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THE GREAT ESCAPE: SOUTH GEORGIA'S BREAK-OUT FROM THE SOUTHERN ANDES

by

Phil Stone

Summarizing a recent review: Dalziel, I.W.D., Macdonald, D.I.M., Stone, P. & Storey, B.C., 2021. South Georgia microcontinent: Displaced fragment of the southernmost Andes. *Earth-Science Reviews*, Volume 220, 103671.

South Georgia is geologically aberrant. Situated approximately 1700 kilometres east of Cape Horn and the southern termination of the Andean Cordillera of South America, the mountainous, glaciated island is the crest of one of the most isolated fragments of continental crust on Earth (Figure 1).

Figure 1. The SW coast of South Georgia at Cape Darnley where the sandstone beds of the Cumberland Bay Formation form steep, ice-bound cliffs plunging dramatically to the sea; R.V. Nathaniel B. Palmer *in the foreground. Image by Nicholas Bayou*.

It is the largest of the several continental blocks – 'microcontinents' – that form parts of the North Scotia Ridge at the northern margin of the Scotia Sea (Figure 2). A continental geology of ancient and varied rock types is not what you might expect for a remote island, most of which have an origin as recently active oceanic volcanoes, and that goes for all the other South Atlantic islands: Ascension, St Helena, Tristan da Cunha, Gough, the South Sandwich group. There are some volcanic lavas on South Georgia, down at the south-east end between Larsen Harbour and Ducloz Head, but those rocks are about 150 million years old, and their origin owes nothing to the present position of the island. Instead, they are part of the geological story that ties South Georgia back to the southern Andes (Dalziel *et al*. 1975). The striking similarities between the geology of the two regions argue for an originally much closer relationship, but the lack of a clearly understood mechanism that would displace South Georgia over such a large distance has encouraged challenges to the correlation.

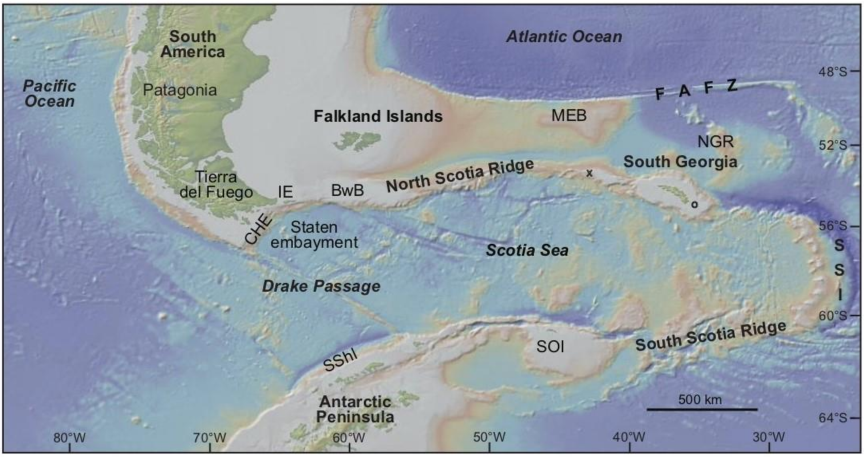

Figure 2. Location map for the South Georgia microcontinent (GeoMapApp). BwB–Burdwood Bank; CHE–Cape Horn escarpment; FAFZ–Falkland-Agulhas Fracture Zone; IE–Isla de los Estados; MEB–Maurice Ewing Bank; NGR–Northeast Georgia Rise; SOI–South Orkney Islands; SSI–South Sandwich Islands; SShI–South Shetland Islands. X–Shag Rocks, o–Clerke Rocks.

The recent reconsiderations of South Georgia's origins have been largely driven by modelling of large geophysical datasets derived from offshore surveys. The compelling evidence for the Andean connection faded into the background and, when inconvenient, was disregarded. It seemed to some of us who had contributed to the geological survey of South Georgia back in the 1970s that a re-examination of the evidence was called for, either to reinforce or amend the correlations with southern

South America. The result was an emphatic confirmation of the Andean connection with recently acquired data strengthening and extending the correlations and confirming the identity of the sediment sources that had been previously proposed. Our detailed findings have now been published at length in the scientific journal *Earth-Science Reviews* (Dalziel *et al*. 2021), and this article for the *Falkland Islands Journal* attempts to summarize the arguments and possibilities. So, what are the Andean geological connections of South Georgia? And how did the island get to its current position?

Geological exploration of South Georgia

South Georgia is primarily composed of Cretaceous sedimentary rocks, sandstone and mudstone, that around 100 to 120 million years ago filled a depositional basin between an ancient continental margin and an offshore arc of volcanic islands – a 'marginal basin' – the growth of which had been initiated a little earlier, about 150 million years ago (see review by Macdonald *et al.* 1987). The floor of the basin was formed partly by stretched and fragmented, older continental crust and partly by volcanic rocks that erupted as the basin expanded and new oceanic crust was formed. Remnants of this mixed continental-oceanic, mostly igneous assemblage are preserved in the south-east of the island, the Cretaceous sandstones form the rest (Figure 3).

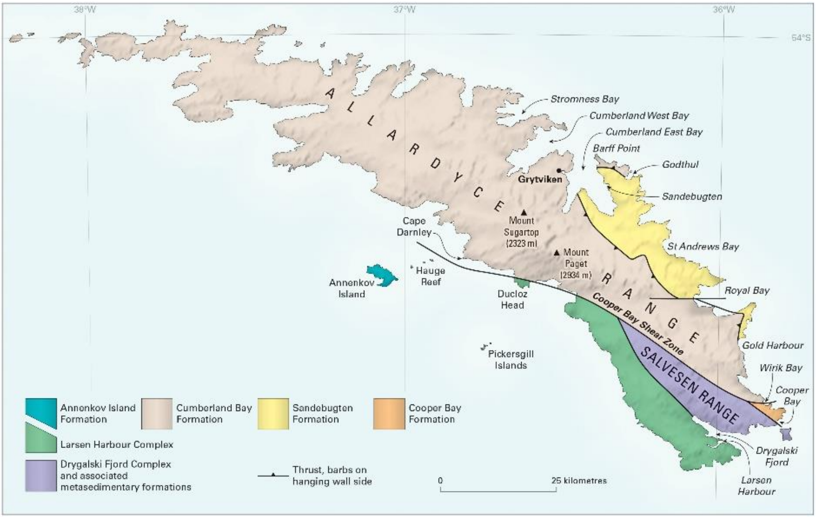

Figure 3. A simplified geological map of South Georgia. A compilation at a scale of 1:250,000 is published by the British Antarctic Survey (Curtis 2011).

The teasing-out of South Georgia's geological history took time. Early, piecemeal contributions were made by passing expeditions with a primary focus further south, and the first attempt at a comprehensive overview was the 1911 survey by the Scottish geologist David Ferguson at the behest of the Salvesen whaling company. The modern synthesis was initiated in the 1950s by Alec Trendall during the South Georgia Survey Expeditions (Trendall 1959), and then more fully developed by a comprehensive programme of geological investigation in the 1970s by the British Antarctic Survey, with some input from the United States Antarctic Program. Subsequently, a few specialised and focussed studies have added to the story. As a result of these combined efforts there is now an extensive geological literature for South Georgia. Space constraints allow only key references to be cited in this article, but a complete bibliography to 2015 accompanied by a supplement to 2021, is available online (Stone 2015), whilst an up-to-date comprehensive discussion is provided by Dalziel *et al*. (2021) in the review paper summarized here.

Figure 4. Drygalski Fjord Complex: dolerite dykes cutting layered gabbro on the NE coast of Drygalski Fjord. Image by Bryan Storey.

The remnants of the continental margin and marginal basin floor at the south-east end of South Georgia form the Salvesen Range of mountains. The continental rocks, gneiss and metasedimentary rocks intruded by gabbro and granite, make up the Drygalski Fjord Complex and are cut by many dolerite dykes that were intruded as the continental margin was stretched and broken (Figure 4). The ages of the various components are not well constrained but the intrusive gabbros and granites have given Early Jurassic radiometric dates in the range 175-200 Ma. The host metamorphic rocks from the continental margin are therefore pre-Jurassic. Eventually, extension of the continental margin resulted in the opening of a small oceanic basin, its floor made up of gabbros, abundant dolerite dykes, basaltic lavas – many with the 'pillow' structure characteristic of submarine eruptions (Figure 5) – and volcaniclastic rocks; these lithologies make up the Larsen Harbour Complex. When preserved in the geological record such a fragment of ancient oceanic crust is known as an 'ophiolite'. The age of the Larsen Harbour Complex dykes is established by relationships with a small gabbroic intrusion at Smaaland Cove which has been dated radiometrically at about 150 Ma. The gabbroic body cuts across some of the dykes, but is itself intruded by others, showing that dyke intrusion, and hence marginal basin extension, spanned that time interval (Figure 6).

Figure 5. Larsen Harbour Complex: pillow lavas on the Hauge Reef. The rounded masses of lava, the pillows, are created during submarine volcanic eruptions. Image by Geoff Tanner.

Figure 6. Larsen Harbour Complex: pale-coloured plagiogranite intruding black basaltic pillow lavas and dykes at Smaaland Cove: note the sharp colour contrast at middle left. Image by Bryan Storey.

Figure 7. Olstad Peak (650 m), the highest point on Annenkov Island, looking north from Rustad Bay. Image by Eric Lawther.

From the oceanward side of the marginal basin, the remains of a volcanic arc are preserved on the south-west coast at Ducloz Head, and on the neighbouring offshore islands, Annenkov Island (Figure 7), the rocks of the Hague Reef, and the Pickersgill Islands. In these areas, volcanic tuff and volcaniclastic breccias form, respectively, the Ducloz Head and Annenkov Island formations. A varied fossil fauna has been found in parts of the Annenkov Island Formation, with ammonites, bivalves and belemnites well-represented in parts of the succession (Figure 8) and indicating an age for the rocks within the Early Cretaceous, probably within the absolute range 100 to 125 Ma. On Pillow Rock, the easternmost island of the Hague Reef (Figure 9), the uppermost part of the Larsen Harbour Complex shows a stratigraphical transition up into the Annenkov Island Formation. This shows how the flanks of the volcanic arc encroached into the marginal basin; the roots of the volcanoes lie further to the south-west, identified by a broad, linear zone of geophysical magnetic anomalies.

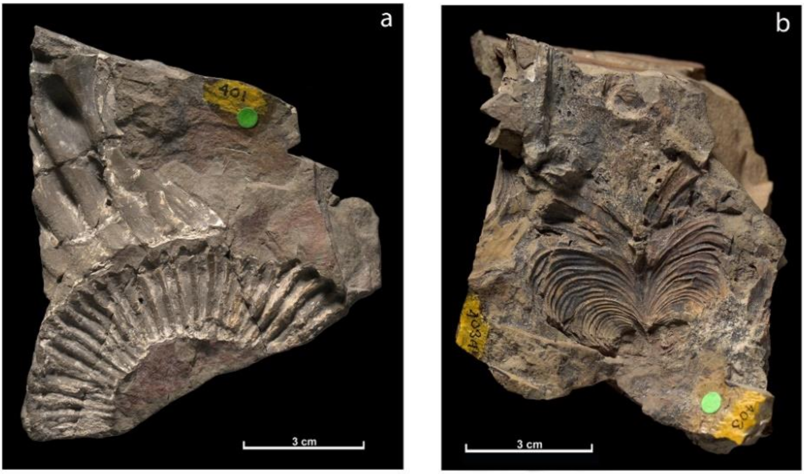

Figure 8. Fossils collected from Annenkov Island in 1954 by Alec Trendall: a) the partial impression of a large ammonite; b) the impression of a pair of conjoined bivalve shells. British Geological Survey images P532005 and P532007 ©BGS/UKRI.

The Cooper Bay Shear Zone, a major tectonic fault with a large lateral offset which runs onshore between Cooper Bay and Ducloz Head, separates the dominantly igneous rock assemblages of SE South Georgia from the sedimentary sandstone successions that make up the greater part of the island. There are two distinct types of sandstone with markedly different compositions. The most widespread type, which forms all of the Allardyce Range, was formed by sediment eroded from the volcanic side of the depositional basin and makes up the Cumberland Bay Formation (Figure 10). A very sparse fossil fauna, isolated ammonites and bivalves, suggests an Early Cretaceous age similar to that established at Annenkov Island. The contrasting sandstone type, seen along the north-east coast of South Georgia, has a composition dominated by quartz grains with little sign of any contemporaneous volcanic influence and was derived from the continental side of the depositional basin; the quartz-rich sandstones make up the Sandebugten and Cooper Bay Formations. No fossils have been found in either of these formations but detrital zircon grains from a Sandebugten Formation sandstone, when radiometrically dated, have proved to be as young as 109 Ma. The interbedding of the two sandstone types in the Barff Point area confirms an overlap in their depositional ages, so the zircon data from the Sandebugten Formation may indicate that it corresponds to the younger part of the Cumberland Bay Formation.

Figure 9. The Hague Reef seen from Annenkov Island, looking across to Cape Darnley, the Christophersen Glacier and Mount Sugartop (2323 m). Image by Eric Lawther.

Although originally of much the same Early Cretaceous age, the sandstone formations were deformed in different fashions when the volcanic arc moved back towards the continent as the marginal basin closed. In the process, the Cumberland Bay Formation was forced up towards the north-east into a series of large asymmetric folds so that it overrode the Sandebugten Formation, which suffered relatively more intense deformation resulting in tight folding; a major tectonic thrust plane now separates the two sandstone types with their contrasting structural styles. Additional, post-thrusting deformation episodes have complicated the record, but in general the intensity of deformation in the Cumberland Bay Formation increases from SW to NE across the island. Deformation intensity in the Sandebugten Formation increase towards the SE, marked particularly by the development of a pervasive cleavage superimposed on earlier structures, and rises further into the Cooper Bay Formation, where the deformation effects merge into the Cooper Bay Shear Zone.

Figure 10. Alternating sandstone and mudstone beds of the Cumberland Bay Formation at Gold Harbour. The King Penguins crowded on the beach provide a sense of scale. Image by Tom Sharpe.

Links to the southern Andes

As work progressed in South Georgia, a geological understanding of the southern Andes was also established. Early investigations contemporary with those of Ferguson on South Georgia had noted the close similarity in age and composition of the Cumberland Bay Formation sandstones and the Yahgan Formation sandstones of Tierra del Fuego; the full range of the correlations that we now recognise are summarized in Figure 11. The age of the Yahgan Formation strata had been first recognised by Charles Darwin during the voyage of HMS *Beagle*, but the formal name was not applied until much later. The correlation with South Georgia was then enhanced in the 1960s by the geological survey work of Rudy Katz and colleagues from Chile's Empresa Nacional del Petróleo, and further developed in a fortuitous collaboration between Katz and Bill Watters, a New Zealand geologist who had joined a 1958-59 British Royal Society expedition to southern Chile (Katz & Watters 1966).

Katz went on to describe a regional interpretation that incorporated a belt of basalt lavas and mafic dykes known in Patagonia as the '*Rocas Verdes*' (green rocks), as the uplifted floor of a marginal basin. The similarities with South Georgia were strengthening and were further enhanced during expeditions to the Patagonian region, led by US geologists, that confirmed the '*Rocas Verdes*' as fragments of the floor of a former small ocean basin comprising basalt lavas, dolerite dykes and masses of gabbros – an ophiolite complex – that had formed, between the Andean continental margin and an offshore volcanic arc. The two major examples of the *Rocas Verdes* were defined as the Sarmiento and Tortuga complexes, and with these as counterparts of the Larsen Harbour Complex the similarities to the story emerging from South Georgia were striking.

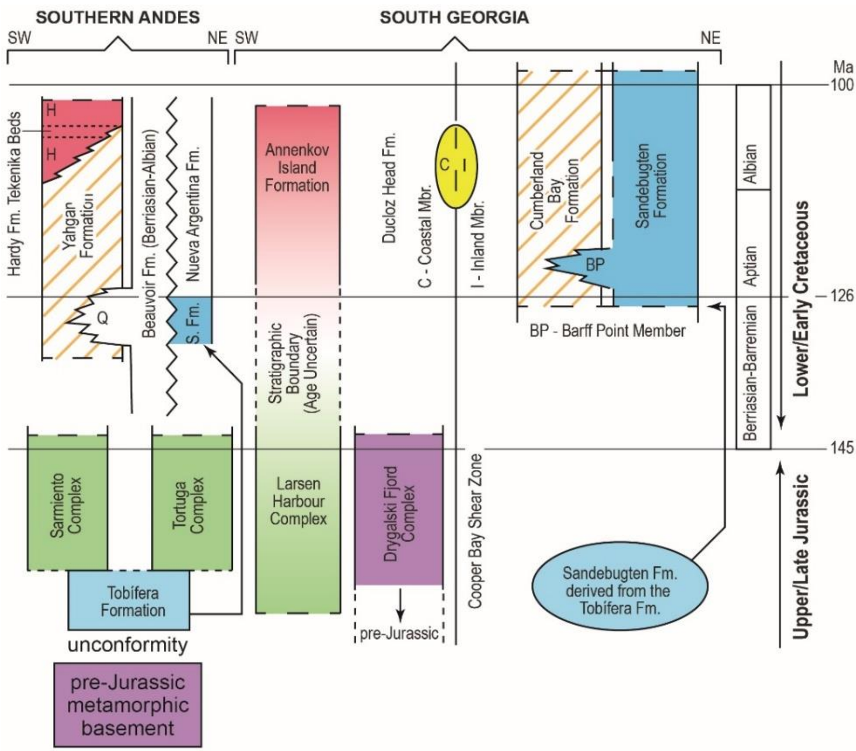

Figure 11. Stratigraphic correlation diagram of South Georgia and southernmost South America. The colours correspond to those in the geological maps of South Georgia (Figure 3). Q–quartzose facies of Yahgan Formation; S Fm–Springhill Formation. After Dalziel et al. (2021).

The Andean ‘marginal basin’ rock assemblage sweeps around to the south of Tierra del Fuego but then is abruptly terminated at a submarine escarpment forming the continental margin immediately east of Cape Horn. This was the original location of South Georgia. It provides an exact match for the geology immediately south of the Beagle Channel that is truncated at the Cape Horn escarpment. Not only do the rock units and tectonic history of South Georgia correlate in every significant respect with those of the Andean Pacific hinterland, exact matches for sources of the sedimentary strata forming much of the island – the Cumberland Bay and Sandebugten formations – occur in the easternmost extremity of the Andean Cordillera. In particular, this position affords a depositional site for the Sandebugten Formation in proximity to Isla de los Estados and its quartz-rich volcanic rocks, known as the Tobifera Formation. The lithologies of the Tobifera Formation are similar to those seen as detrital grains in the Sandebugten Formation, whilst its age of about 170 Ma is also a good match for the age of many of the Sandebugten Formation's dated zircon grains. The younger zircon grains therein, those with an age of about 109 Ma, would also have a convenient source within the granites of the Patagonian batholith.

Figure 12. The jagged islets of Shag Rocks. Image by David Macdonald.

Whereas the stratigraphical correlation between the Cumberland Bay and Yahgan formations is clear and straightforward, the Sandebugten Formation has less obvious Andean correlatives. Quartz-rich interbeds low in the Yahgan Formation invite comparison with the situation at South Georgia around Barff Point. Otherwise, tentative links can be drawn between the Sandebugten Formation and southern Andean rock units which, though dissimilar in sedimentary character, are of similar age and are also believed to have been derived by erosion of the Tobifera Formation. This correlation is partly dependent on borehole records.

It also proved possible to include the Shag Rocks continental block in the expanded scheme of correlation. The isolated Shag Rock pinnacles (Figure 12) had been something of a geological enigma until relatively recently but are now identified as metamorphic schists with lithological similarity to rocks seen in the southern Andes at the eastern extremity of the Cordillera Darwin (the Lapataia Schists).

Continental drift and plate tectonics

As the links between South Georgia and Tierra del Fuego became increasingly apparent, ideas of continental drift afforded a means by which the two regions could have been separated and the Scotia Arc formed. The shape of the latter encouraged early ideas that South Georgia might be the largest of a number of continental fragments broken-off and left-behind as South America and the Antarctic Peninsula, originally joined as parts of the Gondwana supercontinent, drifted west and separated. A refinement on this model envisaged Pacific Ocean crust breaking through an Andes – Antarctic Peninsula landmass as it drifted westwards. But all of these proposals were made at a time when continental drift was mostly dismissed as implausible. Then, everything changed dramatically in the late 1960s, and the recognition of plate tectonics revolutionised ideas of ocean basin origins and continental movement. This, and rapid advances in offshore technology, promoted investigations into the origins of the Scotia Sea, and it proved to be a much more complicated story than had been expected. In particular, it was clear that some of the expansion of the Scotia Sea was the result of independent, internal seafloor spreading. This could explain some of the eastward movement of South Georgia, but by no means all of it, whilst the clearer delineation of the various submarine banks added to the complexity of the continental fragments that had to be accommodated in any reconstruction.

The uncertainties in this regional picture have encouraged different interpretations of South Georgia's origins, driven by the increasing quantity of geophysical data generated by offshore surveys in and around the Scotia Sea. From these emerged the idea that South Georgia originated in proximity to the Falkland Plateau and the Maurice Ewing Bank rather than the southern Andes (Eagles 2010; Eagles & Eicherman 2020). Our reassessment gives an emphatic confirmation of the Andean connection with recently acquired data strengthening and extending the correlations and sediment source identities that had been previously proposed. The suggested alternatives can be eliminated as there are no sources within the Falkland Plateau that are sufficiently young to provide the dated mineral grains in the Sandebugten Formation, and the very much older grains that would have been available from that source are not present in the South Georgia strata.

The geological evidence that the South Georgia microcontinent was formerly a continuation of the Andean Cordillera located immediately east of Tierra del Fuego is overwhelming. Not only do the rock units and tectonic history of South Georgia correlate in every significant respect with those of the Andean hinterland south of the Beagle Channel, exact matches for sources of sedimentary strata forming much of the island occur in the easternmost extremity of the Cordillera. Critically, moreover, South Georgia is an exact geologic match for the region immediately south of the Beagle Channel that is truncated at the Cape Horn escarpment. The distinctive rock assemblage, so spectacularly exposed in southern Tierra del Fuego, is missing from the Staten embayment south of the main range of the Cordillera which trends east through Isla de los Estados to the submerged Burdwood Bank. Although now far apart, both South Georgia and the southern Andes preserve the same geological record: the expansion, infill and deformation of contiguous parts of the same Late Jurassic to Early Cretaceous marginal basin.

The big picture – reconstructing the Scotia Arc

The South Georgia microcontinent is just one of about eight or nine isolated blocks of continental rock that now form islands or submarine banks within the North and South Scotia ridges. Over the years there have been several attempts at reconstructing an original position for the South Georgia microcontinent within the Staten embayment, and some of these have attempted to accommodate the other known continental blocks. However, there have been no attempts to reconstruct the original positions of all the isolated continental blocks within the Scotia Arc since the pioneering efforts of Barker and Griffiths (1972). Despite the paucity of data from the blocks that are totally submerged, to place South Georgia in its original context we have attempted a tentative reconstruction that satisfies all of the closely defined geological correlations. This reconstruction is shown in Figure 13.

The remaining problem is the mechanism for completing South Georgia's eastward escape from the southern Andes, a process completed over about the last 40 million years – at an average speed of about 4 cm per year, quite reasonable in plate tectonic terms. Transport within the plexus of transcurrent faults that make up the North Scotia Ridge transform zone seems most likely, but consideration of the evolving geography of the Scotia Arc raises an additional, intriguing issue: the position of the various continental blocks at any given time would have influenced the pattern of deep ocean currents. The effect of submarine topography on the developing Antarctic Circumpolar Current would have been of particular importance as this would have ramifications for the growth of the Antarctic icecap, and hence for global climate. There are also implications for the position of the Antarctic Peninsula in reconstructions of the Gondwana supercontinent – and this remains a controversial aspect of South Atlantic geology.

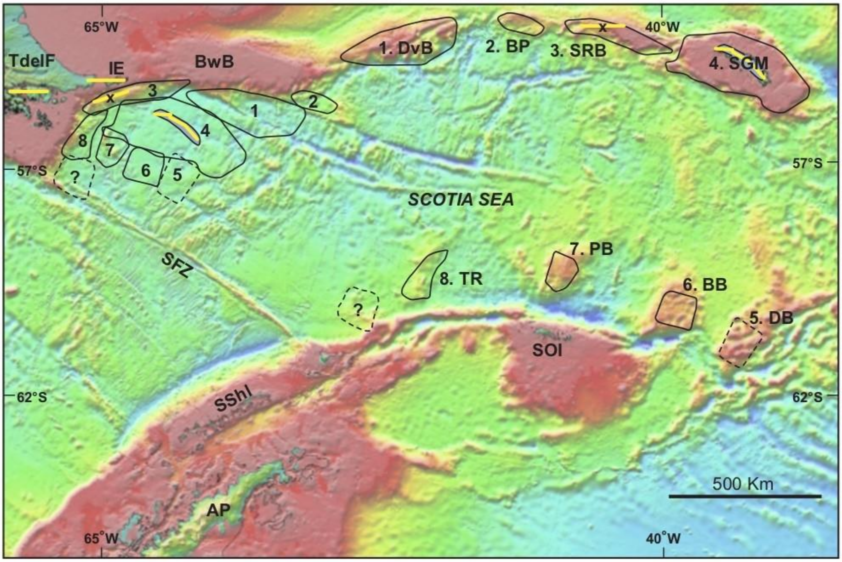

Figure 13. Satellite-altimetry derived gravity image of the Scotia Arc showing the present and palinspastically restored positions of the South Georgia microcontinent and other former fragments of the southernmost Andean Cordillera in the Late Cretaceous, ca 90 Ma. After Dalziel et al. (2021).
AP–Antarctic Peninsula; BB–Bruce Bank; BP–Barker Plateau; BwB–Burdwood Bank; DB–Discovery Bank; DvB–Davis Bank; IE–Isla de los Estados; PB–Pirie Bank; SGM–South Georgia microcontinent; SRB–Shag Rocks Bank; SOI–South Orkney Islands; SShI–South Shetland Islands; T del F–Tierra del Fuego; TR–Terror Rise.

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Phil Stone, British Geological Survey, The Lyell Centre, Edinburgh EH14 4AP, Scotland, UK psto@bgs.ac.uk