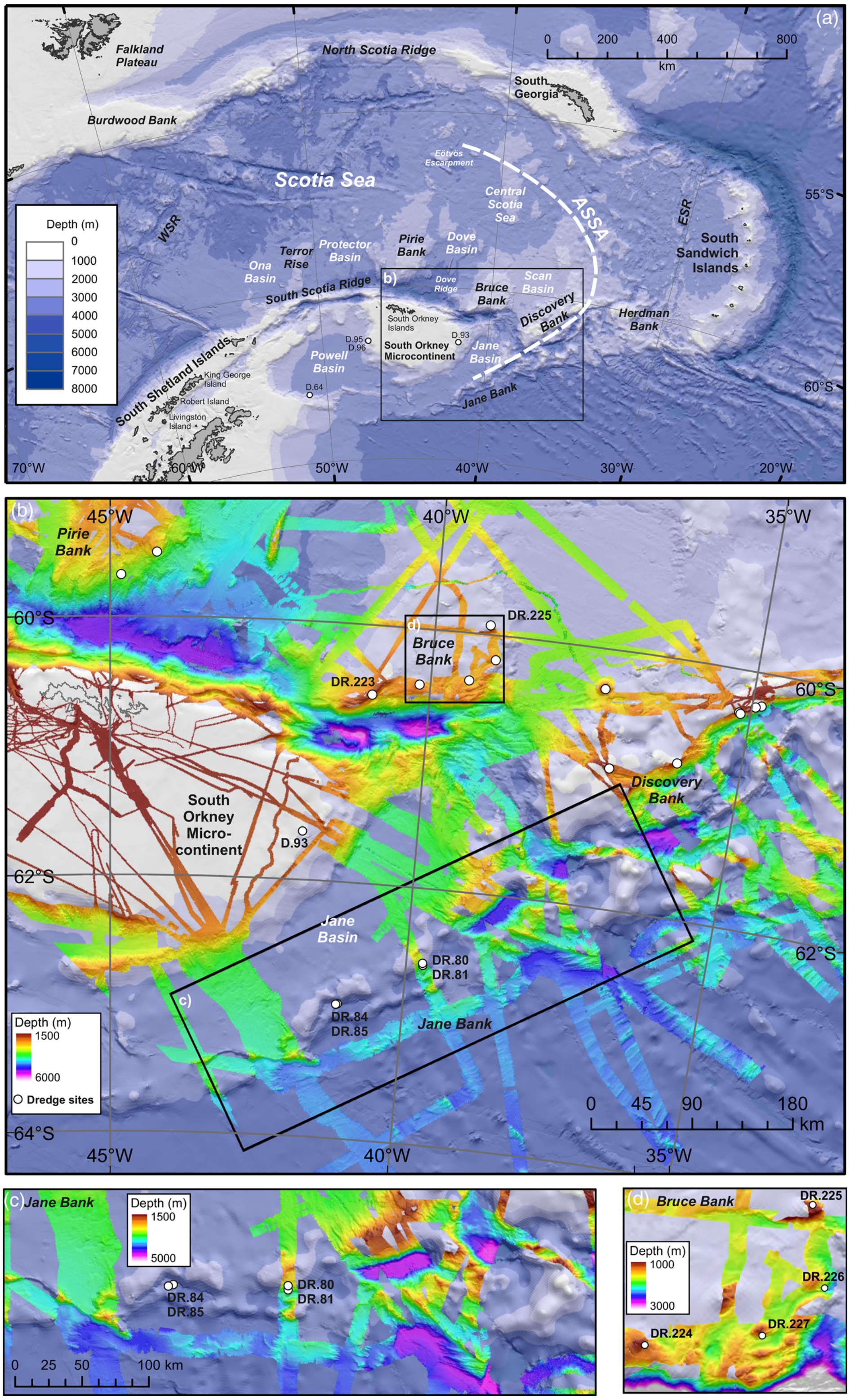

Fig. 2. Bathymetric map of the Scotia Sea. (**b**–**d**) Newly acquired bathymetric data and dredge sites (where new Ar/Ar data are acquired) DR.225 (59.927° S, 039.154° W) and DR.84 (62.468° S, 039.785° W). The Eötvös Escarpment has also been referred to as 'Starfish Seamount'. ASSA, ancestral South Sandwich arc; WSR, West Scotia Ridge; ESR, East Scotia Ridge. Source: in part (a), the position of the ancestral South Sandwich arc is from Pearce *et al.* (2014).

southern Patagonia. We investigate the mafic magmatic rocks of the central Bruce Bank to determine if they are related to the opening of Scan Basin (Pérez *et al.* 2014) or whether they have a pre-translation geological history. We also examine the age of Jane Bank volcanism and whether it forms an extension of the Oligocene–Miocene ASSA (cf. Pearce *et al.* 2014) or forms part of an older magmatic basement to the crustal block.

Bruce Bank is *c.* 120 km wide and is bounded by discrete basins on three sides: Scan Basin to the east, Dove Basin to the west and the deeply incised (*c.* 6000 m depth) Bruce Deep to the south, which separates Bruce Bank from the adjacent South Orkney microcontinental block (Fig. 2b). Seismic data from Scan Basin, east of Bruce Bank (Fig. 2a), indicates that the eastern margin of Bruce Bank has facies of continental or a transitional nature, in contrast with the widespread mafic intrusions and oceanic crust that characterize the seafloor of Scan Basin (Pérez *et al.* 2014). Eagles *et al.* (2006) referred to Scan Basin as the 'Discovery Basin' and suggested it opened prior to 42 Ma or at 36–33 Ma, which is in close agreement with the interpretation of Schreider *et al.* (2017), who determined that oceanic spreading took place in the northern part of the Scan Basin along a NW–SE-trending spreading centre during the interval 35–29 Ma. These estimates also overlap with an age of

30.2 Ma for basin formation derived from heat flow analysis (Barker *et al.* 2013), although Pérez *et al.* (2014) suggested a later (Oligocene) opening for Scan Basin.

Jane Bank is an elongate crustal block separated from the South Orkney microcontinent by Jane Basin (Fig. 2b). Jane Bank was considered by Pearce *et al.* (2014) to form a Miocene segment of the ASSA based on a general younging trend (from the available geochronology) from the north (Oligocene) to the south (Miocene) of the ancestral arc. No geochronology is available for Jane Bank, but geochemical analysis (Barker *et al.* 1984; Pearce *et al.* 2014) of samples collected at two dredge sites (Barker *et al.* 1984) were interpreted to infer an intra-oceanic arc setting akin to the neighbouring Discovery Bank (Fig. 2a). Jane Basin to the NW of Jane Bank (Fig. 2a) has been interpreted to represent a back-arc basin (Barker *et al.* 1984), although a post-subduction origin has also been proposed (Bohoyo *et al.* 2002).

Geological sampling and bathymetry

Geological samples were dredged from several sites across Bruce Bank during British Antarctic Survey cruise DY088 on the RRS *Discovery* (March–April 2018) and sites from Jane Bank were dredged in March 1981 (cruise SHACK80) on the RRS *Shackleton*. Sampling sites with steep topography were selected to reduce the risk of sampling glacial dropstones and to increase the likelihood of recovering *in situ* lithologies.

Site selection on Bruce Bank was determined using the onboard EM-122 multibeam echosounder, combined with available GEBCO data (www.gebco.net/) and an SBP-120 echosounder for sub-bottom profile information to identify sites with only minor draped sediments. The bathymetry data indicated that the eastern and southern margins of the Bruce Bank would provide the most suitable sites for rock dredging because they were characterized by steeper slopes (>25°). The dredge sites on Jane Bank were located on east-facing steep (>25°) scarp slopes (Barker *et al.* 1984). The locations of the dredge sites are shown in Figure 2b–d.

Sample descriptions and methodology

Bruce Bank

Samples were dredged from five sites on the eastern and southern margins of Bruce Bank where the steepest scarp slopes (>25°) were identified following multibeam and sub-bottom profile surveys. Although the sediment cover was anticipated to be minimal on the steepest slopes, three sites (DR.223, DR.224 and DR.226; Fig. 2d) were characterized by the high recovery (>70%) of a poorly lithified, fine-grained sedimentary unit. This unit was examined by Riley *et al.* (2022), who interpreted an Eocene age and cool water deposition for the cover rocks based on their nannofossil assemblage. Alongside the poorly lithified units, coarse-grained, *in situ* sedimentary lithologies were recovered from site DR.223 and were interpreted to represent the bedrock beneath the more recent, poorly lithified cover sediments. The metasedimentary units were examined by Riley *et al.* (2022) and interpreted to be closely related to the Late Mesozoic successions exposed in the South Orkney Islands.

The two other dredge sites (DR.225 and DR.227; Fig. 2d) on Bruce Bank are characterized by mafic magmatic lithologies, including volcanic units, possible dyke rocks and coarser grained lithologies (gabbro and ultramafic units). The recovered material from the dredge sites of eastern Bruce Bank supports the interpretations of both Civile *et al.* (2012) and Pérez *et al.* (2014), who suggested that the margins of Scan Basin and eastern Bruce Bank are likely be dominated by mafic intrusions and volcanic units. Two samples from site DR.225 (*c.* 950 m depth) are examined here for their $^{40}Ar/^{39}Ar$ geochronology and provide the first direct geochronology results for igneous rocks from Bruce Bank. Sample DR.225.14 is from a mafic porphyritic lithology interpreted as a probable hypabyssal unit and DR.225.27 is a fine-grained basaltic lava with phenocrysts of olivine and pyroxene.

Jane Bank

Four sites (DR.80, DR.81, DR.84 and DR.85; Fig. 2c) were selected for rock dredging on the SE margin of Jane Bank at depths in the range 5300–1700 m. The locations were identified based on slope angle analysis, with sites >25° deemed the most suitable for recovering *in situ* material with no sediment cover (Barker *et al.* 1984). The dredge sites yielded a significant return of mafic–silicic volcanic rocks and volcaniclastic lithologies characterized by a thin (few millimetres) Fe–Mn crust. A fine-grained basaltic lava (DR.84.8) from dredge site DR.84 (*c.* 1900 m depth) is dated here. The geochemistry of volcanic rocks from neighbouring dredge sites DR.80 and DR.85 was presented in Pearce *et al.* (2014) and is discussed further here.

Analytical methods

$^{40}Ar/^{39}Ar$ dating was performed at the Department of Earth Sciences, The Open University (Milton Keynes, UK). The samples were crushed using a pestle and mortar and the crushate was sieved and washed repeatedly in deionized water to remove dust and clay particles from the surfaces of all the size fractions. Using a binocular microscope, whole-rock pieces that were free from alteration were selected for further analysis. The picked separates were cleaned ultrasonically in acetone and deionized water, dried using a hot-plate and then packaged in aluminium foil packets *c.* 10 mm × 10 mm in size prior to irradiation.

Samples were irradiated at the McMaster Nuclear Reactor (McMaster University, Hamilton, Ontario, Canada) in reactor position 8E for 120 h using Cd shielding. The neutron flux was monitored using biotite mineral standard GA1550, which has an age of 99.738 ± 0.104 Ma (Renne *et al.* 2010). Standards were packed either side of the unknown samples for irradiation and analysed using the single-grain fusion method with a 1059 nm CSI fibre laser and an MAP215-50 mass spectrometer. The J-values were calculated by linear extrapolation between the two measured J-values. The values for each sample are shown in the data table and a 0.5% error on J-value was used.

The irradiated samples were loaded into an ultra-high-vacuum system and a 1059 nm CSI fibre laser was focused into the sample chamber and used to step-heat the basalt samples. After passing through a liquid nitrogen trap, the extracted gases were cleaned for 5 min using two SAES AP-10 getters (one at 450°C and one at room temperature), following which the gases were introduced into an MAP 215-50 mass spectrometer for analysis. The mass discrimination value was measured at 283 for $^{40}Ar/^{36}Ar$ (using a calibration noble gas mixture of known composition). System blanks were measured before and after every one or two sample analyses. The gas clean-up and inlet was fully automated, with measurements of ^{40}Ar, ^{39}Ar, ^{38}Ar, ^{37}Ar and ^{36}Ar, each for ten scans, and the final measurements are extrapolations back to the inlet time.

The system blanks measured before and after every one or two sample analyses were subtracted from the raw sample data. The results were corrected for ^{37}Ar and ^{39}Ar decay and neutron-induced interference reactions. We used correction factors of $(^{39}Ar/^{37}Ar)Ca = 0.00065 \pm 0.00000325$, $(^{36}Ar/^{37}Ar)Ca = 0.000265 \pm 0.000001325$ and $(^{40}Ar/^{39}Ar)K = 0.0085 \pm 0.0000425$ based on analyses of Ca and K salts. Ages were calculated using the atmospheric $^{40}Ar/^{36}Ar$ ratio of 298.56 (Lee *et al.* 2006) and the decay constants of Renne *et al.* (2010). All data corrections were carried out using an Excel macro and the ages were calculated using Isoplot 4.15 (Ludwig

2012). All ages are reported at the 2σ level and include a 0.5% error on the J-value. Plateau criteria of at least 50% of the ^{39}Ar release in at least three consecutive steps were used. The ^{40}Ar/^{39}Ar data are presented in Supplementary Table 1.

For step-heating experiments, data are usually presented as a step-heating release spectrum and a plateau age can be calculated where the plateau criteria are met. The same data can also be plotted on an inverse isochron correlation plot and the intercepts on this plot allow a calculation of the age of the sample (from the ^{39}Ar/^{40}Ar intercept) and the ^{40}Ar/^{36}Ar ratio of the intercept. The isochron correlation plot allows the ^{40}Ar/^{36}Ar ratio for the sample to be calculated rather than assuming that the ratio is atmospheric, as is the case in the plateau age (^{40}Ar/^{36}Ar of atmospheric Ar 298.56) (Lee *et al.* 2006). Ideally, the agreement between both calculated ages and an atmospheric ratio for the intercept would provide the most confidence that the age calculated is reliable.

Results

^{40}Ar–^{39}Ar geochronology

Three samples from the eastern margin of Bruce Bank and southern Jane Bank were selected for ^{40}Ar/^{39}Ar geochronology. Sample DR.225.14 (dolerite dyke, Bruce Bank) gave a plateau age of 52.9 ± 1.5 Ma (2σ) (Fig. 3a), containing 100% of the ^{39}Ar. The inverse isochron plot for the same sample (Fig. 3b) yielded an age of 52.4 ± 3.0 Ma (2σ) and a ^{40}Ar/^{36}Ar intercept of 302 ± 12, which is within error of the atmospheric value (298.56 determined by Lee *et al.* 2006) and appears to be tightly constrained. Both the plateau and inverse isochron ages overlap at the 2σ level and an ^{40}Ar/^{36}Ar intercept of atmospheric composition suggests that this sample has not been affected by excess Ar.

Sample DR.225.27 (basaltic lava, Bruce Bank) produced a more disturbed release spectra compared with sample DR.225.14 and gave a plateau age of 79.2 ± 2.3 Ma (2σ; MSWD = 1.07) (Fig. 3c), containing 61.7% of the ^{39}Ar. The inverse isochron plot for sample DR.225.27 (Fig. 3d) yielded an age of 78.2 ± 5.2 Ma (2σ) and a ^{40}Ar/^{36}Ar intercept of 295 ± 14, which is within error of the atmospheric value (298.56 determined by Lee *et al.* 2006). Although this seems to be tightly constrained, it is accompanied by a large MSWD (2.1), but an ^{40}Ar/^{36}Ar intercept of atmospheric composition suggests that this sample has not been affected by excess Ar.

Sample DR.84.8 (basaltic lava, Jane Bank) produced a coherent plateau despite some structure and yielded an ^{40}Ar/^{39}Ar plateau age of 97.2 ± 1.1 Ma (2σ; MSWD = 1.03) (Fig. 3e), containing 99.68% of the ^{39}Ar. The inverse isochron plot for sample DR.84.8 (Fig. 3f) yielded an age of 97.4 ± 1.0 Ma (2σ; MSWD = 0.93) and a ^{40}Ar/^{36}Ar intercept of 280 ± 23, which is within error of the atmospheric value (298.56 determined by Lee *et al.* 2006), suggesting that this sample has not been affected by excess Ar.

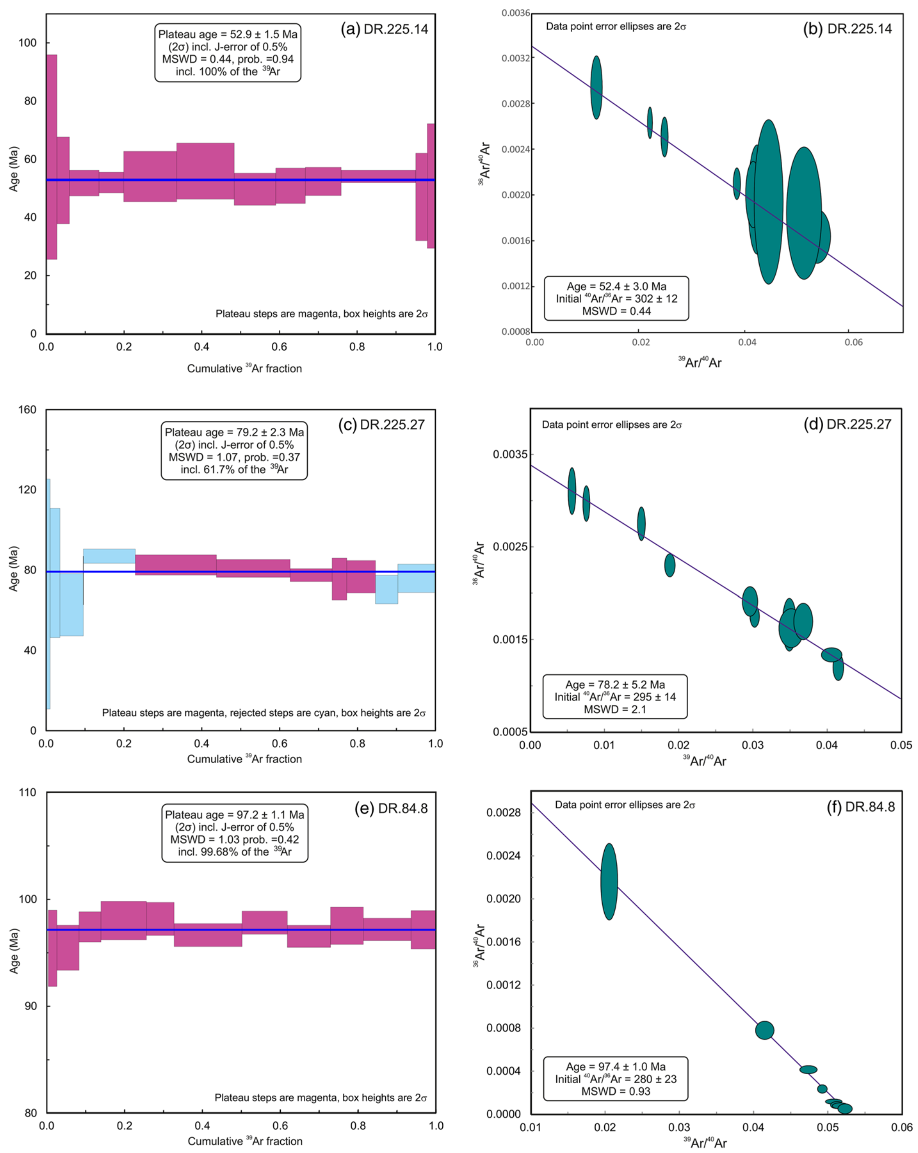

Fig. 3. ^{39}Ar release spectra and inverse isochron plots for (**a**, **b**) sample DR.225.14, (**c**, **d**) sample DR.225.27 and (**e**, **f**) sample DR.84.8.

Petrography and geochemistry

Four samples (DR.225.13, DR.225.14, DR.225.27 and DR.225.30) from site DR.225 on Bruce Bank (Fig. 2b) were examined for their geochemistry (Riley *et al.* 2021). The porphyritic (plagioclase and hornblende) mafic dykes (DR.225.13 and DR.225.14) are calc-alkaline basaltic andesites with Mg values of *c.* 56, weakly enriched ($La_N/Yb_N = 2–4.5$) and have been dated (this study) at 52.9 ± 1.5 Ma (DR.225.14). The fine-grained basaltic lava (DR.225.27) from Bruce Bank (79.2 ± 2.3 Ma) is olivine and pyroxene phyric, is very similar in composition to DR.225.14 and is basaltic andesite (calc-alkaline) in composition. Sample DR.225.30 is a coarse-grained calc-alkaline gabbro dominated by plagioclase and pyroxene phenocrysts. The gabbro is characterized by high MgO (29.3 wt%) and Cr contents >1000 ppm and Ni contents of 330 ppm and may be a cumulate.

Pearce *et al.* (2014) analysed four samples from Jane Bank, which were initially described by Barker *et al.* (1984) as intermediate–acidic island arc tholeiitic volcanic rocks. The lavas are plagioclase phyric and plagioclase–clinopyroxene phyric. Sample DR.80.2 is a basaltic andesite and two samples (DR.81.1 and DR.81.2) from site DR.81 (Fig. 2c) are dacite–rhyolite in composition; a basaltic andesite lava from site DR.85 (adjacent to site DR.84) was also analysed (DR.85.5). Based on their relatively depleted geochemistry, Pearce *et al.* (2014) interpreted the Jane Bank tholeiitic rocks to represent the southern sector of the Oligocene–Miocene ASSA and correlated them with the basaltic lavas of Discovery Bank.

Basaltic rocks were also dredged from the neighbouring South Orkney microcontinent (Fig. 2). Their geochemistry has been described previously by Barber *et al.* (1991). The rocks were dated (K–Ar) as Late Cretaceous (84.6 ± 2.5 Ma to 68.3 ± 4.1 Ma) and Barber *et al.* (1991) interpreted them as calc-alkaline, arc-related basaltic andesites based on their depletion in the high field strength elements. They were interpreted to predate the Oligocene separation of the South Orkney microcontinent from the Antarctic Peninsula and, based on their subduction-related geochemical signature and Late Cretaceous age, the dredged rocks were considered to be an easterly extension of the magmatism of the Antarctic Peninsula (King and Barker 1988).

Mafic rocks from the South Scotia Ridge region are plotted in Figure 4 to aid our understanding of their likely tectonic setting using one of the most useful diagrams (Th/Yb v. Nb/Yb) to interpret contributions from the subducting slab and crustal components in an arc setting. The Bruce Bank and Jane Bank basalts are plotted alongside the mid-ocean ridge basalt–ocean island basalt array and the field of the South Sandwich intra-oceanic arc lavas, which are interpreted to have formed from an asthenospheric source because no pre-existing continental lithosphere is known to exist beneath most of the arc, although older crust may underlie its southern part (Leat *et al.* 2002, 2016). Also plotted are basaltic rocks from several localities across the Scotia Sea region, including basalts from Discovery Bank (Pearce *et al.* 2014; Riley *et al.* 2021), the Eötvös Escarpment (Fig. 2; Dalziel *et al.* 2013*a*), the North Scotia Ridge (Riley *et al.* 2019) and the field of continental arc basalts from Livingston Island (South Shetland Islands; Leat and Riley 2021).

The basalts from the Oligocene–Miocene ASSA exposed at Discovery Bank broadly fall within the field of the present-day South Sandwich island arc lavas, which is representative of an intra-oceanic island arc (Fig. 4). Basaltic rocks from the Eötvös Escarpment (Dalziel *et al.* 2013*a*), which also forms part of the ASSA, plot at slightly higher Nb/Yb values, but are generally depleted. There is a significant range within the composition of the Discovery Bank basalts, from depleted to more enriched compositions, that overlap with those from the North Scotia Ridge (Riley *et al.* 2019) and Bruce Bank (Pearce *et al.* 2014; Riley *et al.* 2021). Two basaltic/basaltic andesite samples (DR.80.2 and DR.85.5) from Jane Bank (Barker *et al.* 1984; Pearce *et al.* 2014) are also plotted and are close in composition to the basalts from the Eötvös Escarpment (Dalziel *et al.* 2013*a*) and a subset of the basalts from Discovery Bank (Pearce *et al.* 2014; Riley *et al.* 2021), suggesting a depleted source. Two basalts from the eastern flank of Bruce Bank (DR.225.30, DR.225.13), one sample from close to the Eötvös Escarpment (Dalziel *et al.* 2013*a*) and two samples from the North Scotia Ridge (Riley *et al.* 2019) all plot at more enriched compositions, with a more significant contribution from the continental lithosphere. Unfortunately, the dredged basaltic samples from the South Orkney microcontinent are not included in Figure 4 as the data tables were not available in Barber *et al.* (1991).

Discussion

The South Scotia Ridge is an array of submerged and subaerial crustal blocks that are interpreted to have rifted from the Antarctic Peninsula and Fuegian Andes during the opening of Drake Passage (e.g. Eagles and Jokat 2014). The current configuration of crustal blocks and basins (Fig. 1) is the result of spreading on the West Scotia Ridge, subduction in the NW Weddell Sea, ridge–trench collisions at the South Orkney microcontinent and Jane Bank (Fig. 5), and extension and oceanic spreading forming basins between the crustal blocks (e.g. Maldonado *et al.* 2014; Pérez *et al.* 2019).

Many researchers favour a close affinity between the South Scotia Ridge and the geology of the Fuegian Andes of southern South America (e.g. King and Barker 1988; Eagles and Jokat 2014; Dalziel *et al.* 2021), whereas Riley *et al.* (2022) have proposed a closer link to the Antarctic plate and, potentially, the Cordillera Darwin metamorphic complex of southern Patagonia (Fig. 5), which includes a metasedimentary basement analogous to the Permian sedimentary rocks of the South Orkney Islands (Hervé *et al.* 2010). Detrital zircon provenance analysis also highlights the contrast between the lithologies of the North and South Scotia ridges, indicating separate geological histories (Riley *et al.* 2019, 2022).

New geochronological data presented here from the basaltic rocks of Bruce Bank and Jane Bank add valuable information to our

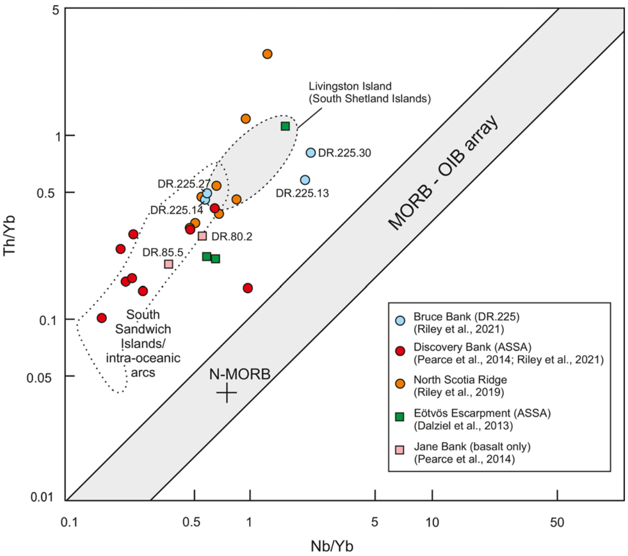

Fig. 4. Variations in Th/Yb v. Nb/Yb showing the composition of mafic rocks from the southern Scotia Sea region relative to the mid-ocean ridge basalt–ocean island basalt array (Pearce and Peate 1995). MORB, mid-ocean ridge basalt; N-MORB, normal-type mid-ocean ridge basalt; OIB, ocean island basalt. Data sources: Discovery Bank, Pearce *et al.* (2014), Riley *et al.* (2021); Jane Bank, Pearce *et al.* (2014); Eötvös Escarpment, Dalziel *et al.* (2013*a*); present day South Sandwich Islands, Pearce *et al.* (1995); and Bruce Bank, Riley *et al.* (2021).

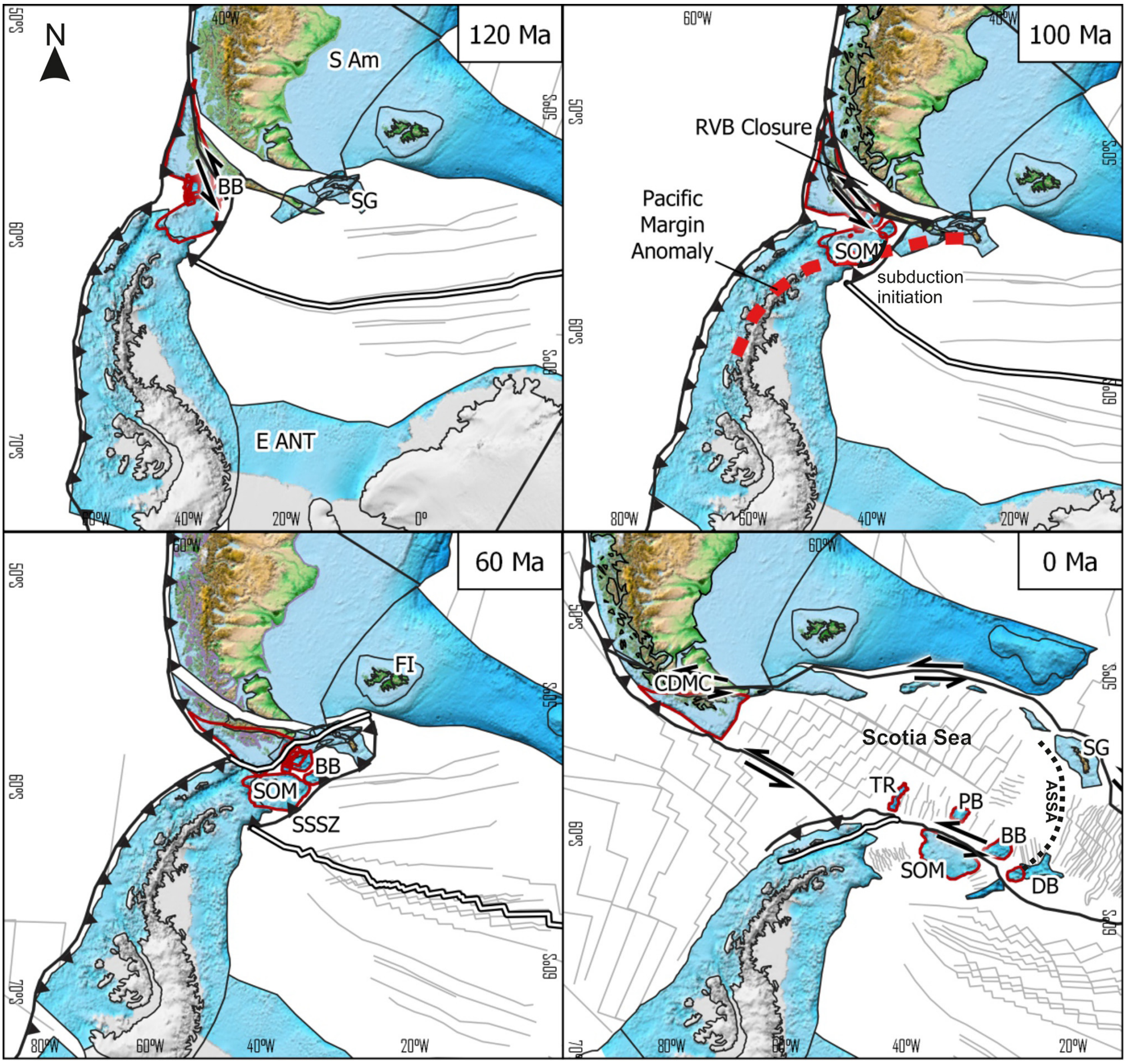

Fig. 5. Mid-Cretaceous to present-day GPlates-derived kinematic reconstruction of the Scotia Sea region. The kinematic reconstruction of van de Lagemaat *et al.* (2021) was modified to incorporate late westwards-directed Cretaceous subduction beneath Jane Bank and the South Orkney microcontinent. The GPlates rotation files and polygons are included in the Supplementary Material. This requires a change in the regional plate boundaries and opening geometry of the Rocas Verdes Basin compared with van de Lagemaat *et al.* (2021), more closely reflecting the tectonic history proposed by Morales-Ocaña *et al.* (2023). It should be noted that the derivation of arc magmatism from westwards-directed subduction beneath Jane Bank in the Late Cretaceous implicitly requires active convergence between the South Orkney microcontinent and the northern conjugate margin of the Weddell Sea (now largely subducted beneath the Scotia plate) in the Late Cretaceous. However, while the plate rotation model of van de Lagemaat *et al.* (2021) has such convergence between *c.* 120–100 Ma and *c.* 80–6 Ma, their plate circuit shows no such convergence between 100 and 80 Ma. Unfortunately, this occurs during the Cretaceous Normal Superchron (120–83 Ma), limiting the resolution of plate reconstructions using seafloor magnetic anomalies. However, we propose that the magmatic history of Jane Bank records continuing convergence throughout this period. The crustal blocks of the South Scotia Ridge are demarcated with a red surround. The potential initiation of South Sandwich subduction to the east of the South Orkney microcontinent is shown in the 100 Ma reconstruction (Schellart *et al.* 2023). ASSA, ancestral South Sandwich Arc; BB, Bruce Bank; CDMC, Cordillera Darwin metamorphic complex; DB, Discovery Bank; E ANT, East Antarctica; FI, Falkland Islands; PB, Pirie Bank; RVB, Rocas Verdes Basin; S Am, South America; SG, South Georgia; SOM, South Orkney microcontinent; SSSZ, South Sandwich subduction zone; TR, Terror Rise. Source: adapted from Riley *et al.* (2022); the position of the Pacific Margin Anomaly (red dashed line) is from Martos *et al.* (2014).

understanding of the geological and tectonic history of the crustal blocks of the South Scotia Ridge, particularly in the light of recent tectonic models (e.g. Morales-Ocaña *et al.* 2023; Schellart *et al.* 2023). Late Cretaceous–Paleogene mafic magmatism has been determined from the eastern Bruce Bank and southeastern Jane Bank, indicating a geological history that is inconsistent with that suggested by Riley *et al.* (2021) and Pearce *et al.* (2014), respectively. The geochemistry of the Bruce Bank mafic rocks was described by Riley *et al.* (2021), who adopted the interpretation of Pérez *et al.* (2014) that they were related to magmatism associated with the Oligocene opening of the Scan and Dove basins. Magmatism on Jane Bank was interpreted by Pearce *et al.* (2014) as likely to be Miocene in age, forming part of the ASSA and a continuation of the Miocene magmatism identified from Discovery Bank (Pearce *et al.* 2014; Riley *et al.* 2021).

Understanding the timing of initiation of the ASSA is crucial in resolving the tectonic development of the Scotia Sea. Several workers have suggested a far longer geological history for the ASSA, with Barker *et al.* (1991), Eagles (2010) and van de

Lagemaat *et al.* (2021) proposing a history extending to the Late Cretaceous, whereas Pearce *et al.* (2014) and Riley *et al.* (2021) suggest an Oligocene–Miocene history based on the available geochronology. In the plate reconstructions of Schellart *et al.* (2023), the initiation of Scotia Sea subduction is considered to be independent of any relative plate motion between the Antarctic Peninsula and South America, as proposed by Barker *et al.* (1991) and van de Lagemaat *et al.* (2021). Instead, they consider that Scotia Sea subduction is only dependent on the dynamics of subduction along the Pacific margin. This subduction zone needs to be at a mature stage of its evolution, with the subducted slab sinking into the lower mantle to generate a whole-mantle poloidal return flow cell, which can generate significant compressive stresses in the overriding plate (e.g. Schellart 2017). Schellart *et al.* (2023) suggested that a precise age for subduction initiation could not be determined, with the maximum age of subduction initiation constrained by the timing of Rocas Verdes basin closure (*c.* 100 Ma). However, the minimum age is constrained by the age of the oldest arc magmatism resulting from the ASSA (*c.* 31 Ma; Pearce *et al.* 2014; Riley *et al.* 2021). A mid- to Late Cretaceous age is also consistent with convergence transitioning to subduction in the northwestern Weddell Sea sector as a consequence of South American–Antarctic plate motion and rotation of the divergence vector (Eagles 2016). This model suggests that early NE-trending transform faults in the NW Weddell Sea would have transitioned to transpression as the divergence vector rotated towards north–south at *c.* 107 Ma, which would fit well with subduction-related magmatism at Jane Bank by *c.* 97 Ma. If westwards-directed subduction initiated in the Late Cretaceous, then it may represent a separate phase of subduction-related magmatism to the Oligocene–Miocene ASSA, particularly given the absence of ages from the Eocene.

Late Cretaceous–Paleogene plate reconstructions determined by Riley *et al.* (2022) from the proto-Scotia Sea region places the crustal blocks of the South Scotia Ridge adjacent to the South Orkney microcontinent and close to the proto-Pacific margin and the South Shetland Islands (Fig. 5). Late Cretaceous–Paleogene magmatism is also recorded from the South Orkney Islands and the South Orkney microcontinent (King and Barker 1988; Barber *et al.* 1991). Mafic magmatism from this interval is also widespread in the South Shetland Islands, particularly King George, Livingston and Robert islands (Fig. 2a; e.g. Leat and Riley 2021). The dominant magmatic rock type is calc-alkaline basalt/basaltic andesite, akin to the mafic rocks from the eastern Bruce Bank. This phase of Cretaceous–Paleogene magmatism is related to subduction along the proto-Pacific (Phoenix plate) margin (Leat and Riley 2021) and may also correlate with Cretaceous arc magmatism from the North Scotia Ridge (Riley *et al.* 2019) and South Georgia (Tanner and Rex 1979).

Sandstone recovered from dredge site DR.225 was examined by Riley *et al.* (2022) for its detrital zircon age profile (Fig. 6). Sample DR.225.28 was interpreted as *in situ* and is characterized by a very different age profile to the metasedimentary rocks from southern Bruce Bank (DR.223; Fig. 2b). The sandstone has prominent age peaks at *c.* 128 Ma and *c.* 185 Ma (Fig. 6) and a maximum likely depositional age of mid-Cretaceous. The detrital zircon age profile of the sandstone is also consistent with metasedimentary successions from the northern and western Antarctic Peninsula (Riley *et al.* 2023) and Patagonia (e.g. Pankhurst *et al.* 2000), which have prominent mid-Cretaceous and Early Jurassic age peaks reflecting enhanced volcanism during these intervals (Pankhurst *et al.* 2000; Riley *et al.* 2018). This indicates a likely palaeoposition of Bruce Bank proximal to the northern Antarctic Peninsula/southern South America during the mid- to Late Cretaceous.

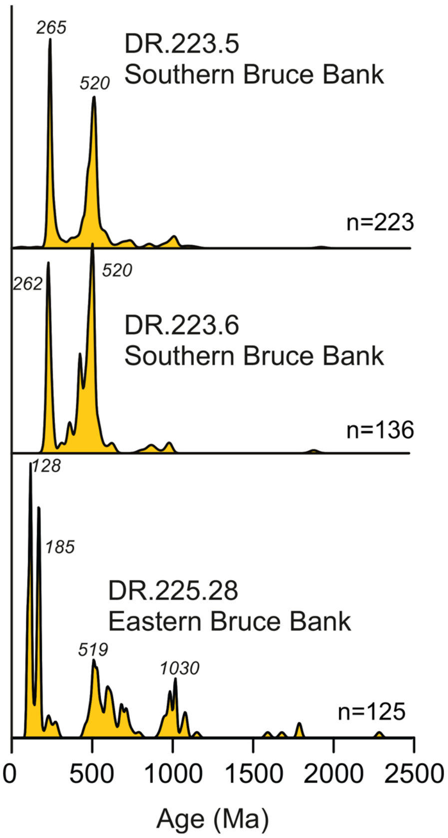

Fig. 6. Kernel density plots of detrital zircon ages from Bruce Bank. Source: Riley *et al.* (2022).

Tectonic setting

Based on our new geochronology and recent plate reconstruction models for the Scotia Sea, we propose three possible tectonic scenarios for the development of Cretaceous–Paleogene magmatism of the South Scotia Ridge that incorporate eastwards- (Phoenix plate) and/or westwards- (Scotia Sea) directed subduction.

(1) Late Cretaceous–Paleogene magmatism at Bruce Bank and Jane Bank is related to eastwards-directed subduction of the Phoenix plate beneath the Antarctic Peninsula and can be correlated to the convergent margin magmatism widely exposed across the South Shetland Islands, the South Orkney microcontinent, and also the arc magmatism of the North Scotia Ridge and South Georgia. The pre-translation position of the crustal blocks of the South Scotia Ridge are consistent with an Antarctic plate origin and a palaeoposition adjacent to the northern Antarctic Peninsula.

(2) The magmatism exposed across Bruce Bank, Jane Bank and the South Orkney microcontinent is related to an early phase of westwards-directed subduction that initiated in the Scotia Sea to the east of the South Orkney microcontinent in the Late Cretaceous. This phase of westwards-directed subduction developed as a result of South America–Antarctic plate rotation, leading to transform fault development in the NW Weddell Sea that transitioned to subduction in the Late Cretaceous. An alternative model is that Jane Bank subduction was triggered by a subduction invasion polarity switch in the Scotia Sea and is likely to be a separate phase of arc magmatism from the Oligocene–Miocene ASSA.

(3) Our favoured interpretation is that magmatism from Jane Bank (*c.* 97 Ma) represents the initiation of westwards-directed subduction in the Late Cretaceous in an intra-oceanic arc setting and shares geochemical characteristics with the Oligocene–Miocene ASSA. However, the magmatism of Bruce Bank and the South Orkney

microcontinent (Early Cenozoic) is more closely associated with the Antarctic Peninsula convergent margin and South Shetland Islands magmatism that developed prior to crustal block translation in the Eocene. The detrital zircon properties of adjacent sandstones from eastern Bruce Bank support a pre-translation history closely aligned to the Antarctic Peninsula.

Pacific margin anomaly

Dredge site DR.225 of the eastern Bruce Bank (Fig. 2) is also characterized by the recovery of abundant *in situ* samples of gabbro. The exact relationship between the Cretaceous basaltic lavas and dolerite dykes of site DR.225 with the gabbroic rocks is uncertain, but they were recovered from the same dredge site. It is tempting to correlate the gabbroic rocks of eastern Bruce Bank with the extensive Pacific margin anomaly (PMA) of the Antarctic Peninsula (Fig. 5; 100 Ma panel). The PMA is a long-wavelength positive magnetic anomaly that has been modelled as a 20 km thick magnetite-rich composite magmatic arc batholith of probable Cretaceous age (Garrett 1990; Johnson 1999). Garrett (1990) placed the PMA to the west of the Antarctic Peninsula and suggested that it extended into the Scotia Sea region. Martos *et al.* (2014) examined a regional compilation of magnetic anomalies from the Scotia Sea and traced the PMA into the crustal blocks of the South Scotia Ridge and potentially parts of the North Scotia Ridge. Martos *et al.* (2014) mapped the extent of the PMA through the South Scotia Ridge from the South Orkney microcontinent, southern Discovery Bank and possibly into Herdman Bank (Fig. 5). This was refined by Morales-Ocaña *et al.* (2023) to show the detailed extent of the PMA across the southern part of the South Orkney microcontinent. Magnetic anomalies from Bruce Bank match those of the southern South Orkney crustal block and Discovery Bank and may indicate that the PMA also extends into the eastern Bruce Bank. The Cretaceous magmatic ages of the eastern Bruce Bank reported here lend support to the gabbroic rocks forming a distal segment of the Late Cretaceous PMA.

Conclusions

Direct geochronology is absent from almost all the submerged banks of the South Scotia Ridge, which hampers geological and tectonic interpretations of the configuration of the continental fragments prior to the opening of the Scotia Sea and also how they evolved through the Cenozoic and controlled the development of the Antarctic circumpolar current. Our new $^{40}Ar/^{39}Ar$ geochronology results from mafic magmatic rocks of the crustal blocks of the South Scotia Ridge allow us to place firmer constraints on the tectonic history of the Scotia Sea. We have dated samples from the eastern Bruce Bank and southern Jane Bank, which yield Cretaceous–Paleogene ages that are inconsistent with current models. Bruce Bank magmatism was interpreted to be related to the post-translation volcanism associated with the Oligocene opening of Scan Basin, whereas Jane Bank was interpreted as a distal segment of the Miocene ASSA.

Based on our new data, combined with recently updated plate reconstruction models for the Scotia Sea, our preferred interpretation is that magmatism from Jane Bank (*c.* 97 Ma) represents the initiation of westwards-directed subduction in the Late Cretaceous in an intra-oceanic arc setting and shares geochemical characteristics with the Oligocene–Miocene ASSA. We consider it unlikely that Jane Bank originated as a product of eastward-directed subduction at the Pacific margin. In such a setting, Jane Bank would have been distal from the trench and separated from it by the South Orkney microcontinent and its accretionary complex. Therefore Jane Bank would have been in a rear-arc position relative to an eastwards-directed subduction zone, which is inconsistent with its depleted, intra-oceanic arc chemistry indicating closer proximity to a trench. Jane Bank is separated from the ASSA by the South Scotia Ridge transform fault and has a separate geological history from the Oligocene–Miocene arc.

Jane Basin could represent a back-arc rifted basin associated with mid-Cretaceous subduction. The magmatism of Bruce Bank and the South Orkney microcontinent (Early Cenozoic) is more closely associated with the Antarctic Peninsula–Patagonia convergent margin and the South Shetland Islands magmatism that developed prior to crustal block translation in the Eocene. The detrital zircon properties of adjacent sandstones from eastern Bruce Bank support a pre-translation history closely aligned to the Antarctic Peninsula/Patagonia. This is further supported by the occurrence of gabbroic rocks from Bruce Bank, which are tentatively correlated to the widespread Cretaceous PMA that extends from the western Antarctic Peninsula into the crustal blocks of the South Scotia Ridge.

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Author contributions **TR**: conceptualization (lead), investigation (lead), methodology (lead), project administration (lead), writing – original draft (lead), writing – review and editing (lead); **AB**: investigation (supporting), writing – original draft (supporting); **KAH**: investigation (supporting), writing – original draft (supporting); **AC**: writing – original draft (supporting); **PTL**: investigation (supporting), writing – original draft (supporting).

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Data availability The data that support this research are all available as Supplementary files linked to this article. Full datasets are also hosted at the British Antarctic Survey's Polar Data Centre at https://doi.org/10.5285/417A7F70-4FF2-428E-829D-0423772F66B4

References

Barber, P.L., Barker, P.F. and Pankhurst, R.J. 1991. Dredged rocks from Powell Basin and the South Orkney Microcontinent. *In*: Thomson, M.R.A., Crame, J.A. and Thomson, J.W. (eds) *Geological Evolution of Antarctica: Proceedings V International Conference Antarctic Earth Science*. Cambridge University Press, Cambridge, 361–367.

Barker, P.F. 2001. Scotia Sea regional tectonic evolution; implications for mantle flow and palaeocirculation. *Earth-Science Reviews*, **55**, 1–39, https://doi.org/10.1016/S0012-8252(01)00055-1

Barker, P.F., Barber, P.L. and King, E.C. 1984. An early Miocene ridge crest-trench collision on the South Scotia Ridge near 36°W. *Tectonophysics*, **102**, 315–332, https://doi.org/10.1016/0040-1951(84)90019-2

Barker, P.F., Dalziel, I.W.D. and Storey, B.C. 1991. Tectonic development of the Scotia Arc region. *In*: Tingey, R.J. (ed.) *The Geology of Antarctica*. Clarendon Press, Oxford, 215–248.

Barker, P.F., Lawver, L.A. and Larter, R.D. 2013. Heat-flow determinations of basement age in small oceanic basins of the southern central Scotia Sea. *Geological Society, London, Special Publications*, **381**, 139–150, https://doi.org/10.1144/SP381.3

Beniest, A. and Schellart, W.P. 2020. A geological map of the Scotia Sea area constrained by bathymetry, geological data, geophysical data and seismic tomography models from the deep mantle. *Earth-Science Reviews*, **210**, 103391, https://doi.org/10.1016/j.earscirev.2020.103391

Bohoyo, F., Galindo-Zaldívar, J., Maldonado, A., Schreider, A.A. and Suriñach, E. 2002. Basin development subsequent to ridge-trench collision: the Jane Basin, Antarctica. *Marine Geophysical Researches*, **23**, 413–421, https://doi.org/10.1023/B:MARI.0000018194.18098.0d

Bohoyo, F., Galindo-Zaldívar, J., Jabaloy, A., Maldonado, A., Rodríguez-Fernández, J., Schreider, A. and Suriñach, E. 2007. Extensional deformation and development of deep basins associated with the sinistral transcurrent fault zone of the Scotia–Antarctic plate boundary. *Geological Society, London, Special Publications*, **290**, 203–217, https://doi.org/10.1144/SP290.6

Carter, A., Curtis, M.L. and Schwanenthal, J. 2014. Cenozoic tectonic history of the South Georgia microcontinent and potential as a barrier to Pacific–Antarctic through flow. *Geology*, **42**, 299–302, https://doi.org/10.1130/G35091.1

Civile, D., Lodolo, E., Vuan, A. and Loreto, M.F. 2012. Tectonics of the Scotia–Antarctica plate boundary constrained from seismic and seismological data. *Tectonophysics*, **550–553**, 17–34, https://doi.org/10.1016/j.tecto.2012.05.002

Dalziel, I.W.D., Lawver, L.A. *et al.* 2013*a*. A potential barrier to deep water Antarctic circumpolar flow until the late Miocene? *Geology*, **41**, 947–950, https://doi.org/10.1130/G34352.1

Dalziel, I.W.D., Lawver, L.A., Norton, I.O. and Gahagan, L.M. 2013*b*. The Scotia arc: genesis, evolution, global significance. *Annual Reviews in Earth and Planetary Sciences*, **41**, 767–793, https://doi.org/10.1146/annurev-earth-050212-124155

Dalziel, I.W.D., Macdonald, D.I.M., Stone, P. and Storey, B.C. 2021. South Georgia microcontinent: displaced fragment of the southernmost Andes. *Earth-Science Reviews*, **220**, 103671, https://doi.org/10.1016/j.earscirev.2021.103671

Eagles, G. 2010. The age and origin of the central Scotia Sea. *Geophysical Journal International*, **183**, 587–600, https://doi.org/10.1111/j.1365-246X.2010.04781.x

Eagles, G. 2016. Plate kinematics of the Rocas Verdes Basin and Patagonian orocline. *Gondwana Research*, **37**, 98–109, https://doi.org/10.1016/j.gr.2016.05.015

Eagles, G. and Jokat, W. 2014. Tectonic reconstructions for paleobathymetry in Drake Passage. *Tectonophysics*, **611**, 28–50, https://doi.org/10.1016/j.tecto.2013.11.021

Eagles, G. and Livermore, R.A. 2002. Opening history of Powell Basin, Antarctic Peninsula. *Marine Geology*, **185**, 195–205, https://doi.org/10.1016/S0025-3227(02)00191-3

Eagles, G., Livermore, R.A. and Morris, P. 2006. Small basins in the Scotia Sea: the Eocene Drake Passage gateway. *Earth and Planetary Science Letters*, **242**, 343–353, https://doi.org/10.1016/j.epsl.2005.11.060

Flowerdew, M.J., Riley, T.R. and Haselwimmer, C.J. 2011. *Geological Map of the South Orkney Islands (1:150 000 scale)*. BAS GEOMAP 2 Series, Sheet 3. British Antarctic Survey, Cambridge.

Galindo-Zaldívar, J., Balanyá, J.C. *et al.* 2002. Active crustal fragmentation along the Scotia–Antarctic plate boundary east of the South Orkney microcontinent (Antarctica). *Earth and Planetary Science Letters*, **204**, 33–46, https://doi.org/10.1016/S0012-821X(02)00959-7

Garrett, S.W. 1990. Interpretation of reconnaissance gravity and aeromagnetic surveys of the Antarctic Peninsula. *Journal of Geophysical Research*, **95**, 6759–6777, https://doi.org/10.1029/JB095iB05p06759

Hervé, F., Fanning, C.M., Pankhurst, R.J., Mpodozis, C., Klepeis, K., Calderón, M. and Thomson, S.N. 2010. Detrital zircon SHRIMP U–Pb age study of the Cordillera Darwin metamorphic complex of Tierra del Fuego: sedimentary sources and implications for the evolution of the Pacific margin of Gondwana. *Journal of the Geological Society, London*, **167**, 555–568, https://doi.org/10.1144/00167649200912

Johnson, A.C. 1999. Interpretation of new aeromagnetic anomaly data from the central Antarctic Peninsula. *Journal of Geophysical Research (Solid Earth)*, **104**, 5031–5046, https://doi.org/10.1029/1998JB900073

King, E.C. and Barker, P.F. 1988. The margins of the South Orkney microcontinent. *Journal of the Geological Society, London*, **145**, 317–331, https://doi.org/10.1144/gsjgs.145.2.0317

Larter, R.D., Vanneste, L.E., Morris, P. and Smythe, D.K. 2003. Structure and tectonic evolution of the South Sandwich arc. *Geological Society, London, Special Publications*, **219**, 255–285, https://doi.org/10.1144/GSL.SP.2003.219.01.13

Leat, P.T. and Riley, T.R. 2021. Antarctic Peninsula and South Shetland Islands: volcanology. *Geological Society, London, Memoirs*, **55**, 185–212, https://doi.org/10.1144/M55-2018-52

Leat, P.T., Riley, T.R., Wareham, C.D., Millar, I.L., Kelley, S.P. and Storey, B.C. 2002. Tectonic setting of primitive magmas in volcanic arcs: an example from the Antarctic Peninsula. *Journal of the Geological Society, London*, **159**, 31–44, https://doi.org/10.1144/0016-764900-132

Leat, P.T., Fretwell, P.T. *et al.* 2016. Bathymetry and geological setting of the South Sandwich Islands volcanic arc. *Antarctic Science*, **28**, 293–303, https://doi.org/10.1017/S0954102016000043

Lee, J.-Y., Marti, K., Severinghaus, J.P., Kawamura, K., Yoo, H.-S., Lee, J.B. and Kim, J.S. 2006. A redetermination of the isotopic abundances of atmospheric Ar. *Geochimica et Cosmochimica Acta*, **70**, 4507–4512, https://doi.org/10.1016/j.gca.2006.06.1563

Lodolo, E., Civile, D., Vuan, A., Tassone, A. and Geletti, R. 2010. The Scotia–Antarctica plate boundary from 35°W to 45°W. *Earth and Planetary Science Letters*, **293**, 200–215, https://doi.org/10.1016/j.epsl.2009.12.045

Ludwig, K.R. 2012. *User's Manual for Isoplot 3.75*. Berkeley Geochronology Center, Special Publications, **5**.

Maldonado, A., Bohoyo, F. *et al.* 2006. Ocean basins near the Scotia–Antarctic plate boundary: influence of tectonics and paleoceanography on the Cenozoic deposits. *Marine Geophysical Research*, **27**, 83–107, https://doi.org/10.1007/s11001-006-9003-4

Maldonado, A., Bohoyo, F. *et al.* 2014. A model of oceanic development by ridge jumping: opening of the Scotia Sea. *Global and Planetary Change*, **123**, 152–173, https://doi.org/10.1016/j.gloplacha.2014.06.010

Martos, Y.M., Catalán, M., Galindo-Zaldívar, J., Maldonado, A. and Bohoyo, F. 2014. Insights about the structure and evolution of the Scotia Arc from a new magnetic data compilation. *Global and Planetary Change*, **123**, 239–248, https://doi.org/10.1016/j.gloplacha.2014.07.022

Morales-Ocaña, C., Bohoyo, F. *et al.* 2023. 3D geophysical and geological modelling of the South Orkney microcontinent (Antarctica): tectonic implications for the Scotia Arc development. *Tectonics*, **42**, e2022TC007602, https://doi.org/10.1029/2022TC007602

Muller, V.A.P., Calderón, M. *et al.* 2021. The closure of the Rocas Verdes Basin and early tectono-metamorphic evolution of the Magallanes fold-and-thrust belt, southern Patagonian Andes (52–54°S). *Tectonophysics*, **798**, 228686, https://doi.org/10.1016/j.tecto.2020.228686

Pankhurst, R.J., Riley, T.R., Fanning, C.M. and Kelley, S.P. 2000. Episodic silicic volcanism along the proto-Pacific margin of Patagonia and the Antarctic Peninsula: plume and subduction influences associated with the break-up of Gondwana. *Journal of Petrology*, **41**, 605–625, https://doi.org/10.1093/petrology/41.5.605

Pearce, J.A. and Peate, D.W. 1995. Tectonic implications of the composition of volcanic arc magmas. *Annual Reviews in Earth and Planetary Sciences*, **23**, 251–285, https://doi.org/10.1146/annurev.ea.23.050195.001343

Pearce, J.A., Baker, P.E, Harvey, P.K. and Luff, I. W. 1995. Geochemical evidence for subduction fluxes, mantle melting and fractional crystallization beneath the South Sandwich island arc. *Journal of Petrology*, **36**, 1073–1109, https://doi.org/10.1093/petrology/36.4.1073

Pearce, J.A., Hastie, A.R. *et al.* 2014. Composition and evolution of the ancestral South Sandwich arc: implications for the flow of deep ocean water and mantle through the Drake Passage gateway. *Global and Planetary Change*, **123**, 298–322, https://doi.org/10.1016/j.gloplacha.2014.08.017

Pérez, L.F., Lodolo, E. *et al.* 2014. Tectonic development, sedimentation and paleoceanography of the Scan Basin (southern Scotia Sea, Antarctica). *Global and Planetary Change*, **123**, 344–358, https://doi.org/10.1016/j.gloplacha.2014.06.007

Pérez, L.F., Hernández-Molina, F.J., Lodolo, E., Bohoyo, F., Galindo-Zaldívar, J. and Maldonado, A. 2019. Oceanographic and climatic consequences of the tectonic evolution of the southern Scotia Sea basins, Antarctica. *Earth-Science Reviews*, **198**, 102922, https://doi.org/10.1016/j.earscirev.2019.102922

Renne, P.R., Mundil, R., Balco, G., Min, K. and Ludwig, K.R. 2010. Joint determination of ^{40}K decay constants and ^{40}Ar*/^{40}K for the Fish Canyon sanidine standard, and improved accuracy for ^{40}Ar/^{39}Ar geochronology. *Geochimica et Cosmochimica Acta*, **74**, 5349–5367, https://doi.org/10.1016/j.gca.2010.06.017

Riley, T.R., Burton-Johnson, A., Flowerdew, M.J. and Whitehouse, M.J. 2018. Episodicity within a mid-Cretaceous magmatic flare-up in West Antarctica: U–Pb ages of the Lassiter Coast intrusive suite, Antarctic Peninsula and correlations along the Gondwana margin. *GSA Bulletin*, **130**, 1177–1196, https://doi.org/10.1130/B31800.1

Riley, T.R., Carter, A. *et al.* 2019. Geochronology and geochemistry of the northern Scotia Sea: a revised interpretation of the North and West Scotia ridge junction. *Earth and Planetary Science Letters*, **518**, 136–147, https://doi.org/10.1016/j.epsl.2019.04.031

Riley, T.R., Burton-Johnson, A., Leat, P.T., Hogan, K.A. and Halton, A.M. 2021. Geochronology and geochemistry of the South Scotia Ridge: Miocene island arc volcanism of the Scotia Sea. *Global Planetary Change*, **205**, 103615, https://doi.org/10.1016/j.gloplacha.2021.103615

Riley, T.R., Carter, A., Burton-Johnson, A., Leat, P.T., Hogan, K.A. and Bown, P.R. 2022. Crustal block origins of the South Scotia Ridge. *Terra Nova*, **34**, 495–502, https://doi.org/10.1111/ter.12613

Riley, T.R., Millar, I.L. *et al.* 2023. Evolution of an accretionary complex (LeMay Group) and terrane translation in the Antarctic Peninsula. *Tectonics*, **42**, e2022TC007578, https://doi.org/10.1029/2022TC007578

Schellart, W.P. 2017. Andean mountain building and magmatic arc migration driven by subduction-induced whole mantle flow. *Nature Communications*, **8**, 2010, https://doi.org/10.1038/s41467-017-01847-z

Schellart, W.P., Strak, V., Beniest, A., Duarte, J.C. and Rosas, F.M. 2023. Subduction invasion polarity switch from the Pacific to the Atlantic Ocean: a new geodynamic model of subduction initiation based on the Scotia Sea region. *Earth-Science Reviews*, **236**, 104277, https://doi.org/10.1016/j.earscirev.2022.104277.

Schreider, A.A., Schreider, A.A., Galindo-Zaldívar, J., Maldonado, A., Sazhneva, A.E. and Evsenko, E.I. 2017. Age of the Scan Basin (Scotia Sea). *Oceanology*, **57**, 328–336, https://doi.org/10.1134/S0001437016060138

Tanner, P.W.G. and Rex, D.C. 1979. Timing of events in an Early Cretaceous island arc-marginal basin system on South Georgia. *Geological Magazine*, **116**, 167–179, https://doi.org/10.1017/S0016756800043582

Udintsev, G.B., Kurentsova, N.A. *et al.* 2012. Tectonics of the Drake Passage–Scotia Sea zone in the southern ocean. *Doklady Earth Sciences*, **445**, 1029–1035, https://doi.org/10.1134/S1028334X12080260

van de Lagemaat, S.H., Swart, M.L. *et al.* 2021. Subduction initiation in the Scotia Sea region and opening of the Drake Passage: when and why? *Earth-Science Reviews*, **215**, 103551, https://doi.org/10.1016/j.earscirev.2021.103551

Vérard, C., Flores, K. and Stampfli, G. 2012. Geodynamic reconstructions of the South America–Antarctica plate system. *Journal of Geodynamics*, **53**, 43–60, https://doi.org/10.1016/j.jog.2011.07.007