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The geological exploration of the sub-Antarctic island of South Georgia: a review and bibliography, 1871-2015

Geology and Regional Geophysics Programme

Internal Report OR/15/058

BRITISH GEOLOGICAL SURVEY

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P Stone

Keywords

South Georgia; Scotia Arc, South Atlantic Ocean, Falkland Islands Dependencies Survey; British Antarctic Survey, historical geology.

Front cover

A field camp at Iris Bay South Georgia in December 1973; by 2015 the Herz Glacier in the background had retreated by almost 2 km from the position shown.

Bibliographical reference

STONE, P. 2015. The geological exploration of the sub-Antarctic island of South Georgia: a review and bibliography, 1871-2015. *British Geological Survey Internal Report*, OR/15/058. 48pp.

Keyworth, Nottingham British Geological Survey 2015

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Foreword

This report compiles a record of contributions to the geological exploration of the island of South Georgia, and its relationship to the North Scotia Ridge and Scotia Arc. The contributions are discussed in their appropriate historical context within the development of a geological understanding of South Georgia's origins and regional tectonic setting. A comprehensive bibliography is provided.

Acknowledgements

Thanks are due to many colleagues for their assistance in discovering and accessing the material used to compile this report: in particular to Adrian Rushton (The Natural History Museum, London), John Faithfull (Hunterian Museum, University of Glasgow) and Andrew Gray (British Antarctic Survey). Teal Riley (British Antarctic Survey) provided a most helpful review of the preliminary text. The unsung heroes of the South Georgia geological investigations are the scientific field assistants: from a personal perspective I should like to thank sincerely, for their support and companionship, G. 'Jim' Whitworth (1970-71), Eric Lawther (1971-72), and G. 'Dog' Holden and Roger Daynes (1973-74). This report is released by permission of the Executive Director, British Geological Survey (NERC).

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The earliest geological explorations of South Georgia in the late 19th and early 20th centuries were generally piecemeal and opportunistic, often being undertaken by expeditions with a primary focus further south. German, Swedish and British expeditions all contributed, with the development of the shore-based whaling industry from 1904 onwards providing invaluable logistic support and infrastructure. It was the commercial interests of one of the whaling companies that stimulated in 1911 the first systematic appraisal of the island's geology in terms of its economic mineralisation potential. Although the results were disappointing, the work led to a productive cooperation with geological specialists at the University of Glasgow. Thereafter, visits by Norwegian expeditions added to the overall state of geological knowledge until such activities were curtailed by World War II between 1939 and 1945.

An important post-war development was the establishment of the Falkland Islands Dependencies Survey (FIDS) with a responsibility for scientific research in the region. Nevertheless, the next major advance in South Georgia geology arose from the series of three independent South Georgia Survey Expeditions between 1951 and 1956. Preliminary FIDS investigations into South Georgia geology followed from about 1959, lapsed during the early 1960s, but then recommenced determinedly in about 1965; at about the same time geologists from the USA began to work on the island. This renewal of interest gathered pace with the opening of a permanent base on South Georgia in 1969 by the British Antarctic Survey (BAS), the renamed successor to FIDS from 1962. The 1970s then saw the most intense phase of BAS geological activity with several geologists in the field during most austral summers. Initially this work focussed on regional survey, but increasingly the principal thrust of the investigations evolved towards specialist study of geological processes. By the end of the 1970s, the overall pattern and origin of South Georgia's geology had been largely established as representing an active continental margin split by the opening of an island arc and backarc basin system, with the subsequent closure of the basin and deformation of its sedimentary fill of turbidite strata. Various manifestations of the latter form most of the island including the Allardyce Mountain Range. The igneous rocks form the Salvesen Mountains in the south-east of the island and parts of the south-west coast including offshore islands such as Annenkov and the Pickersgills.

In 1982, scientific work on South Georgia was once again interrupted by military conflict, this time the short-lived occupation of the island by Argentine forces. Since the re-establishment of British administration geological knowledge has been augmented by the work of an independent New Zealand expedition and additional work by BAS in pursuit of specialist interests. There has also been an expansion of regional studies integrating South Georgia into the development history of the Scotia Arc. The appreciation of that feature as a dynamic geological construct arising from large-scale lateral tectonics, and South Georgia as an itinerant continental fragment with South American associations, were clear in some early accounts of the region. Such propositions were generally discounted until ideas of continental drift matured into plate tectonics from the late-1960s onwards, when many of the early 'pro-drift' ideas were independently rediscovered by proponents of the new global interpretation. Geologists based in the USA were prominent in this phase of regional research.

1 Introduction

The island of South Georgia (centred at about 54°20′S, 36°40′W) is an isolated terrestrial outpost in the midst of the South Atlantic Ocean. Measuring about 170 km NW-SE, and with a maximum NE-SW width of 30 km, it is the largest emergent feature of the mostly submarine North Scotia Ridge, and a part of the arcuate chain of banks and islands that link Tierra del Fuego, in southernmost South America, with Graham Land, in the north of the Antarctic Peninsula, enclosing the Scotia Sea in a huge, eastward-closing physiographic loop (Figure 1). Together, these features form the Scotia Arc, a widely used but still, *sensu stricto*, an unofficial geographical descriptor (Hattersley-Smith 1980). The names celebrate the *Scotia*, the ship that carried the Scottish National Antarctic Expedition, 1902-1904, and from which bathymetric survey work first confirmed the existence of the arcuate submarine ridge (Bruce 1905). Many early workers referred to the arcuate assemblage of features as the Southern Antilles or South Antilles Arc, after the perceived similarity to the island chain enclosing the Caribbean Sea, but the appellation ‘Scotia’ has been in general use following Herdman (1932).

This review (an admittedly subjective summary) documents the growth of geological knowledge of South Georgia and its regional status in the South Atlantic; it is concerned only with research into the island’s bedrock geology and its wider implications. Many of the geologists whose work is cited also made important contributions in other disciplines such as physiography, geomorphology and glaciology, and these areas of research were of course also studied independently by specialists in those fields. There is some overlap, particularly in the earlier publications, but on the whole the results of research into the broader aspects of landscape evolution are neither dealt with in this review nor included in the bibliography.

The first known landing on South Georgia (a British Overseas Territory but also claimed by Argentina under the name *Isla de San Pedro*) was made in January 1775, from *HMS Resolution*, during Capt. James Cook’s second voyage of exploration. Geological investigations followed only very slowly and intermittently, and in 1900 South Georgia was still largely *terra incognita* in geological terms. The uncertainty allowed various accommodations within opposing models as the issue of continental drift was argued through the first half of the 20th century, following the championing of the concept by Wegener from 1912 onwards. Of particular interest is the way in which increasing knowledge played into the arguments for or against the theory of continental drift and, in local terms, for either a dynamic or *in situ* origin for the components of the Scotia Arc (Stone 2015). As a frame of reference for the assessment of those historical contributions, and their modern successors, it is appropriate to consider first the current consensus on South Georgia’s geology, which has been summarized in geological maps compiled by Macdonald and others (1987) and Curtis and Riley (2011) and is illustrated in Figure 2. For a comprehensive modern assessment of the Scotia Arc, as its origin and evolution are now commonly (although not unanimously) interpreted, see Dalziel and others (2013).

Much of South Georgia is underlain by a thick succession of Lower Cretaceous volcaniclastic sandstone and mudstone (**Cumberland Bay Formation**) originally deposited by deep-marine turbidity currents. The strata were then asymmetrically folded and thrust towards the north-east to structurally overlie a more intensely deformed and cleaved succession of quartzose turbiditic sandstones (**Sandebugten Formation**), which may nevertheless be of a similar Cretaceous age. A major shear zone separates the Cumberland Bay and Sandebugten formations and broadly similar (but still more deformed) sedimentary rocks (**Cooper Bay Formation**) from a very different lithological assemblage that forms the south-east end of the island: gneiss and metasedimentary rocks intruded by gabbro and probably Triassic granite, with mafic dykes locally forming up to 80% of the outcrop (**Drygalski Fjord Complex** with minor associated metasedimentary formations), Upper Jurassic lavas and volcaniclastic rocks (**Larsen Harbour Complex**) and Lower Cretaceous tuff and volcaniclastic breccias (**Annenkov Island and Ducloz Head formations**). In total, the geology of South Georgia illustrates an active continental margin split by the opening of an island arc and backarc basin system, with the subsequent closure of the basin and deformation of its sedimentary fill.

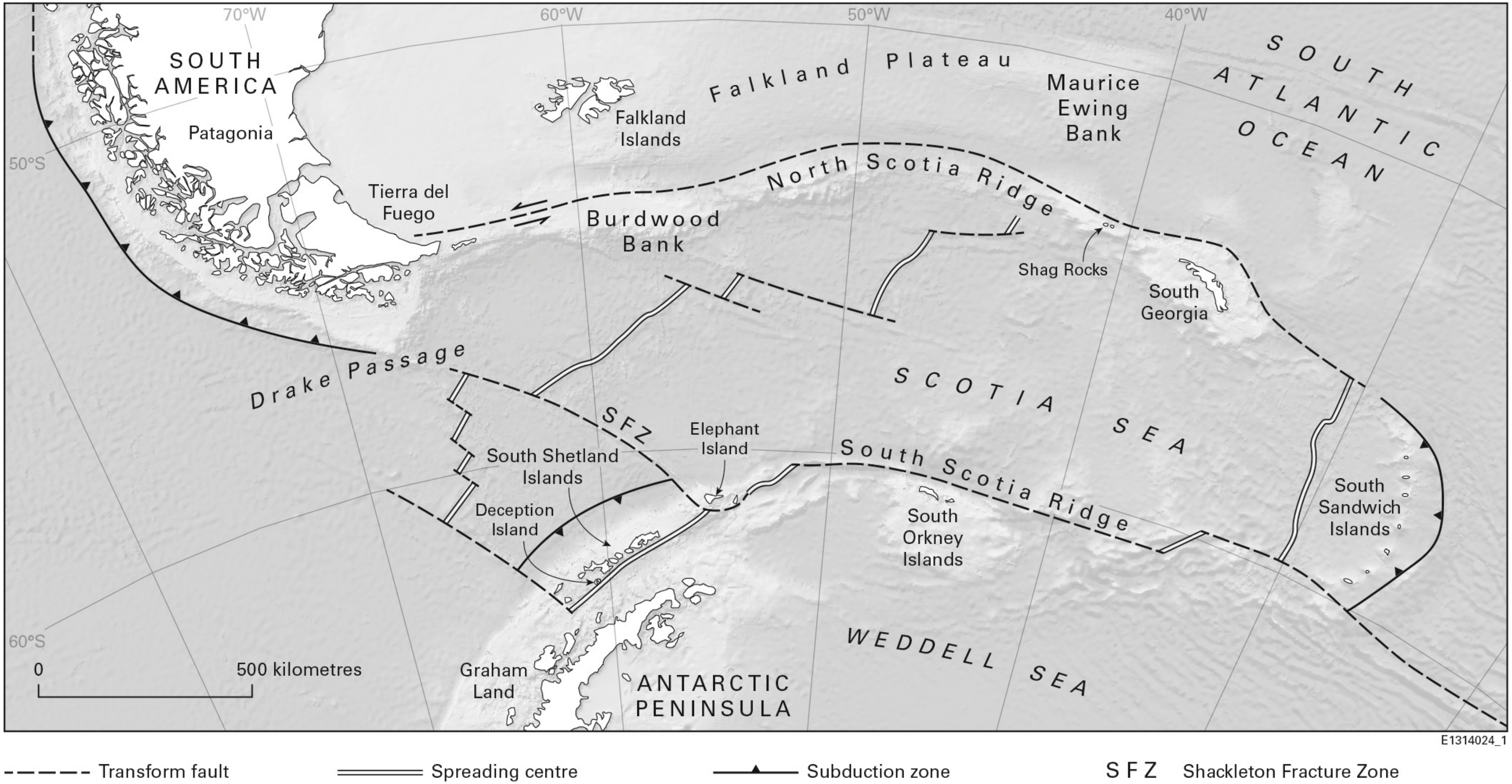

Figure 1. The geography of the Scotia Arc showing the principal tectonic features of the region simplified from Dalziel and others (2013, figures 2 and 10). Some uncertainty remains at the boundary between the Scotia Sea and the Weddell Sea, which is a particularly complex zone.

Figure 2. Outline geology of South Georgia (after Curtis and Riley 2011).

2 Geological reconnaissance: 1871-1939

The first record of geological specimens being collected at South Georgia dates from 1871 when R.W. Chappell, an American whaling captain, picked up a number of beach pebbles that he later presented to Yale University. These pebbles eventually found their way to Scotland, to Glasgow University, where they were described (as metasedimentary rocks) along with other specimens from the island by Tyrrell (1916). Had Chappell's specimens been identified earlier, the description of South Georgia's rocks by Klutschak (1881) might have been rather different. Klutschak, an Austrian adventurer, accompanied a sealing expedition to South Georgia in 1877. He was no geologist, writing (1881: 1967 English translation p. 88): "The island's formation is that of a mountain range some 4,000 to 5,000 ft in height, a range of once mighty but now extinct volcanoes which only reveal their former activity in their sharp, cone-shaped peaks and great beds of lava." A truer picture emerged as local knowledge of the geology of South Georgia increased substantially at the end of the 19th and beginning of the 20th centuries.

During the German International Polar Year Expedition (1882-1883) rock specimens were collected which were subsequently described by Thürach (1890) as phyllites (some calcareous and some described as 'phyllitgneiss'), argillaceous slate, tuff and 'greenstone'. The expedition's principal purpose was to observe a transit of Venus during the first International Polar Year, for which a base was established in Royal Bay. The phyllite, tuff and slate can all be matched with lithologies exposed in the Royal Bay area and now included within the Sandebugten and Cumberland Bay formations (Stone 1980); the 'greenstone' could refer to altered dolerite found in rare intrusive sheets. However, the German expedition's exploration was limited to the Royal Bay area so the gneiss, reported by Adie (1957a) as "a high-grade paragneiss with sillimanite and andalusite" was most probably a glacial erratic. It may possibly have been derived from the Drygalski Fjord Complex, located in the far south-east of the island, but Gregory (in Ferguson and others 1914) describes the specimen as a "shore pebble" and so an entirely exotic, ice-rafted origin cannot be ruled out.

The German expedition found no fossils so had no evidence for the age of the South Georgia rocks. The first clue to that was obtained twenty years later, when members of the Swedish South Polar Expedition (1901-1903) visited the island during the 1902 austral winter. Andersson discovered in Moraine Fjord (the south-west corner of Cumberland East Bay) a fossil bivalve that was indicative of a late Palaeozoic or early Mesozoic age. He was clearly well-aware of the importance of the discovery, recounting (Nordenskjöld and Andersson 1905, p 362) that recovery of the specimen took four men two days, and involved rock drills and blasting powder. The fossil was found in strata that would now be assigned to the Cumberland Bay Formation. Andersson (1907, 725-726) stressed the importance of the fossil and also commented on the widespread development of spectacular folding: "beautiful folds, which run apparently parallel to the longitudinal axis of the island".

Contemporary with the Swedish expedition was the Scottish National Antarctic Expedition (1902-1904). The Scots did not visit South Georgia, but the expedition spent much time in the South Orkney Islands and geological work there came to have a significant influence on interpretations of South Georgia. In rocks that were superficially similar to those of South Georgia, the discovery of a graptolite was reported by Pirie (1905), which supposedly established an Early Palaeozoic age. There will be more on Piries's putative graptolite latter in this narrative.

Back on South Georgia, a considerable advance in geological knowledge was contributed late in 1911 by the German South Polar Expedition (1911-1913). Heim (1912) described the bulk of the island as comprising dark shales and greenish tuffs, with a poorly preserved ammonite found at Prince Olav Harbour seeming to confirm a Mesozoic age for the rocks. As with Andersson's bivalve, the ammonite was found in strata that would now be assigned to the Cumberland Bay Formation. The other major discovery reported by Heim was the presence of a substantial body of igneous rocks at the south-east end of the island, now divided between the intrusive rocks of the Drygalski Fjord Complex and the volcanogenic Larsen Harbour Complex.

Shortly after the departure of the German expedition, the first attempt at a comprehensive geological assessment of South Georgia began. This was a strictly commercial affair initiated by the Christian Salvesen Whaling Company. When that company established an onshore whaling station in Stromness Bay in 1909, naming it Leith Harbour after the company's home port in Scotland, the mineral rights to South Georgia were also negotiated with the Government of the Falkland Islands (at the time the island was a Dependency of the Falkland Islands; South Georgia and the South Sandwich Islands now comprise a separate British Overseas Territory). To carry out prospecting work, the Salvesen Company employed David Ferguson, an experienced Scottish geologist and mine surveyor who had close connections with the Geology Department at the University of Glasgow. Ferguson's work in South Georgia and subsequently in the Falkland Islands and South Shetland Islands has been assessed in some detail by Stone and Faithfull (2013).

Ferguson arrived at Leith Harbour on 7 January 1912, only a month after the departure of the German expedition. Though he would have known nothing of the detail of their work, he gathered some information on their findings from staff at the whaling stations. For example, he was shown a sketch of the poorly preserved ammonite from Prince Olav Harbour that was supportive of the Mesozoic age previously suggested by Andersson's bivalve. But Ferguson doubted the identification of the fossil and prematurely dismissed the possibility of a Mesozoic age since he had rapidly formed the opinion that the South Georgia rocks were very much older than that. He had misidentified trace fossils found near Leith Harbour as 'fucoids' (a common misconception at that time) and, subsequently supported by Gregory (1915), thought that these supposed marine plant fossils had an Early Palaeozoic aspect. He also knew of Pirie's putative graptolite from the South Orkney Islands, the geology of which he had discussed with William Speirs Bruce (leader of the *Scotia* expedition) before departing for South Georgia (Stone and Faithfull 2013). Ferguson favoured a correlation between the superficially similar rocks from the two Scotia Arc components, so saw Pirie's fossil as confirmation of an Early Palaeozoic age for at least part of the South Georgia succession.

Pirie concurred. Back in Glasgow he had seen Ferguson's specimen collection whilst preparing a contribution to the planned eighth volume in the series of *Scotia* scientific reports. This volume was never published but a galley proof of Pirie's description of the geology of the South Orkney Islands (Pirie 1913) is held by the British Antarctic Survey. In it, Pirie wrote that Ferguson's South Georgia specimens "present remarkable similarity to the greywackes of the South Orkneys, and I think it extremely probable that they will prove to be, if not of identical age, at least older than Upper Palaeozoic."

Overall, the South Georgia sedimentary succession was interpreted by Ferguson as a conformable series of three divisions, which he differentiated largely on the basis of colour. In two relatively small areas of the island, in Cumberland East Bay and at Godthul (Figure 2), he thought that the middle division lay unconformably on much older sedimentary strata with a more complex structural history. He was partially correct in that the intensely folded and cleaved succession now assigned to the Sandebugten Formation has been overthrust by the less pervasively deformed Cumberland Bay Formation in Cumberland East Bay (Dalziel and others 1975) and at Godthul and around Royal Bay (Stone 1980), but there is no unconformity. Although Ferguson noted and photographed folding at numerous localities and mentions thrusting several times in his field notes (held by the University of Glasgow Archive Services) and in a single sentence in his published account (Ferguson 1915, p. 812), the implications of such deformation were largely ignored in the geological map and cross-section that he constructed (Ferguson 1915, plates 81 and 82). Further, his reliance on colour for correlation led to unlikely outcrop patterns, in places requiring horizontal beds over considerable areas. This structural arrangement was demonstrably absent and it is odd that Ferguson's experienced mentors at Glasgow University, Professor J.W. Gregory and Dr G.W. Tyrrell, did not identify this fundamental problem prior to the publication of their joint summary in the *Geological Magazine* (Ferguson and others 1914) and three individual, complementary papers in the *Transactions of the Royal Society of Edinburgh* (Ferguson 1915; Gregory 1915; Tyrrell 1915). Perhaps Tyrrell's focus was entirely on petrography, whilst in his comprehensive biography of Gregory, Leake (2011, p. 146) notes that the interpretations of South Georgia "reveal Gregory's poor knowledge of structural geology." However, Gregory did accept the evidence of the ammonite fossils as establishing a Mesozoic age for at least part of the South Georgia succession. Correspondence held by the Hunterian Museum, University of Glasgow, shows that he had arranged to borrow the specimen collected by the German Expedition (Heim 1912).

A second, although very minor contribution to the geology of South Georgia was facilitated by the Salvesen whaling company during the 1913-14 austral summer. Two zoologists from what was then the British Museum (Natural History), G.E. Barrett-Hamilton and P. Stammwitz, collected data and biological samples from whales at the Leith Harbour factory, but also gathered a small selection of rock specimens. These were never described but are still held in London at The Natural History Museum. There are ten specimens and although they are poorly located, their character is compatible with a provenance in the Leith Harbour area. The scientific investigations came to an unfortunately premature end when Barrett-Hamilton died at Leith Harbour after a heart attack.

After publication of Ferguson's (1915) account of South Georgia's geology, and despite the support provided by Gregory and Tyrell, it was not long before his interpretation was challenged. Shackleton's ill-fated *Endurance* expedition had called at South Georgia on its voyage south in November 1914, and the expedition's geologist, J. M. Wordie (another of Gregory's protégés), had done much geological work during a stay of about four weeks. Despite the subsequent vicissitudes of the *Endurance* expedition and being badly injured during service with the Royal Field Artillery towards the end of the Great War, Wordie eventually published a summary of his geological observations. Therein (Wordie 1921, p. 19), he dismissed Ferguson's "unfortunate attempt at subdividing the sedimentary series" of South Georgia, supported its likely Mesozoic age, and stressed the importance of folding. By the time Wordie published, Shackleton had embarked on his final expedition (during which he died, at South Georgia, on 5 January 1921) aboard the *Quest*, with G. V. Douglas as geologist. In that expedition's report, Douglas (1930, p. 9) noted with respect to the geology of South Georgia: "J. M. Wordie's paper … appeared after the *Quest* had sailed, and the present writer arrived independently at the conclusions to which Wordie had also come." The rock specimens collected during the *Quest* expedition were described by Tyrrell (1930), in the last of his series of papers concerned solely with South Georgia petrography. Macdonald and others (1987) note that this experience enabled Tyrrell, in his 1930 paper, to produce one of the best of the early stratigraphical schemes for South Georgia even though he never visited the island.

The conclusions of Wordie were also supported by Holtedahl (1929) who had studied the geology of South Georgia during the Norwegian Antarctic Expedition, 1927-1928. Holtedahl was able to examine much of the island and concluded that there was a single sedimentary succession of Mesozoic age. Expedition members found more fossils to support that age, notably a collection from Annenkov Island that included an ammonite and several types of bivalve. The other important aspect of Holtedahl's work was his assessment of the igneous rocks in the SE of the island. He suggested an interbedded relationship between basalt lavas and the youngest part of the sedimentary succession, with still younger intrusive granite and gabbro. During a brief visit to Cooper Bay (CB on Figure 2) he noted the highly sheared contact between igneous and sedimentary rocks that is now known as the Cooper Bay Shear Zone.

Soon after Holtedahl's study, South Georgia was revisited during the 1928-1929 austral summer by L. Kohl-Larsen, who had first arrived in 1911 as a member of the German South Polar Expedition; on that occasion, appendicitis had forced him to leave the expedition and recuperate at the Grytviken whaling station. On his second visit, which was not primarily concerned with geology, Kohl-Larsen recovered more fossils (bivalves and ammonites) from Annenkov Island. These, together with Holtedahl's collection, were formally described by Wilckens (1932, 1937, 1947) as being undoubtedly Early Cretaceous in age. Wilckens (1933) also attempted to integrate the geology of South Georgia into the broader pattern of the Scotia Arc, stressing that correlation with Tierra del Fuego was more likely than the links with the South Orkney Islands favoured by Pirie (1913) and Tyrrell (1915). Writing of his experiences in South Georgia, Kohl-Larsen (1930) demonstrated that David Ferguson was well-remembered by the whaling community. A location near Leith Harbour was pointed out to him where "an English (*sic*) geologist had found plant fossils". Kohl-Larsen acquired explosives from the whaling station and blasted out a collection of specimens that he sent back to the Senckenberg Museum in Frankfurt, Germany. The 'plants' – the fucoids of Gregory (1915) – were correctly identified and described as marine trace fossils by Wilckens (1947). In a previous publication Wilckens (1932) had similarly challenged most of the interpretations made by Gregory (1915) of Ferguson's 'fossil' specimens.

Holtedahl's rock specimens were described by Barth and Holmsen (1939). In his 1929 account Holtedahl had been deeply suspicious of Wegener's 'displacement' hypothesis, but Barth and Holmsen (1939) had enjoyed a decade more to consider the matter and were less dismissive of continental drift. Although their contribution was primarily an account of petrology and geochemistry, Barth and Holmsen concluded with a short section on the "Origin of the South Antillean Arc". Whilst admitting that the nature of the tectonic forces involved remained a puzzle, they envisaged an origin by continental drift (Barth and Holmsen 1939, p. 62) – "if we believe, with Wegener, in a single huge continent that split into fragments which drifted apart." Visualising two of those fragments as South America and the Antarctic Peninsula, linked by a narrow isthmus, Barth and Holmsen continued:

"If now this twin continent was drifting westward, then the connecting landbridge, due to its lesser moment of inertia, would lag behind … The result would be an arcuate ridge pulled out to a large loop that eventually would break up to pieces."

South Georgia would be one of those pieces.

The Second World War (1939-1945) imposed a starkly different set of priorities and effectively curtailed geological exploration in South Georgia and the wider South Atlantic region. However, one outcome of wartime activity that was to have important scientific consequences in the longer term went by the code name *Operation Tabarin*. As described by Dudeney and Walton (2012) and Luxton (2014), this saw the covert establishment of British naval outposts in the South Shetland Islands and northern Graham Land in response to the perceived threats from German commerce-raiding warships and possible interventions from Argentina. At war’s end, the naval operation was transformed into a civilian organisation and renamed, now overtly, the Falkland Islands Dependencies Survey (FIDS). This organisation was to play a major role in South Georgia’s post-war geological renaissance.

3 The beginnings of the modern synthesis: 1950-1965

The resolution of South Georgia's stratigraphy and geological structure was initiated in the 1950s by the work of A.F. Trendall during the first two of the three South Georgia Survey Expeditions: 1951-52 and 1953-54 (Carse 1959; Trendall 1953, 1959). His participation in the first expedition was terminated prematurely when he fell into a crevasse high on the Ross Glacier and broke his leg; the second expedition was beset by logistical problems (Trendall 2011). Despite these difficulties, Trendall achieved an impressively comprehensive overview. Initially, he thought it possible that the Cumberland Bay and Sandebugten 'series' had an unconformable relationship, but subsequently revised that opinion in favour of them representing facies (and/or provenance) variations within a single, thick succession of turbidite strata; he accordingly modified his terminology, describing Cumberland Bay type and Sandebugten type strata. The early Cretaceous age of his Cumberland Bay type rocks was confirmed by new fossil discoveries on Annenkov Island. Trendall also provided much new information on the intrusive sequence of the igneous rocks in the south-east of the island (defining a 'South-eastern Igneous Complex'), where he also confirmed the interbedding of basaltic pillow lavas and 'Cumberland Bay type' turbidite strata. His explanation of the structural problems invoked overfolding, refolding and thrusting but, nevertheless, the precise nature of the relationship between Cumberland Bay and Sandebugten type rocks remained uncertain.

Some progress towards resolving that 'relationship problem' was made by the first Falkland Islands Dependencies Survey (FIDS) geologists to work on South Georgia. N. Aitkenhead and P.H.H. Nelson were en route to the FIDS base at Hope Bay on the Antarctic Peninsula, but were able to make a short visit to the Cumberland Bay area during the December 1959 to January 1960 interval. Their observations were summarized in an unpublished report (Aitkenhead and Nelson 1962) now held by the British Antarctic Survey (the FIDS was renamed the British Antarctic Survey – BAS – in 1962). From the north-west coast of the Barff Peninsula they described a discordant contact between tightly folded and steeply inclined Sandebugten type strata and an overlying succession of strata that was more similar to the Cumberland Bay type and which showed a markedly different, more open structural style. However, the interpretation remained equivocal, with the preferred option an unconformity subsequently modified by thrusting.

Some geological work was also carried out during the 1964-65 austral summer by members of the Combined Services Expedition. Although this was primarily a mountaineering and topographical surveying venture, J.D.C. Peacock had responsibility for geological observations and the collection of specimens. Geological results were not independently published but were summarised in an expedition report by Burley (1966). Large-scale folding was widely noted, intrusive igneous sills were located between Moraine Fjord and St Andrews Bay, whilst small-scale, intense folding was recorded around the north side of Royal Bay where the main surveying effort was focussed (Fagan 1966). The British Antarctic Survey holds the expedition's unpublished archive (ref. AD6/2M/1964/L) and specimen collection (ref. ES3/GYX26).

Regional correlations

Trendall did not speculate on the regional associations of the South Georgia sedimentary succession, although the stratigraphical revision made between his 1953 and 1959 reports was most probably influenced by the reappraisal of Pirie's (1905) putative graptolite from the South Orkney Islands, a fossil that had underpinned, via correlations southward, the proposed Lower Palaeozoic age for the Sandebugten division.

The 'graptolites' from the South Orkney Islands had been verified by no lesser palaeontological authorities than Gertrude Elles and Ben Peach, the latter also identifying phyllocarid remains (Pirie 1905, 1913); Pirie's 1905 paper was presented to the Royal Society of Edinburgh by John Horne, another eminent Scottish geologist well-versed in Lower Palaeozoic geology. With such an *imprimatur*, the fossils were not unmasked (as most probably indeterminate plant material) for another 50 years, and not before another erroneous 'graptolite' discovery by Argentine geologists (Cordini 1955, 273-277), as reported by Thomson (1977). When Pirie's specimens (National Museum of Scotland specimen numbers 1954.2.28 and 29) were re-examined by the Birmingham University palaeontologist (and graptolite specialist) Dr Isles Strachan, he reported, as quoted by Adie (1957b, p. 22): "The fragmentary specimens from the South Orkney Islands are extremely poorly preserved. No thecae can be seen on the supposed graptolite stipes and the markings on the other organic fragments can be explained in several ways. There is no positive evidence for an Ordovician-Silurian age for the shales although, of course, the specimens can be interpreted to agree with such an age. They could, however, equally well be identified as plant fragments and assigned to the Carboniferous." It took some time for this reassessment to become established with, for example, King and Downard (1964) still citing the graptolitic evidence for a Lower Palaeozoic age, but eventually the supposedly graptolitic rocks yielded Triassic conodonts and radiolaria (Dalziel 1979; Dalziel and others 1981).

Nevertheless, despite the palaeontological revisions, there was a continuing view that, whilst not Lower Palaeozoic, the Sandebugten type strata might still be older then the demonstrably Mesozoic Cumberland Bay type. Trendall (1959, p. 42) thought it "probable that the Sandebugten-type is also of Mesozoic age, though there is still the possibility that it is Palaeozoic." Adie (1964, p. 122) agreed, citing the unpublished work of Aitkenhead and Nelson. He re-emphasised the lithofacies similarities between a resurrected Sandebugten Series and the Trinity Peninsula Series of Graham Land and the Greywacke-Shale Series of the South Orkney Islands (source of Pirie's 'graptolite' and now known to be Triassic), both of which divisions he considered to be probably Carboniferous.

Correlations westward from South Georgia, towards Tierra del Fuego, had also been contentious. At first it was thought unlikely that there was any geological association between the two areas, a view given prominence by Professor J Gregory's (1929) Presidential Address to the Geological Society of London. Therein, South Georgia, and the other islands of the Scotia Arc were regarded as vestiges of a foundered continent that had once occupied the South Atlantic region. Gregory would have based his opinion largely on the work of his protégé Ferguson, and justified his regional interpretation with the observation that "[t]he sedimentary rocks also indicate for South Georgia a different history from that of the Andes" (Gregory 1929, p. cxi). This opinion was immediately challenged by Holtedahl (1929, p. 105-106) writing after the 1927-28 Norwegian Antarctic Expedition: "To me it seems that the sedimentary rocks of the extreme south of South America … remind one very strongly of the South Georgia series.” Subsequent work confirmed this view. After extensive work in Tierra del Fuego, (Kranck 1934) noted the geological similarities with South Georgia and made specific lithostratigraphical correlations with the South Georgia divisions proposed by Ferguson (1915). In Tierra del Fuego, Krank established the Yahgan Formation, which later work on Navarino Island, southern Chile, confirmed as having a close correspondence to the Cumberland Bay Formation of South Georgia (Katz and Waters 1966). These aspects of South Georgia geology played into the wider, early 20th century debate over the validity of continental drift, and its role in the formation of the Scotia Arc.

4 Systematic survey and research: 1966-1977

The sedimentary succession

The development of Trendall's interpretation of South Georgia geology by subsequent workers has been detailed by Macdonald and others (1987) who stressed (and listed in their Table 1) the contributions of geologists from the British Antarctic Survey and the United States Antarctic Research Program.

After a hiatus during the early 1960s, geological interest in South Georgia from both the UK and the USA recommenced in 1966 and gathered pace thereafter. During the 1965-66 austral summer, a limited pilot study of sedimentolgy and palaeocurrent analysis was carried out in the Cumberland Bay Formation by L.A. Frakes from the University of California. Frakes (1966) described results from Cumberland East Bay and the vicinity of Leith Harbour which showed a variable palaeocurrent flow, interpreted as showing that the Cumberland Bay Formation was derived from both sides of its depositional basin.

The 1965-66 austral summer also saw renewal of South Georgia investigations by the BAS when, en route to the BAS base at Halley Bay, D. Brook was able to spend time examining the geology of the area between Cumberland West Bay and Stromness Bay. During the following austral summer, 1966-1967, this work was continued westward from Stromness Bay to Fortuna Bay by M.J. Skidmore, who also spent time in the Prince Olav Harbour area early in 1969 during his journey north at the conclusion of his Halley Bay posting. Skidmore (1972) described the geology of the Cumberland Bay Formation as seen in the areas studied by himself and Brook. The turbidite sedimentology of the strata was detailed, their volcaniclastic composition quantified and their low-grade metamorphic facies established. The turbidite beds were shown to be incorporated into large-scale folds, overturned towards the north and with a well-developed axial plane cleavage. Skidmore's was the first account in which the significance of plate tectonics was tentatively addressed. He reaffirmed the correlation of the Cumberland Bay Formation with the Yahgan Formation of Navarino Island and noted the similarity of structural style in the two areas, evidence for their having once been in much closer proximity.

The involvement of the BAS in South Georgia was much strengthened late in 1969 by the establishment of a permanent base at King Edward Point, Cumberland East Bay, close to the abandoned whaling station of Grytviken. The first geological beneficiary of this new facility was P. Stone, who spent the 1970-71 austral summer surveying the geology of the Barff Peninsula between Cumberland East Bay and St Andrews Bay, and in the process relocating and reinterpreting the important boundary between Cumberland Bay and Sandebugten 'type' strata that had been noted by Aitkenhaed and Nelson (1962). In a report acknowledged as having been submitted for publication in October 1975, Stone (1980) defined the two divisions as formations and regarded the boundary as a thrust that had carried his Cumberland Bay Formation (CBF) over the Sandebugten Formation (SDF). The outcrop of CBF strata at the northern end of the Barff Peninsula was interpreted as a structural klippe that comprised interbedded Cumberland

Bay and Sandebugten 'types'. It was designated the Barff Point Member of the CBF and regarded as the most distal preserved part of the 'Cumberland Bay' thrust sheet.

Stone returned for the 1971-72 austral summer, extending his geological survey southwards from St Andrews Bay, and through the Royal Bay area as far south as Gold Harbour. R.B. Crews assisted in the Royal Bay area and then worked independently around the Cumberland bays. Stone's work effectively covered the entirety of SDF outcrop. The distinctively quartzo-feldspathic turbidite strata were disposed into broadly upright, tight to isoclinal and chevron folds, with axial planar slaty cleavage, that across the Barff Peninsula formed a NW-SE trending anticlinorium. Southward, the effects of a second episode of deformation became increasingly dominant, with all of the earlier fabrics transposed by a shallow, pervasive crenulation cleavage axial planar to overturned or reclined folds. A second, steeply-dipping crenulation cleavage also increased in intensity southwards, being most apparent to the south of Royal Bay on the Cape Charlotte promontory. Subsequent minor deformational effects were also noted, as were a few small, pre-deformation, intrusive sheets of doleritic rock, now highly altered. On the south side of Royal Bay the thrust contact between the SDF and the overlying CBF was traced from Will Point, across the Cape Charlotte promontory and southwards into Gold Harbour. Belemnite fragments recovered from a CBF moraine cobble at Little Moltke Harbour (Royal Bay) suggested a Late Jurassic to Early Cretaceous age (Stone and Willey 1973). However, the fauna (together with some subsequently collected material from the same general area) was later reassessed by Doyle (1985) as comprising only indeterminate belemnite fragments that provided evidence for only a broad Jurassic-Cretaceous age.

The 1972-73 austral summer saw the involvement of an American team led by I.W.D. Dalziel and funded by the United States Antarctic Research Program, whilst the BAS geological survey programme was continued by T.H. Pettigrew and R.A.S. Clayton. Accompanying Dalziel were R.L. Bruhn, R.H. Dott and R.D. Winn: Dalziel and Bruhn were based at Columbia University, New York; Dott and Winn were based at the University of Wisconsin.

Early in 1973 the American team made detailed observations in the Cumberland Bay and Stromness Bay areas, supplemented by brief visits to the Bay of Isles and Bird Island. In Cumberland East Bay, on the Dartmouth Point promontory (now Greene Peninsula) they located a thrust contact between the Cumberland Bay and Sandebugten formations and from structural analyses showed that the deformation in the two divisions was broadly contemporaneous, despite the differences in style (Dalziel and others 1975). An assessment of palaeocurrent indicators showed dispersal towards the north-west in the Cumberland Bay Formation, but a more complicated pattern in the Sandebugten Formation dominated by a south-directed component; the structural restoration of the data was detailed by Dott (1974). From a regional perspective, the American team brought the advantage of direct familiarity with the likely correlative geology in the extreme south of South America. This allowed the development of a regional model for the origin of South Georgia (and the South American correlatives) in a marginal basin lying between the continental margin and a rifted continental sliver carrying a calc-alkaline volcanic arc. Sediment was derived from both sides of the basin, with deformation initiated by basin closure and the resulting arc-continent collision (Dalziel and others 1975; Winn 1978). This interpretation brought South Georgia geology squarely into the plate tectonic era.

Pettigrew spent the 1972-73 austral summer on a detailed investigation of the geology of Annenkov Island, submitting his report (Pettigrew 1981) for publication in July 1975. Two members of an Annenkov Island Formation were recognized and had experienced only very minor deformation, allowing a sedimentary thickness of about 2000 m to be measured. A Lower Tuff Member comprised mostly interbedded tuff and tuffaceous mudstone; an Upper Breccia Member comprised mostly volcaniclastic breccia and sandstone. The lower member is the most fossiliferous although preservation is not good. The assemblage of bivalves, ammonites, fish fragments plant fossils etc., as described by Wilckens (1932, 1937, 1947) was confirmed, with an additional Early Cretaceous belemnite fauna recovered from the upper member (Pettigrew and Willey (1975). Both members contain rare interbedded basaltic lavas and are cut by a range of basaltic and andesitic minor intrusions. Pettigrew described the Annenkov Island succession as representing parts of a volcanic island arc and marginal basin and, in collaboration with M. Suarez (Instituto de Investigaciones Geológicas de Chile), developed a regional model in those terms incorporating South Georgia and the southern Andes (Suarez and Pettigrew 1976).

During the 1972-73 austral summer Clayton worked around the Bay of Isles, in the north-west of South Georgia; during the following summer, 1973-74, he extended his mapping across to the south coast of the island, in the Ice Fjord to King Haakon Bay area, accompanied by R.N. Mortimore. All of this area comprised part of the outcrop of the Cumberland Bay Formation. Detailed sedimentological analysis of the turbidite succession focussed particularly on relative proximality indicators (Mortimore 1979; Clayton 1982a), with a qualitative assessment of the detrital composition and subsequent alteration of the wacke-type sandstones during diagenesis and low-grade metamorphism (Clayton 1982b). Large-scale close to open folds were shown to be asymmetric and locally overturned towards the north, with a pervasive axial planar cleavage (Clayton 1983). Stereographic analysis suggested that a second phase of open folding had affected the main structures and cleavage, whilst subsequent minor structures were recognised locally. In a more wide-ranging study, Clayton (1982c) compared the whole-rock geochemistry of the Cumberland Bay Formation sandstones in the north-west of South Georgia, to that found in other parts of its outcrop, and extended the comparison to the Sandebugten Formation and Cooper Bay area, utilising specimens collected by Skidmore and Stone. All four of Clayton's papers had been submitted for publication between November 1975 and July 1976.

Stone had also returned to South Georgia for the 1973-74 austral summer, extending his work on the north-east coast southwards to Iris Bay and Cooper Bay; some additional infill work was completed at St Andrews Bay and on the south side of Royal Bay. The polyphase folding of the Cumberland Bay Formation to the south-east of Royal Bay was established (Stone 1980), with an early suite of minor folds thought to pre-date the main, large scale structures that continued the trends seen elsewhere in the island, here with hinges trending NW-SE. The two fold sets were axially co-planar so that a slaty cleavage was cut by a closely sub-parallel micro-crenulation cleavage. A second, locally cross-cutting crenulation cleavage was associated with minor overturned folds.

Farther south, in the Cooper Bay area, deformation proved to be more intense, with an apparently thinly-bedded turbidite succession converted into a series of schistose rocks, slates and cataclasites. Within the metasedimentary succession were widespread boudinaged sheets of a pervasively altered, but originally doleritic intrusive rock. Stone (1982) – a paper submitted for publication in October 1975 – defined the metasedimentary succession as the Cooper Bay Formation and described its polyphase deformation. The earliest small-scale folds, with an associated slaty cleavage, were identified from their interference patterns with a series of tight, minor folds with an axial planar crenulation cleavage. The latter was then folded into large-scale, upright folds to which a steeply inclined, second crenulation cleavage was axial planar; all of these structures were cross-cut by a range of minor, late and locally developed folds and crenulations. At the south-western margin of its outcrop, the structures affecting the Cooper Bay Formation merged into a polyphase, mylonitic shear zone that separated the metasedimentary rocks from Trendall's (1959) South-eastern Igneous Complex.

In summing up the deformation history seen on the north-east coast of South Georgia, Stone (1980) built on the marginal basin model of Dalziel and others (1975), envisaging its sedimentary fill experiencing diachronous, supra-subduction zone deformation as the basin closed. In modern terms this would be described as accretionary tectonics.

The 1973-74 austral summer marked a turning point in the BAS South Georgia geology programme as specialist studies began in parallel with the final phase of the regional mapping work. The structural geology and overall tectonic regime were investigated in particular by P.W.G. Tanner, who spent that summer and the subsequent 1975-76 summer on a wide-ranging field programme. His work, and the rest of the specialist research theme, will be returned to in a later section of this account.

The south-eastern igneous complex

The final phase of the BAS regional geology work on South Georgia focussed on the igneous rocks in the south-east of the island, the South-eastern Igneous Complex of Trendall (1959). Investigations in this area by C.M. Bell, B.F. Mair and B.C. Storey began in the 1974-75 austral summer. Storey returned in the following summer, 1975-76, to work particularly in the Drygalski Fjord and Ducloz Head area, whilst Mair returned in the 1976-77 summer to work particularly in the Larsen Harbour and Leon Head areas. During this period of field studies Cooper Island was also visited, whilst traverses across the mylonitic shear zone into the Cooper Bay Formation helped to establish the regional relationship of the igneous and metasedimentary rocks.

A series of publications arose from the work in the south-east with the overall divisions established by Bell and others (1977) and Storey and others (1977). The igneous rocks were divided into the ophiolitic Larsen Harbour Formation (subsequently redefined as a Complex) of submarine basalt lavas and breccias and sheeted basic dykes, and the Drygalski Fjord Complex of mostly gabbroic plutons, with subordinate granitic rocks, intruded into metasedimentary rocks ranging in grade up to siliceous paragneisses. The gabbro bodies were regarded as the root zone of the sheeted dykes and volcanic lavas, intruded into a continental basement of which the metasedimentary units were relics. Storey and Mair (1982) developed these ideas within the marginal basin model for South Georgia describing the ophiolitic Larsen Harbour Formation/Complex, and the pre-Jurassic basement with its gabbroic and granitic intrusions, as remnants of the composite floor of the Cretaceous back-arc basin in which the South Georgia sedimentary successions accumulated. The Larsen Harbour Complex ophiolite comprised pillow lavas and breccias with interbedded tuffs, intruded by mafic and felsic dykes and by gabbro and composite gabbro-plagiogranite plutons. The basement metasedimentary gneisses were intruded by layered gabbro bodies, dioritic and granitic rocks, and by a multitude of mafic dykes.

Some compositional and geochemical data were given by Storey and Mair (1982), with more detailed, comprehensive descriptions and interpretations provided later: for the Larsen Harbour

Formation/Complex by Mair (1983, 1987) and for the Drygalski Fjord Complex by Storey (1983a). The Larsen Harbour lava succession was shown to be about 2 km thick, dipping moderately towards the west. It forms the upper part of an autochthonous ophiolite sequence with a broad lithostratigraphical zonation. Breccias with subordinate pillow lavas form the base of the succession, where they are cut by multiple mafic dykes, and are overlain by voluminous pillow lavas, with subordinate breccia and interbedded volcaniclastic sedimentary layers. Compositionally most of the rocks resembled oceanic tholeiites. Within the Drygalski Fjord Complex, Storey (1983a) divided the metasedimentary, continental basement rocks into three formations: Salomon Glacier, Cooper Island and Novosilski Glacier. The Salomon Glacier Formation comprised siliceous paragneiss and layered migmatite; the other two formations comprised various metasedimentary clastic rocks. After deformation and metamorphism of this ‘basement’ assemblage, intrusion of a differentiated, tholeiitic magma produced a range of rocks from layered gabbros to granite; other granitic intrusions showed calc-alkaline trends. This intrusive phase was followed by swarms of mafic dykes linked to the generation of the Larsen Harbour Formation ophiolite.

Storey’s work extended north-westward to the Ducloz Head area, and north-eastward across the mylonite zone at the margin of the igneous rocks into the Cooper Bay area. At Ducloz Head a succession of volcaniclastic rocks and pillow lava, tuffs and mudstone was defined as the Ducloz Head Formation (Storey 1983b). The formation had been affected by widespread ductile and brittle deformation and was separated from the adjacent Cumberland Bay Formation by a steep fault zone. Storey recognised similarities with all of the other South Georgia sedimentary divisions, but thought the likely regional association to be as an intermediate between the Annenkov Island and Larsen Harbour formations. At Cooper Bay, Storey (1983a) broadly confirmed the lithofacies and polyphase structural interpretation of Stone (1982), but thought that the structural history within the mylonite zone was more complicated than previously proposed. In particular, the mylonite zone may have been initiated earlier in the structural history than was indicated in Stone’s interpretation.

By the time that Mair and Storey published, the first radiometric dates (Rb-Sr) had become available from granite within the Drygalski Fjord Complex and from a granitic intrusion coeval with the later episodes of dyke intrusion in the Larsen Harbour Formation/Complex (Tanner and Rex 1979). The former gave ages in the approximate range 180-200 Ma, the latter gave an age of 127±4 Ma. Storey (1983a) and Mair (1987) incorporated these results, and Storey also described the heterogeneous migmatite aureole that surrounded the intrusive plutonic rocks – but note that Storey (1983b) and Mair (1983) were received for publication in August 1978 and October 1976 respectively, before the radiometric dates were available.

In addition to his work on the Larsen Harbour Formation/Complex Mair also investigated the geology in the Moraine Fjord area of Cumberland East Bay during a short period in 1977. He described a number of small, pre-tectonic, dioritic and gabbroic sheets intruded into strata of the Cumberland Bay Formation, and traced out the structural contact and contrasts between that formation and the structurally subjacent Sandebugten Formation (Mair 1981) to the south of Dartmouth Point (the promontory now known as Greene Peninsula). This was the area from which Dalziel and others (1975) had described a thrust contact between the two formations.

5 Specialist research and regional models: 1973-1982

In parallel with the closing contributions to the BAS geological mapping programme, specialist studies sought to integrate accumulated data into a regional interpretation and development model. Key to this phase of the BAS programme were the structural interpretations of P.W.G. Tanner and the sedimentological work of D.I.M. Macdonald. As previously noted, Tanner visited many localities around South Georgia during the 1973-74 austral summer. He returned for the 1975-76 summer, working mostly in the coastal region between Fortuna Bay and Cumberland East Bay, whilst at the same time Macdonald worked in the extreme north-west mainland of South Georgia in the Elsehul to North Cape area, and along the south-west coast of the island between Queen Maud Bay and Cape Darnley. Both researchers made landings on the Hauge Reef and Pickersgill Islands in collaboration with Storey, and jointly interpreted their geology in terms of an island arc assemblage (Tanner and others 1981). A sedimentary succession of tuff and mudstone overlain by volcaniclastic breccia was correlated with the Annenkov Island Formation, and overlay pillowed basaltic lavas correlated with the Larsen Harbour Formation. The geochemistry of the assemblage confirmed its tholeiitic association (Storey and Tanner 1982). The sedimentary unit was cut and hornfelsed by a wide range of mafic sills and gabbroic to dioritic intrusions, also largely tholeiitic. Radiometric dates (Rb-Sr and K-Ar) reported by Tanner and Rex (1979) were approximately in the 80 - 100 Ma range.

As part of his sedimentological studies Macdonald investigated the nature of the fossil wood fragments that had been widely reported from the Cumberland Bay Formation (Jefferson and Macdonald 1981). The data gathered informed both the assessment of sediment diagenesis and, by virtue of the fragments' orientations, the assessment of regional palaeocurrent patterns. Macdonald (1982) also reviewed the trace fossil assemblages from the Cumberland Bay Formation. Again, these had been widely reported by previous workers but not systematically assessed in terms of depositional facies. Macdonald regarded the ichnofaunal assemblages as indicative of deposition in relatively deep water, with low faunal diversity (and indications of a high physical stress) pointing to a partially anoxic environment.

All of the palaeontological evidence for the age of the South Georgia sedimentary succession was reviewed by Thomson and others (1982) and integrated with K-Ar radiometric dates that reflected uplift and cooling following regional metamorphism. Apart from the faunal assemblage found in the Annenkov Island Formation evidence was very sparse, but sufficient material was available to indicate a uniform Aptian (Early Cretaceous) depositional age, ca 113-126 Ma (Gradstein and others 2012). One previous K-Ar age of ca 70 Ma had been given for the Cumberland Bay Formation by Grikurov and others (1967). The more extensive data reported by Thomson and others (1982) gave an age range of 51-135 Ma for the Cumberland Bay Formation and 64-84 for the Sandebugten Formation. The older ages were thought to be influenced by the presence of detrital white mica. The best estimate for the minimum age of metamorphism was thought to be 82-91 Ma, with post-orogenic uplift continuing to at least 50-60 Ma. Thomson and others compared their results from South Georgia with the comparable evidence from the Yahgan Formation of southern Patagonia and supported its previously proposed correlation with the Cumberland Bay Formation.

Tanner (1982a) brought together all of the available evidence in a review of the geological evolution of South Georgia, a process that could now be described in terms of a late Jurassic to Early Cretaceous island arc and marginal basin system. The regional importance of the mylonitic shear zone (the Cooper Bay dislocation in Tanner's account), separating the igneous rocks of the basin floor and its associated continental relics from the turbidite strata deposited in the basin, was also given prominence. The shear zone was one of the geological elements utilised by Tanner in a correlation of the litho-tectonic divisions of South Georgia with those of southern Patagonia and Tierra del Fuego. From these relationships Tanner inferred a pre-drift position for South Georgia to the south of Burdwood Bank, a more easterly position than had featured in previous reconstruction (e.g. Dalziel and Elliot 1971). Tanner was also able to include the Shag Rocks microcontinental block in his reconstruction with more confidence than had been previously possible, having examined and described rare specimens from those inaccessible rock pinnacles (Tanner 1982b).

In 1982, the island of South Georgia was invaded and briefly occupied by an Argentine military force. The events surrounding the occupation and the recovery of the island by British forces have been described by Headland (1984). The ensuing need for rehabilitation and the clearance of mines and unexploded munitions, prevented the resumption of scientific field work for some considerable time. Publication of the results of the earlier research continued however, with three papers summarising the depositional and structural history of the sedimentary successions as the result of opening and closing of a Mesozoic back-arc basin.

Tanner and Macdonald (1982) and Macdonald and Tanner (1983) focussed in particular on the Cumberland Bay Formation, thought to be more than 8 km thick. Previous interpretations of the palaeocurrent patterns were confirmed by a much enlarged database. For the Aptian (Early Cretaceous) Cumberland Bay Formation, andesitic, volcaniclastic sediment was derived from the south-east by turbidity currents flowing along the axis of the depositional basin in a linear, tectonically-controlled trough. In contrast, the Sandebugten Formation, probably of similar age, had a lateral derivation from a continental and silicic volcanic provenance on the north side of the basin. Deformation during closure of the basin resulted in increasingly tight and overturned folds toward the NE, with shortening calculated at up to 55% and an original basin width of about 60 km. Both the sedimentary and tectonic models were extended westward to link South Georgia with the contemporary back-arc basin in the southern Andes and Tierra del Fuego.

In the third paper, Storey and Macdonald (1984) reviewed the earlier stages in the history of basin extension, the relic continental crust of the Drygalski Fjord and the ophiolitic Larsen Harbour complexes, and related the island arc succession of the Annenkov Island Formation to the main depositional basin. The thick units of volcaniclastic breccia in the Annenkov Island succession were regarded as channel-fill, debris flow deposits; laterally equivalent turbidites formed the Cumberland Bay Formation.

6 After the Falklands conflict: geological research since 1982

As an adjunct to the 1982 Falklands Islands conflict, South Georgia was also briefly occupied by an Argentine military force, and whilst these events were immensely damaging, they did raise the international profile of the island. Perhaps as a result, the first post-war geological research was carried out by members of a private expedition: the 1984 New Zealand South Georgia Expedition. During the 1984-85 austral summer the area inland from Royal Bay, between the Heaney and Weddell glaciers, was examined, in effect extending inland the earlier study by Stone (1980). Arising from this work, Craw and Turnbull (1986) gave a description of the geology which, to the east of Mount Brooker, included the thrust contact between the Cumberland Bay and Sandebugten formations. Bivalve fossils indicative of an Early Cretaceous age were discovered in Cumberland Bay Formation strata on the south side of the Ross Pass. Two discrete structural domains were defined in the Cumberland Bay Formation, one with a single phase of deformation, the other with two phases, and these were contrasted with a third domain described from the Sandebugten Formation outcrop. The structural interpretation was taken further by Turnbull and Craw (1988) who saw similarities in tectonic style between the Sandebugten Formation and the most deformed parts of the Cumberland Bay Formation. They also challenged the regional model wherein the contrasting Cumberland Bay and Sandebugten sedimentary lithologies were derived from opposite sides of a depositional basin. Instead, Turnbull and Craw cited examples of arc-derived sediment from the Pacific margins in support of derivation of all of the South Georgia sedimentary divisions from one evolved volcanic arc with a sialic basement.

Geological work by the British Antarctic Survey recommenced in the 1988-89 austral summer when T. Alabaster revisited the Larsen Harbour Formation, confirmed the chronology of lava eruption and dyke intrusion and carried out detailed geochemical sampling in the Smaaland Cove area. From the geochemical data obtained, five basalt groups were recognized (Alabaster and Storey 1990): the oldest three derived from magmas generated during the early stages of continental lithospheric extension, the younger two groups were thought similar to some mid-ocean ridge basalts. Overall, Alabaster and Storey favoured eruption of the Larsen Harbour Formation at an oblique-slip continental margin (the Gulf of California provided an analogy) rather than in the supra-subduction, back-arc setting that had been preferred previously.

Alabaster and Storey (1990) were able to cite a U-Pb date of ca 150 Ma from zircon in the Smaaland Cove pluton that had been presented in conference abstracts by Mukasa and others (1988, 1989), a team based at the universities of Michigan and Texas, USA. Full details of this radiometric anlaysis were not published for some years, until Mukasa and Dalziel (1996) provided full results for this and several other dates from the southernmost Andes. The 150±1 Ma age given for the Smaaland Cove pluton provided a minimum age for the Larsen Harbour Formation basalts because the pluton intruded the lowermost part of the lava succession. Radiometric ages for the pluton that had been previously published for the pluton by Tanner and Rex (1979) were younger: 78±3 Ma, K-Ar hornblende; 127±4 Ma, Rb-Sr whole-rock. As had been suspected by Tanner and Rex, these younger ages were regarded by Mukasa and Dalziel as the result of partial resetting by hydrothermal alteration and metamorphism, coupled with sparse original data.

The relationship between the igneous complexes in the south-east of South Georgia and the adjacent metasedimentary Cooper Bay Formation was further investigated by M.L. Curtis of the British Antarctic Survey during three austral summers between 2005 and 2009. From the Cooper Bay Shear Zone Curtis (2007) described two deformational phases. The earliest displacement was associated with dip-slip reverse shear and resulted in mylonitised granitic rocks along the south-west margin of the shear zone. To the north-east, the mylonitised margin of the Cooper Bay Formation's outcrop arose from sinistral strike-slip shear. Superimposition of narrow sinistral shear bands on the dip-slip granitic mylonites suggested that the sinistral shear followed the dip-slip shear. The interpretation was carried forward by Curtis and others (2010) in terms of kinematic partitioning with the timing of shear displacement constrained by radiometric dating. Two U-Pb ages from zircon in pre-tectonic granitic rocks caught up in the shear zone were in agreement at about 160 Ma. In contrast, a Rb-Sr age of ca 83 Ma from biotite in a schist at Cooper Bay was interpreted as recording uplift and exhumation shortly after the first episode of shearing and metamorphism to affect the area. Curtis and others (2010) stressed the analogy of their model for the Cooper Bay Shear Zone to interpretations of the main Andean deformation in the Cordillera Darwin, Patagonia.

As an additional part of his South Georgia field programme, Curtis field-tested digital mapping equipment and applications being developed by BAS for more general use (Curtis and others 2011). This involved visits to a number of localities within the outcrops of the Sandebugten, Cumberland Bay and Annenkov Island formations, where specimens were collected and subsequently utilised for detrital zircon dating and apatite fission-track analysis and thermocronometry. This was a collaborative project between BAS and Birkbeck and University colleges, London, with results from South Georgia and the southern Andes compared and correlated by Carter and others (2014). The detrital zircon population extracted from two Sandebugten Formation sandstones matched that seen in the Rocas Verdes back-arc basin, southern Andes, making an original close association highly likely. The apatite results were interpreted in terms of the separation of South Georgia from South America at about 45 Ma, followed by a kilometre-scale reburial until uplift and exhumation from about 10 Ma onwards. Carter and others' (2014) integration of South Georgia geology into models for the overall development of the Scotia Arc was the latest in a long series of such attempts.

7 Early impressions of South Georgia as part of the Scotia Arc

After his misidentification of South Georgia as a volcanic island, Klutschak (1881, English translation p. 88) continued, "[a]s regards its relation to other continents, South Georgia is part of a submarine range of high mountains connecting the uplands of South America with the Antarctic continent. The highest peaks of this range between Cape Horn and the Cape of Good Hope are represented by the Falkland Islands, South Georgia, the South Orkneys [and] the South Sandwich Islands. With the exception of the Falkland Islands … they are all of the same volcanic nature."

The concept of a geological link between South America and the Antarctic Peninsula via the islands of the Scotia Arc was not a new idea. After sailing to the South Sandwich Islands from South Georgia at the beginning of 1820, the Russian explorer Thaddeus von Bellingshausen (1831) had proposed that they were "the summits of a mountain range" now submerged between them and continuing westward as a submarine ridge to the South American mainland via the Falkland Islands (1945 English translation, p. 110). At about the same time, Sir John Barrow (1831, p. 62), noted that the South Shetland Islands "seem to be a continuation of the cordillera of the Andes, and Archipelago of Tierra del Fuego; being for the most part precisely of the same formation with the latter and their strata even inclining in the same way". Barrow was not writing from first hand experience but, as Second Secretary to the British Admiralty (1804-1845) was well-placed to receive geographical intelligence.

The geological assumptions inherent in Barrow's account were naïve, inevitably so given the circumstances. A more informed assessment followed the Belgian Antarctic Expedition of 1897-1899, when Arçtowski (1895) concluded, independently, that the mountains of Graham Land were the geological continuation of the Andes. A little later, in 1901, in a discussion of the objectives of the proposed British National Antarctic Expedition, Professor John Gregory of Glasgow University illustrated a continuation of the Andes into the Antarctic Peninsula via an eastward-closing loop, admittedly one that closed far to the west of South Georgia (Gregory 1901). At the time he wrote, Gregory had anticipated leading the National Antarctic Expedition's science programme, but in the event he did not take part and the 1901-1904 *Discovery* expedition was led by Captain R. F. Scott, with Dr Edward Wilson as chief scientist. The proposal that the Andes continued southwards to Graham Land via an eastward, horseshoe-shaped bend was then discussed in some detail by Eduard Suess (1909, 488-497). One possibility that he considered was that a submerged geological link followed the arcuate submarine ridge recently discovered during the *Scotia* expedition (Bruce 1905). This feature – the Scotia Arc (Herdman 1932) – extends through South Georgia, around the South Sandwich Islands and on into the South Orkney Islands (Figure 1) but Suess, whilst supporting the broad idea, felt it more likely that the eastward bend closed to the west of these islands, linking Burdwood Bank with Elephant Island and the South Shetlands. This left the more easterly, poorly known islands as geological enigmas.

Like most important scientific concepts, continental drift had a long history of maverick (and in some cases bizarre) manifestations, but it only attracted the attention of the geological mainstream once promoted by Alfred Wegener from 1912 onwards (Wegener 1912, 1915, 1929). In a specific reference, Wegener (1929) insisted that the development of the Scotia Arc was best explained by ‘drift theory’, noting palaeontological evidence that supported a terrestrial link between the Antarctic Peninsula and Tierra del Fuego until as recently as the Pliocene. He citied bathymetry to conclude (1929, p. 94) that “[s]ince then they have drifted from there [the vicinity of the South Sandwich Islands] westward … In the depth chart one can clearly see how the echeloned chains were torn off *seriatim* from the drifting blocks and then left behind.”

Despite the best efforts of Wegener and his supporters – notably Alexander Du Toit and Lester King in South Africa, and Arthur Holmes in Britain - continental drift was at first generally dismissed as implausible (Newman 1995; Oreskes 1999). In the prevailing view, the necessary intercontinental connections required by palaeobiogeography were provided by land bridges that had now foundered. An extensive review of these putative structures was given by Schuchert (1932) who reproduced as a starting point (1932, figure 1) Melchior Neumayr’s palaeogeographical map from 1887 which featured a vast ‘Brazil-Ethiopian Continent’ occupying the Jurassic South Atlantic as far south as the Falkland Islands. This putative landmass had been extended by Gregory (1922, 1929) to include South Georgia and its Mesozic fossils, but it was reduced in Schuchert’s (1932) Permian palaeogeography to a much more restricted ‘bridge’ linking Brazil and West Africa. Farther south, Schuchert proposed another land bridge running from Tierra del Fuego to Graham Land via South Georgia and the South Orkney Islands, but cutting obliquely across the Scotia Sea to avoid the actively volcanic South Sandwich Islands for which there was no evidence of a continental basement.

In his preview of the British National Antarctic Expedition, Gregory (1901) had assumed that there was no geological similarity between South Georgia and Tierra del Feugo. This notion was subsequently challenged by both Wegener (1929) and Holtedahl (1929), but the two men had very different regional perspectives. Wegener (1929, p. 94) cited the geological relationships as “a model for demonstrating drift theory”. In contrast, Holtedahl favoured predominantly vertical tectonic movements and was not convinced of the reality of continental drift, deciding (1929, p. 110) that “I can see nothing in the geological character of the whole area here discussed [the Scotia Arc] that speaks decidedly against the old theory of a connection through an *old folding range*. On the contrary, there are a number of important features in favour of it” – italics as in the original. So, whilst there might have been agreement that some sort of ‘Scotia Arc’ existed, there was no agreement as to its origins.

The majority view undoubtedly favoured Holtedahl, and was prominently articulated by Gregory (1929) in his Presidential Address to the Geological Society of London. Therein, the Falkland Islands, South Georgia, and the other islands of the Scotia Arc were regarded as vestiges of a foundered continent that had once occupied the South Atlantic region. But there was also an informed alternative view. Arthur Holmes had established an absolute time-scale based on the decay rates of radioactive elements in igneous rocks and realised that the thermal effects of radioactive decay had implications for the continental drift debate. In a remarkably prescient paper published in the *Transactions of the Geological Society of Glasgow*, Holmes (1929) described a mechanism for continental drift based on deep thermal convection currents and amongst the detailed examples cited, referred to the Scotia Arc as arising from the westward drift of South America and Antarctica (1929, p. 595): “The island arc here is probably a lag effect due to a strung-out belt of sial having been dragged against part of the Pacific floor left between the two continental blocks as they advanced.” This interpretation, similar in most respects to Wegener’s earlier proposal, was clearly illustrated by Holmes (1929, figure 7). There has been much speculation that Holmes’ choice of an ‘obscure’ journal in which to publish his ideas arose from an uncertainty as to their validity (e.g. Wood, 1985, p. 94). Be that as it may, there is some irony in the fact that publication was on Gregory’s ‘home turf’; he retired as Professor of Geology at the University of Glasgow at the end of September 1929.

Gregory’s opinion of the Scotia Arc and its geology had been much influenced by the work of Ferguson on South Georgia. In particular, the ultimately erroneous evidence for early Palaeozoic rocks there had encouraged interpretations of the island as forming a relic of a foundered ancient continent; Gregory’s (1915) palaeontology was certainly instrumental in fostering that view. Nevertheless, in his assessment of Ferguson’s South Georgia work, Gregory (1915, p. 822) clung to his earlier (1901) view of the Scotia Arc and felt that the evidence presented [by Ferguson] was insufficient to determine whether the island formed part of the “mountain loop that must once have connected Patagonia [South America] with Graham Land [Antarctic Peninsula]”, or whether that ‘loop’ passed west of the island leaving South Georgia as the vestige of a foundered Atlantic continent, Neumayr’s ‘Brazil-Ethiopian Continent’ or ‘Flabellite Land’ as it had been designated by Schwarz (1906) based on the distribution of a small Devonian brachiopod then known as *Leptocoelia flabellites* (Southern Hemisphere examples are now known as *Australocoelia palmata*). Tyrrell (1915), in an accompanying description of the petrography of Ferguson’s South Georgia specimens, stressed their similarity to rocks from the South Orkney Islands – as had Pirie (1913) in his unpublished Scotia report – but was equally non-commital with regard to the overall regional structure. However, after reviewing the subsequently collected specimen suites Tyrrell (1918) came down against Suess’s ‘great loop’, preferring that “South Georgia and the South Orkneys are remnants of an ancient continental land which once occupied the South Atlantic”. Pirie (1913, p 8) had also debated the various possible lines of a structural link between South America and the Antarctic Peninsula and found the Falkland Islands particularly problematical. One possibility, he concluded, was that “they are, along with South Georgia and the South Orkneys, fragments of an ancient “Flabellites land”.”

Gregory (1922) illustrated the ‘Brazilio-Ethiopian Continent’ spanning the South Atlantic, and such thinking carried through to his (1929) Presidential Address to the Geological Society of London, wherein he included South Georgia (but not the South Orkney Islands) within a Devonian ‘Flabellites Land’ and both South Georgia and the Falkland Islands within a late Palaeozoic ‘Gondwanaland’ that included the entire area of the South Atlantic Ocean. Clearly Gregory was not convinced by Du Toit’s (1927) reconstruction in which the South Atlantic was eliminated and geological links between Africa and South America were emphasised; these had first been detailed by the Argentine geologist Juan Keidal (1916). In his reconstruction Du Toit moved the Falkland Islands a considerable distance north to align their geology with the structural and stratigraphical trends seen in the two, now contiguous continents. Du Toit (1937) developed his continental drift interpretations and reconstruction of Gondwana in the seminal geological classic *Our Wandering Continents*. Therein, (1937, figure 7) the Scotia Arc is shown looping into the Palaeozoic ‘Samfrau Geosyncline’, a situation influenced by the presumption that Lower Palaeozoic rocks formed at least part of South Georgia. In the accompanying text (pp 195-196) Du Toit linked the origin of the Scotia Arc islands with that of the Falkland Islands, writing:

“Our interpretation views the near-by Falkland Islands as having drifted from some position off the south-western Cape [South Africa]. South Georgia and the South Orkneys could in similar fashion have been derived from the north-east and inferentially from the Samfrau geosyncline.”

It is worth noting that Du Toit's assessment of the Falkland Islands was soundly based. The geological association of the Falklands with South Africa had been established from palaeontological evidence in the late 19th and early 20th centuries, as described by Stone and Rushton (2012). Broader geological links had been researched by Halle (1911) and, particularly, by Baker (1924) who emphatically adopted a continental drift solution in principle, but did not propose any specific palaeogeography.

8 Research around the Scotia Arc after the Second World War

The outbreak of the Second World War in 1939 overshadowed any further interest in such long-term issues as continental drift, even though techniques developed for warfare were to be subsequently fundamental to the establishment of plate tectonics theory as the definitive culmination of the continental drift debate. How that happened has been the subject of numerous books, such as the well-known examples by Hallam (1973) and Wood (1985). Another outcome of wartime activity had been the establishment of British naval outposts in the South Shetland Islands and northern Graham Land (*Operation Tabarin*) which, at war's end, were transferred to the management of the newly-formed Falkland Islands Dependencies Survey (FIDS). At the new FIDS bases scientific research became the priority and several geologists who were involved there in Antarctic work also contributed subsequently to the interpretation of the Scotia Arc.

J.R.F. Joyce spent the 1946 austral winter at the Stonington FIDS base on the Antarctic Peninsula and then returned to work on his results at Imperial College, London. This led, in 1950, to a presentation at the annual meeting of the British Association for the Advancement of Science (BAAS), held that year in Birmingham. The BAAS meeting was a wide-ranging affair, but it included a one-day symposium to discuss "The Theory of Continental Drift"; six speakers covered aspects of biogeography and geology. In the published account of his presentation Joyce (1951) figured a reconstruction of the Gondwana section of Pangaea in which the islands of the Scotia Arc were strung out along that portion of the supercontinental margin formed by South Africa and the Antarctic. He stressed the South African associations of the Falkland Islands, and proposed linking the Cretaceous strata of South Georgia with supposedly similar-aged rocks in Mozambique. The present-day spatial arrangement of the islands forming the Scotia Arc was thus seen as a partly original feature, with their arcuate distribution being strongly accentuated as a consequence of continental drift during the break-up of Gondwana. Joyce's main problem was the relatively hostile mood of the BAAS meeting, with opposition to the concept of continental drift led by the eminent geophysicist Professor Harold Jeffreys. His contribution to the BAAS meeting (Jeffreys 1951) was a rather patronising and world-weary dismissal of the continental drift idea since any conceivable mechanism must, he claimed, conflict with the basic physical properties of solids and liquids that "[w]e have all learnt at school" (1951, p 79); he bemoaned the fact that "[t]his is the fourth time that I have taken part in a public discussion of this theory" (p 80), implying that the time had come to call a halt to speculation. Against this background Joyce (1951, p 87) ended defensively: "The suggestion is therefore made that *if Pangaea did in fact exist* then this new organisation of continental masses and island arcs *at the opening of the Palaeozoic era* is more in accord with the known data" – italics as in original.

In his reconstruction Joyce had moved the Falkland Islands towards the south-east coast of present-day South Africa. This may have influenced, or been influenced by, the work of a near-contemporary FIDS geologist, R.J. Adie. Adie spent three austral winters, 1947 to 1949, at the Hope Bay and Stonington FIDS bases; the third winter was unplanned and came about when ice conditions prevented relief of the Stonington base. Thereafter he spent time in the Falkland Islands during his journey north. He was a South African geologist who had graduated from the

University of Natal, from a geology department led by Professor Lester King. Alexander Du Toit had died in 1948, but the cause of continental drift had found a new champion in King so Adie would have been well-primed in its applications. Adie (1952) proposed an even more radical solution to the mismatched regional geology of the Falkland Islands than had been envisaged by Du Toit. In a remarkably prescient contribution, Adie (1952) used the alignment of structural and sedimentological trends to support his proposal that the Falklands had been rotated by 180° from an original position adjacent to the east coast of South Africa. This solution to the enigma of Falklands geology was completely neglected by the geological mainstream until it was 'rediscovered' in terms of microplate rotation (Mitchell and others 1986) late in the plate tectonic revolution. It is now widely (although not universally) accepted in principle.

During the 1950s, the geology of South Georgia became better known through Trendall's field-work and the subsequent publication of his two FIDS scientific reports (Trendall 1953, 1959). The 1953 report included a speculative correlation of the wacke sandstone successions with superficially similar successions in the Antarctic Peninsula and the South Orkney Islands. At that time, regional stratigraphic correlation was much influenced by the supposed graptolite from the South Orkney Islands (Pirie 1905) and, as already noted, it was thought possible that the unfossiliferous Sandebugten Formation of South Georgia might correlate with the apparently Lower Palaeozoic rocks of the South Orkneys.

Though Trendall's second report was not published until 1959, the manuscript is recorded as having been received in December 1954. Adie had become FIDS Chief Geologist in 1956 (he later became Deputy Director), and would have been involved in its scientific editing. The veracity of the South Orkneys 'graptolite' was probably in doubt for some time prior to its unmasking by Strachan in Adie (1957b) and Trendall's 1959 report (completed in 1954) presented a revised, entirely Mesozoic stratigraphy for South Georgia. Therein, despite remaining uncertainties, the volcaniclastic Cumberland Bay Formation, and the quartzose Sandebugten Formation were proposed as possible facies variations within a single succession. Barker (1970) has suggested that Trendall (1959) envisaged the volcaniclastic sandstones as having been derived from a precursor South Sandwich arc, but this is an over-interpretation of Trendall's model in which the South Sandwich arc was more probably presented as an indicative illustration rather than a palaeogeographical specific.

Whilst Trendall worked in South Georgia, FIDS geologists were exploring the South Orkney and South Shetland archipelagos further south, and two of them, D. H. Matthews and D. D. Hawkes, attempted to fit their observations into a wider geological interpretation of the Scotia Arc.

Matthews spent the 1956 austral winter at the Signy Island base in the South Orkney Islands. In 1959, and by then at the University of Cambridge, he published an assessment of the Scotia Arc based on bathymetry and the sparse marine geophysical data that was then available. That paper (Matthews 1959) presents two alternatives: either the islands of the Scotia Arc represented fragments of a disrupted continental mass, or they must be the highest parts of a mostly submerged continental block underlying most of the Scotia Sea. Citing Adie (1952) he noted that continental drift was "an attractive hypothesis" to apply to the geological situation of the Falkland Islands, but found the Scotia Arc altogether less tractable. If the islands were disrupted fragments, and derived as envisaged by Barth and Holmsen (1939) then breaks would be expected in the submarine ridges linking the islands; Matthews saw little evidence for such breaks. Conversely, if continental crust underlay the Scotia Sea, it would be associated with a large gravity anomaly; again, supporting evidence was not forthcoming. One complicating factor stressed by Matthews, reiterating a point raised by several previous workers, was the presence of thick clastic successions, in South Georgia and the South Orkney Islands, which required to have been deposited in proximity to a continental provenance. In a conclusion to his 1959 paper that he admitted was unsatisfactory, Matthews was forced to speculate that the Scotia Sea and arc represented some kind of transition between continental and oceanic crust. However, from this beginning, Matthews' marine geology interpretations blossomed and only a few years later he contributed to one of the seminal papers of the plate tectonic revolution (Vine and Matthews 1963) that explained the pattern of linear magnetic anomalies distributed symmetrically across oceanic spreading ridges.

Hawkes worked on Deception Island, South Shetlands, during the 1957-58 austral summer, and reviewed extensive specimen collections from King George Island. He also made an interpretation of the structure of the Scotia Arc that returned to the concept of the disruption, by continental drift, of an original isthmus connecting Patagonia and Graham Land (Hawkes 1962). However, whereas Holmes (1929) and Barth and Holmsen (1939) had envisaged westward drift, with the isthmus breaking up to leave the islands of the Scotia Arc as abandoned relicts, Hawkes saw the islands as being driven eastwards. Starting with a linear continental connection between Patagonia and Graham Land, Hawkes proposed that an advance of 'Pacific' crust forced the break-up and the progressive eastward drift of the Scotia Arc islands. A succession of island arcs migrated eastward as part of the development of the Scotia Sea which, like Matthews, Hawkes thought of as in some way transitional between oceanic and continental states. The pre-drift, 'linear' reconstruction by Hawkes presaged the subsequently influential, rectilinear models of the early plate-tectonic era, such as that published by Dalziel and Elliot (1971). Hawkes' exposition of the Scotia Arc's origins had been guaranteed a wide audience when it was reproduced by Holmes (1965) as Figure 873 in the second edition of his classic text book *Principles of Physical Geology*.

The paucity of geophysical information from the Scotia Sea meant that both Matthews' and Hawkes' proposals were poorly constrained. This gap in knowledge began to be filled in the early 1960s and the complexities involved were made apparent by Griffiths and others (1964). The authors attempted an integration of gravity, magnetic and seismic data but, spread as it was over such a wide area, the interpretation remained ambiguous and the Scotia Sea crust still seemed possibly transitional. Griffiths and others (1964, p 42) concluded:

"The presence of a region in the Scotia Sea with a crust which may be of mixed type raises the problem … as to whether this is relic or potential continental crust. This is a problem that at the present time has not been resolved … although the possible presence of a crust of this type lends some support to the geological speculations of both Hawkes and Matthews".

The report by Griffiths and others is recorded as having been received for publication in November 1963. Meanwhile, Matthews had been busy elsewhere, and two months earlier, in September, the collaborative Vine and Matthews (1963) paper had provided a radical new insight into the significance of marine magnetic data. Through the rest of the 1960s the plate tectonic revolution gained momentum and more extensive survey data accumulated from the Scotia Sea and Arc. By the end of the decade, Barker (1970) was able to present an interpretation of the region involving sea-floor spreading in the Drake Passage and West Scotia Sea over at least the last 20 million years, and in the back-arc zone of the South Sandwich Islands volcanic arc for at least the last eight million years, together creating a separate 'Scotia' oceanic plate. Barker and Griffiths (1972) then established from further marine geophysical surveys that the

Scotia ridges, both North and South, were indeed defined by continental blocks. They proposed the post-Cretaceous fragmentation of a continental area linking Patagonia and the Antarctic Peninsula and illustrated a tentative reconstruction that brought South Georgia to the south of the Burdwood Bank.

Stone (2015) has described how one consequence of the plate tectonic revolution was the independent devising and description of mechanisms for the Scotia Arc's origins that had previously been formulated in terms of continental drift. Large-scale, global reviews by several of the leading partisans touched on the South Atlantic, usually coupling an interpretation of the Scotia Arc with the Caribbean/Antillean arc much farther to the north, and brought a new-found scientific respectability to ideas long-neglected as unfeasible but now independently rediscovered. For example, Hamilton (1966, p. 178) summed-up his assessment in the abstract to his paper as follows: "If the continents [North and South America and Antarctica] are regarded as having drifted westward into the Pacific Ocean basin, then the two arcs can be pictured as formed by the disruption of the narrow bridges, which lagged behind the continents." This process is essentially the circumstance described almost 30 years earlier by Barth and Holmsen (1939), which in turn followed Wegener (1929, pp 94-95) and Holmes (1929, pp 594-595) – all three contributions were apparently overlooked by Hamilton.

As in the earlier debate, the proposal that the Scotia Arc originated by means of westward continental drift was soon followed by a proposal invoking eastward drift. Moores (1970) developed a model to explain Mesozoic orogenies at the western margins of North and South America. He envisaged a Pacific island arc system colliding with the continental margins, resulting in orogeny, but that "[w]here no continent was present (as between North and South America and south of South America), the remnants of this island arc system simply continued migration, forming the Caribbean and Scotian (*sic*) Seas" (Moores 1970, caption to figure 6, p. 842). Unsaid but implied would be the detachment by the eastward-migrating 'Scotian Sea arc' of continental blocks from the South American and Antarctic Peninsula continental terminations, which were then strung-out to form the North and South Scotia Ridges. Moores' model in respect of the Scotia Arc (a very minor component of the whole paper it must be stressed) is not that far removed from the situation envisaged by Hawkes (1962) wherein a thin, rectilinear continental connection between South America and the Antarctic Peninsula was disrupted by "an eastward advance of the Pacific crust" (Hawkes 1962, abstract); Moores did not cite Hawkes' paper which had also envisaged island arcs migrating eastward.

9 Towards consensus on South Georgia and the Scotia Arc

The uncertainties imposed on the early attempts at 'pre-drift' reconstructions of the Scotia Arc are well exemplified by the fact that a geological description of *in situ* specimens from Shag Rocks (Figure 1) was not published until 1982, although the greenschist-facies metamorphic rocks were collected in 1974 (Tanner 1982b). Prior to that, the only geological information available for the Shag Rocks continental block derived from similar schistose rocks dredged from the sea floor in 1930 and described by Tyrrell (1945). Progress elsewhere saw confirmation of the correlations between South Georgia and parts of Tierra del Fuego (Katz and Watters 1966; Frakes 1966; Skidmore 1972, Winn 1978) that had been previously suggested by Wilckens (1933) and Kranck (1934), yet the details of the regional picture remained unclear.

The Barker and Griffiths (1972) pre-drift reconstruction had been based largely on geophysical evidence but was disputed, in advance of its publication and on geological grounds, by Dalziel and Elliot (1971) who referred to it as being 'in press'. No submission date is recorded in the published Barker and Griffiths paper but the authors, and many others including Dalziel and Elliot, had contributed Scotia Arc papers trailing their positions at a 1970 symposium on Antarctic Geology and Geophysics held in Oslo, Norway (Adie 1972). Dalziel and Elliot's objection lay primarily in the position of the South Georgia continental block. Barker and Griffiths had placed it at the easternmost edge of their re-assembly forming the 'Atlantic' margin. In contrast, and arguing from the evidence of geological comparisons and correlations, Dalziel and Elliot modelled the original South America – Antarctic Peninsula connection as narrow and rectilinear rather than the broader zone extending, cusp-shaped, into the proto-Atlantic, as favoured by Barker and Griffiths. Furthermore, Dalziel and Elliot placed the South Georgia block on the Pacific side of that originally rectilinear continental strip. In their model, the rectilinear strip was intact until the end of the Mesozoic, and was disrupted by oroclinal bending towards the east early in the Cenozoic; only at that stage was South Georgia brought to a position to the south of the Burdwood Bank. Subsequent eastward drift of the Scotia Arc continental blocks was accompanied by a convergence of South America and the Antarctic Peninsula to accentuate the arc physiography.

Bringing together the marine geophysical evidence and new interpretations from South America, Dalziel and others (1975) described the geology of South Georgia in terms of an Early Cretaceous marginal basin that formed "between a calc-alkaline volcanic arc built on a sliver of old South American continental crust and the main part of the South American continent from which the sliver moved away" (1975, abstract). The continental foundation to the arc is now represented by the Drygalski Fjord Complex, an arc-proximal shelf facies by the Annenkov Island Formation, the oceanic crust of the marginal basin by the Larsen Harbour Complex, and the turbiditic basin-fill sediment by the Cumberland Bay and Sandebugten formations (Figure 2) (Curtis and Riley 2011 and references therein). Asymmetrical deformation accompanied closure of the marginal basin in the middle to Late Cretaceous, as the volcanic arc complex moved back to rejoin the continental margin (Dalziel and others 1975).

The collision between the volcanic arc complex and the continental margin initiated its tectonic break-up and the subsequent development of the Scotia Arc, as has been recently reviewed and illustrated in detail by Dalziel and others (2013). These authors note that the origins of the Scotia Arc can be ultimately traced back to the Jurassic fragmentation of Gondwana. Thereafter, they conclude (2013, p 786):

“The North and South Scotia Ridges resulted from the eastward motion of fragments of the Pacific margin cordillera of both South America and Antarctica that was initiated in the early Cenozoic as a result of left-lateral transtensional relative movement between the two continents. This resulted in seafloor spreading that generated the northwestern and southeastern portions of today’s Scotia plate.”

The currently accepted configuration of the region is summarised in Figure 1. However, the route by which that configuration was achieved is still a matter of some controversy. In the view summarised by Dalziel and others (2013) South Georgia originated at the Pacific margin of Gondwana and thence drifted a considerable distance eastward relative to South America following disruption of an original continental link between that continent and the Antarctic Peninsula. There are alternative views. For example, concerned by the length of eastward drift required, Eagles (2010) has proposed a reconstruction wherein the Antarctic Peninsula is removed to the west of South America, and South Georgia becomes part of a Gondwana margin that swings eastward towards South Africa. Debate at this level of geotectonics seems likely to continue.

10 Postscript – Tourism in the 21st century

Few of those involved in the geological exploration of South Georgia would have anticipated that by the beginning of the 21st century the island would host a burgeoning tourist industry. Annual visitor numbers for the 2014-2015 austral summer exceeded 8000, with visits by cruise ships on 65 occasions and by yachts on 21 occasions. The need for informative scientific literature aimed at a lay audience was met by a comprehensive visitors' guide (Poncet and Crosbie 2005) to which P. Stone contributed a section on geology. In advance of the guidebook's publication, Stone had also arranged publication of three geologically-orientated 'popular science' brochures, two of which described aspects of South Georgia's bedrock geology (Stone and Smellie 2002; Stone and Tanner 2004).

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

ADIE, R J. 1952. The position of the Falkland Islands in a reconstruction of Gondwanaland. *Geological Magazine*, **89**, 401-410.

ADIE, R J. 1957a. Geological investigations in the Falkland Islands Dependencies before 1940. *Polar Record*, **8**, 502-513.

ADIE, R J. 1957b. The petrology of Graham Land: III. Metamorphic rocks of the Trinity Peninsula Series. *Falkland Islands Dependencies Survey Scientific Report*, **20**, 26 pp.

ADIE, R J. 1964. Geological History. In: Priestly, R.E., Adie, R.J. and Robin, G. de Q. (eds) *Antarctic Research*. Butterworth, London. 118-162.

ADIE, R J. (ed.) 1972. *Antarctic Geology and Geophysics*. Section 1: The Scotia Arc and Antarctic Peninsula. Universitetsforlaget, Oslo. 1-160.

AITKENHEAD, N, and NELSON, P.H.H. 1962. The geology of the area between Cumberland West Bay and Cape George, South Georgia. *British Antarctic Survey Preliminary Geological Report*, **15**, 13pp. Unpublished.

ALABASTER, T, and STOREY, B C. 1990. Modified Gulf of California model for South Georgia, north Scotia Ridge, and implications for the Rocas Verdes back-arc basin, southern Andes. *Geology*, **18**, 497-500.

ANDERSSON, J G. 1907. On the principal results of the Swedish Antarctic Expedition. *Compte Rendu 10ème Congrès géologique international, Mexico 1906*, **10**. 723-733.

ARÇTOWSKI, H. 1895. Observations sur l'intérêt que présente l'exploration géologique des Terres Australes. *Bulletin Société géologique de France*. 3[e] série, **23**, 589-591.

BAKER, H A. 1924. *Final Report on Geological Investigations in the Falkland Islands, 1920-1922*. Government Printer, Stanley. 38 pp, map, cross-section and 18 figures.

BARKER, P F. 1970. Plate Tectonics of the Scotia Sea Region. *Nature, London*, **228**, 1293-1296.

BARKER, P F, and GRIFFITHS, D H. 1972. The evolution of the Scotia Ridge and Scotia Sea. *Philosophical Transactions of the Royal Society of London*, **271**, 151-183.

BARROW, J. 1831. Introductory note to an Account of the Island of Deception, one of the New Shetland Isles. *Journal of the Royal Geographical Society, London*, **1**, 62.

BARTH, T F W, and HOLMSEN, P. 1939. Rocks from the Antarctandes and the Southern Antilles. *Scientific Results of the Norwegian Antarctic Expedition 1927–1928*, **18**. I Kommisjon Hos Jacob Dybwad, Oslo. 64 pp + 4 plates.

BELL, C M, MAIR, B F, and STOREY, B C. 1977.The geology of part of an island arc–marginal basin system in southern South Georgia. *British Antarctic Survey Bulletin*, **46**, 109-127.

BELLINGSHAUSEN, T. von. 1831. English translation: Debenham, F. (ed.) 1945. *The Voyage of Captain Bellingshausen to the Antarctic Seas, 1819–1821*. The Hakluyt Society, London. **1**, xxx and 1-259; **2**, viii and 260-474.

BRUCE, W S. 1905. Bathymetric Survey of the South Atlantic Ocean and Weddell Sea. *Scottish Geographical Magazine*, **21**, 402-412 + 2 maps.

BURLEY, M K. 1966. Combined Services Expedition to South Georgia 1964-5. *Explorers Journal*, **44**, 106-118.

CARSE, V D. 1959. The Survey of South Georgia, 1951–57. *Geographical Journal*, **125**, 20-37.

CARTER, A, CURTIS, M, and SCHWANETHAL, J. 2014. Cenozoic tectonic history of the South Georgia microcontient and potential as a barrier to Pacific-Atlantic through flow. *Geology*, **42**, 295-298. doi: 10.1130/G35091.1.

CLAYTON, R A S. 1982a. The geology of north-western South Georgia: II. Sedimentology. *British Antarctic Survey Bulletin*, **51**, 55-78.

CLAYTON, R A S. 1982b. The geology of north-western South Georgia: III. Petrology. *British Antarctic Survey Bulletin*, **51**, 79-88.

CLAYTON, R A S. 1982c. A preliminary investigation of the geochemistry of greywackes from South Georgia. *British Antarctic Survey Bulletin*, **51**, 89-109.

CLAYTON, R A S. 1983. The geology of north-western South Georgia: IV. Structural Geology. *British Antarctic Survey Bulletin*, **52**, 187-204.

CORDINI, I R. 1955. Contribución al conocimiento del sector Antártico Argentine. *Publicaciónes del Instituto Antártico Argentino*, **1**. 277 pp.

CRAW, D, and TURNBULL, I M. 1986. Geological observations in the Ross Glacier area, South Georgia. *British Antarctic Survey Bulletin*, **71**, 1-10.

CURTIS, M L. 2007. Main Andean sinistral shear along the Cooper Bay Dislocation Zone, South Georgia? In: Cooper, A.K., Raymond, C.R. and others (eds). Antarctica: A Keystone in a Changing World – Online Proceedings of the10th ISAES. *USGS Open-File Report* **2007-1047**, Short Research Paper 034, 4 pp.

CURTIS, M L, and RILEY, T R. 2011. Geological Map of South Georgia (1:250 000 scale). BAS GEOMAP 2 Series, Sheet 4, British Antarctic Survey, Cambridge, UK.

CURTIS, M L, FLOWEDEW, M J, RILEY, T R, WHITEHOUSE, M J, and DALY, J S. 2010. Andean sinistral transpression and kinematic partitioning in South Georgia. *Journal of Structural Geology*, **32**, 464-477.

CURTIS, M L, RILEY, T R, FLOWEDEW, M J, and TATE, A. 2011. The application and benefits of digital geological mapping in Antarctica. *Antarctic Science*, **23**, 387-388.

DALZIEL, I W D. 1979. The mythical graptolites of the South Orkney Islands. *The Edinburgh Geologist*, **6**, 2-9.

DALZIEL, I W D, and ELLIOT, D H. 1971. Evolution of the Scotia Arc. *Nature, London*, **233**, 246-252.

DALZIEL, I W D, DOTT, R H, WINN, R D, and BRUHN, R L. 1975. Tectonic Relations of South Georgia Island to the Southernmost Andes. *Geological Society of America Bulletin*, **86**, 1034-1040.

DALZIEL, I W D., ELLIOT, D H, JONES, D L, THOMSON, J W, THOMSON, M R A, WELLS, N A, and ZINSMEISTER, W J. 1981. The geological significance of some Triassic microfossils from the South Orkney Islands, Scotia Ridge. *Geological Magazine*, **118**, 15-25.

DALZIEL, I W D, LAWVER, L A, NORTON, I O, and GAHAGAN, L M. 2013. The Scotia Arc: Genesis, Evolution, Global Significance. *Annual Review of Earth and Planetary Science*, **41**, 767-793.

DOTT, R H. 1974. Paleocurrent analysis of severely deformed flysch-type strata – A case study from South Georgia island. *Journal of Sedimentary Petrology*, **44**, 1166-1173.

DOUGLAS, G V. 1930. Topography and geology of South Georgia. *British Museum (Natural History) Report on the Geological Collections made during the voyage of the "*Quest*" on the Shackleton-Rowett Expedition to the South Atlantic and Weddell Sea in 1921-22*. Trustees of the British Museum, London. 4-24.

DOYLE, P. 1985. Comments on belemnite fragments from 'Cumberland Bay type' sediments, south-eastern South Georgia. *British Antarctic Survey Bulletin*, **69**, 79-80.

DUDENEY, J R, and WALTON, D W H. 2012. From *Scotia* to 'Operation Tabarin': developing British policy for Antarctica. *The Polar Record*, **48**, 342–360.

DU TOIT, A L. 1927. *A geological comparison of South America and South Africa* (with a palaeontological contribution by F.R. Cowper Reed). Carnegie Institution of Washington, Washington. 158 pp, 16 plates and folded map insert.

DU TOIT, A L. 1937. *Our Wandering Continents*. Oliver and Boyd, Edinburgh and London, 366 pp.

EAGLES, G. 2010. South Georgia and Gondwana's Pacific Margin: Lost in translation? *Journal of South American Earth Sciences*, **30**, 65-70.

FAGAN, P F. 1966. Surveys in South Georgia. *Geographical Journal*,**132**, 61-64.

FERGUSON, D. 1915. Geological observations in South Georgia. *Transactions of the Royal Society of Edinburgh*, **50**, 797-814, 10 plates.

FERGUSON, D, TYRRELL, G W. and GREGORY, J W. 1914. The geology of South Georgia. *Geological Magazine*, **1**, Decade 6, 53-64.

FRAKES, L A. 1966. Geologic Setting of South Georgia Island. *Geological Society of America Bulletin*, **77**, 1463-1468.

GRADSTEIN, F M., OGG, J G., SCHMITZ, M D. and OGG, G M. (eds). 2012. *The Geologic Time Scale*. Elsevier, Oxford, Amsterdam and Waltham MA.

GREGORY, J W. 1901. The work of the National Antarctic Expedition. *Nature*, **63**, 609-612.

GREGORY, J W. 1915. The Geological Relations and Some Fossils of South Georgia. *Transactions of the Royal Society of Edinburgh*, **50**, 817-822 + 2 plates.

GREGORY, J W. 1922. Supplementary Note on the Geology of Benguella in relation to its Cephalopods and the History of the South Atlantic. *Transactions of the Royal Society of Edinburgh*, **53**, 161-163.

GREGORY, J W. 1929. The Geological History of the Atlantic Ocean. *Quarterly Journal of the Geological Society, London*, **85**, Proceedings lxviii-cxxii.

GRIFFITHS, D H, RIDDIHOUGH, R P, CAMERON, H A D, and KENNETT, P. 1964. Geophysical investigations of the Scotia Arc. *British Antarctic Survey Scientific Report*, No. 46, 43 pp.

GRIKUROV, G E., KRYLOV, A.Ya, and SILIN, Yu.I. 1967. Absolute age of some rocks from the Scotia Arc and Alexander I Land (western Antarctica). Originally published in Russian. English translation: *Proceedings of the Academy of Sciences of the USSR., Geological Sciences Section*, **172**, 19-22.

HALLAM, A. 1973. *A Revolution in the Earth Sciences*. Oxford University Press, Oxford. 127 pp.

HALLE, T G. 1911. On the geological structure and history of the Falkland Islands. *Bulletin of the Geological Institution of the University of Uppsala*, **11**, 115-229.

HAMILTON, W. 1966. Formation of the Scotia and Caribbean arcs. *Geological Survey of Canada Paper*, **66-15**, 178-185.

HATTERSLEY-SMITH, G. 1980. The History of Place-names in the Falkland Islands Dependencies (South Georgia and the South Sandwich Islands). *British Antarctic Survey Scientific Reports*, **101**, 112 pp.

HAWKES, D D. 1962. The Structure of the Scotia Arc. *Geological Magazine*, **99**, 85-91.

HEADLAND, R. 1984. *The Island of South Georgia*. Cambridge University Press, Cambridge. 293 pp.

HEIM, F. 1912. Geologische Beobachtungen über Süd-Georgien. *Zeitschrift der Gesellschaft für Erdkunde zu Berlin*, **6**, 451-456.

HERDMAN, H F P. 1932. Report on soundings taken during the Discovery Investigations, 1926–1932. *Discovery Reports*, **6**, 205-236. Cambridge.

HOLMES, A. 1929. Radioactivity and Earth Movements. *Transactions of the Geological Society of Glasgow*, **18**, 559-606.

HOLMES, A. 1965. *Principles of Physical Geology* (2nd edition). Nelson, London and Edinburgh. 1288 pp.

HOLTEDAHL, O. 1929. On the Geology and Physiography of some Antarctic and Sub-Antarctic Islands. *Scientific Results of the Norwegian Antarctic Expedition 1927–1928*, **3**. I Kommisjon Hos Jacob Dybwad, Oslo. 172 pp + 52 plates.

JEFFERSON, T H. and MACDONALD, D I M. 1981. Fossil wood from South Georgia. *British Antarctic Survey Bulletin*, **54**, 57-64.

JEFFREYS, H. 1951. Mechanical Aspects of Continental Drift and Alternative Theories. *The Advancement of Science*, **8**, 79-80.

JOYCE, J R F. 1951. The Relation of the Scotia Arc to Pangaea. *The Advancement of Science*, **8**, 82-88.

KATZ, H R, and WATTERS, W A. 1966. Geological investigation of the Yahgan Formation (Upper Mesozoic) and associated igneous rocks of Navarino Island, Southern Chile. *New Zealand Journal of Geology and Geophysics*, **9**, 323-359.

KEIDEL, J. 1916. La Geología de las Sierras de la Provincia de Buenos Aires y sus Relaciones con las Montañas de Sud Africa y los Andes. *Annales del Ministerio de Agricultura de la Nación, Sección Geolgía, Mineralogía y Minería*, **11** (3), 5-78.

KING, L C, and DOWNARD, T W. 1964. Importance of Antarctica in the hypothesis of continental drift. *In*: Adie, R. J. (ed.) *Antarctic Geology*. North Holland Publishing Co., Amsterdam. 727-735.

KLUTSCHAK, H W. 1881. Ein Besuch auf Süd Georgien. English translation by Boumphrey, R.S. 1967. A Visit to South Georgia. *British Antarctic Survey Bulletin*, **12**, 85-92.

KOHL-LARSEN, L. 1930. *An den Toren der Antarktis*. English translation by Barr, W. 2003. *South Georgia: Gateway to Antarctica*. Bluntisham Books, Huntingdon. 294 pp.

KRANCK, E H. 1934. The South Antillean Ridge. *Bulletin de la Commission Géologique de Finlande*, **104**, 99-103.

LEAKE, B E. 2011. *The Life and Work of Professor J. W. Gregory FRS (1864-1932): Geologist, Writer and Explorer*. Geological Society, London, Memoirs, **34**, 234 pp.

LUXTON, D. 2014. Operation Tabarin. *Falkland Islands Journal*, **10** (3), 97-122.

MACDONALD, D I M. 1982. Palaeontology and ichnology of the Cumberland Bay Formation, South Georgia. *British Antarctic Survey Bulletin*, **57**, 1-14.

MACDONALD, D I M. and TANNER, P W G. 1983. Sediment dispersal patterns in part of a deformed Mesozoic back-arc basin on South Georgia, South Atlantic. *Journal of Sedimentary Petrology*, **53**, 83-104.

MACDONALD, D I M., STOREY, B C, and THOMSON, J W. 1987. *South Georgia*. BAS GEOMAP Series, Sheet 1, 1:250 000, Geological map and supplementary text, 63 pp. Cambridge, British Antarctic Survey.

MAIR, B F. 1981. Geological observations in the Moraine Fjord area, South Georgia. *British Antarctic Survey Bulletin*, **53**, 11-19.

MAIR, B F. 1983. The Larsen Harbour Formation and associated intrusive rocks of southern South Georgia. *British Antarctic Survey Bulletin*, **52**, 87-107.

MAIR, B F. 1987. The Geology of South Georgia: VI. Larsen Harbour Formation. *British Antarctic Survey Scientific Reports*, **111**, 60 pp.

MATTHEWS, D H. 1959. Aspects of the Geology of the Scotia Arc. *Geological Magazine*, **96**, 425-441.

MITCHELL, C, TAYLOR, G K, COX, K G. and SHAW, J. 1986. Are the Falkland Islands a rotated microplate? *Nature,* **319**, 131-134.

MOORES, E. 1970. Ultramafics and Orogeny, with Models of the US Cordillera and the Tethys. *Nature, London*, **228**, 837-842.

MORTIMORE, R N. 1979. Distal and proximal turbidites at Nilse Hullet, western South Georgia. *British Antarctic Survey Bulletin*, 47, 117-128.

MUKASA, S B, and DALZIEL, I W D. 1996. Southernmost Andes and South Georgia Island, North Scotia Ridge: Zircon U-Pb and muscovite ^{40}Ar/^{39}Ar age constraints on tectonic evolution of Southwestern Gondwanaland. *Journal of South American Earth Sciences*, **9**, 349-365.

MUKASA, S B, DALZIEL, I W D, and BRUECKNER, H K. 1988. Zircon U-Pb constraints on the kinematic evolution of the northern Scotia Arc. *Geological Society of America Abstracts with Programs*, **20**, A12.

MUKASA, S B, DALZIEL, I W D, and KUNK, M. 1989. ^{40}Ar/^{39}Ar and U-Pb age constraints on kinematic evolution of the northern Scotia Arc. *28th International Geological Congress, Abstracts with Programs*, **2**, 476.

NEWMAN, R P. 1995. American Intransigence: The Rejection of Continental Drift in the Great Debates of the 1920s. *Earth Sciences History*, **14**, 62-83.

NORDENSKJÖLD, O, and ANDERSSON, J G. 1905. *Antarctica or Two years amongst the ice of the South Pole*. Hurst and Blackett, London. 608 pp.

ORESKES, N. 1999. *The Rejection of Continental Drift*. Oxford University Press, New York and Oxford, xi + 420 pp.

PETTIGREW, T H. 1981. The geology of Annenkov Island. *British Antarctic Survey Bulletin*, **53**, 213-254.

PETTIGREW, T H, and WILLEY, L E. 1975. Belemnite fragments from Annenkov Island. *British Antarctic Survey Bulletin*, **40**, 33-36.

PIRIE, J H H. 1905. On the Graptolite-bearing Rocks of the South Orkneys. *Proceedings of the Royal Society of Edinburgh*, **25**, 463-470.

PIRIE, J H H. 1913. Geology of the South Orkneys. Galley proof for part of the unpublished *Scottish National Antarctic Expedition Scientific Report*, **8**, 11 pp. Copy held by the British Antarctic Survey, Cambridge.

PONCET, S, and CROSBIE, K. 2005. *A visitor's guide to South Georgia*. WildGuides. 179 pp.

SCHUCHERT, C. 1932. Gondwana Land Bridges. *Bulletin of the Geological Society of America*, **43**, 875-916.

SCHWARZ, E H L. 1906. The former land connection between Africa and South America. *Journal of Geology*, **14**, 81-90.

SKIDMORE, M J. 1972. The Geology of South Georgia: III. Prince Olav Harbour and Stromness Bay areas. *British Antarctic Survey Scientific Reports*, No. 73, 50 pp + 6 plates.

STONE, P. 1980. The Geology of South Georgia: IV. Barff Peninsula and Royal Bay areas. *British Antarctic Survey Scientific Reports*, No. 96, 45 pp + 8 plates.

STONE, P. 1982. Geological observations in the Cooper Bay – Wirik Bay area, South Georgia. *British Antarctic Survey Bulletin*, **51**, 43-53.

STONE, P. 2015. Geological exploration of South Atlantic islands and its contributions to the continental drift debate of the early 20th century. *Proceedings of the Geologists' Association*, **126**, 266-281.

STONE, P, and FAITHFULL, J. 2013. The mineral prospecting expeditions to the South Atlantic islands and Antarctic Peninsula region made by the Scottish geologist David Ferguson, 1912–1914. *Scottish Journal of Geology*, **49**, 59-77.

STONE, P, and RUSHTON, A W A. 2012. The pedigree and influence of fossil collections from the Falkland Islands: From Charles Darwin to continental drift. *Proceedings of the Geologists' Association*, **123**, 520-532.

STONE, P, and SMELLIE, J L. 2002. *South Georgia and the South Sandwich Islands. Rocky enigmas in the South Atlantic explained*. British Geological Survey and British Antarctic Survey for the Government of South Georgia and the South Sandwich Islands.

STONE, P, and TANNER, P W G. 2004. *South Georgia. The rocks and fossils*. British Geological Survey and British Antarctic Survey for the Government of South Georgia and the South Sandwich Islands.

STONE, P, and WILLEY, L E. 1973. Belemnite fragments from the Cumberland Bay type sediments of South Georgia. *British Antarctic Survey Bulletin*, **36**, 129-131.

STOREY, B C. 1983a. The Geology of South Georgia: V. Drygalski Fjord Complex. *British Antarctic Survey Scientific Reports*, No. 107, 88 pp.

STOREY, B C. 1983b. The geology of the Ducloz Head area, South Georgia. *British Antarctic Survey Bulletin*, **52**, 33-46.

STOREY, B C, and MACDONALD, D I M. 1984. Processes of formation and filling of a Mesozoic back-arc basin on the island of South Georgia. In: Kokelaar, B.P. and Howells, M.F. (eds) *Marginal Basin Geology*. Geological Society of London, Special Publication **16**, 207-218.

STOREY, B C, and MAIR, B F. 1982. The composite floor of the Cretaceous back-arc basin of South Georgia. *Journal of the Geological Society, London*, **139**, 729-738.

STOREY, B C, and TANNER, P W G. 1982. Geochemistry of a Mesozoic island-arc assemblage and ocean-floor basalts from South Georgia. *British Antarctic Survey Bulletin*, **56**, 7-24.

STOREY, B C, MAIR, B F, and BELL, C M. 1977. The occurrence of Mesozoic oceanic floor and ancient continental crust on South Georgia. *Geological Magazine*, **114**, 203-208.

SUAREZ, M, and PETTIGREW, T H. 1976. An Upper Mesozoic island-arc–back-arc system in the southern Andes and South Georgia. *Geological Magazine*, **113**, 305-328.

SUESS, E. 1909. *The Face of the Earth*. (English translation of *Das Antlitz der Erde* by H. B. C. Sollas), **4**. The Clarendon Press, Oxford. 673 pp.

TANNER, P W G. 1982a. Geologic Evolution of South Georgia. In: Craddock, C. (ed.) *Antarctic Geoscience*. The University of Wisconsin Press, Madison. 167-176.

TANNER, P W G. 1982b. Geology of Shag Rocks, part of a continental block on the North Scotia Ridge, and possible regional correlations. *British Antarctic Survey Bulletin*, **51**, 125-136.

TANNER, P W G, and MACDONALD, D I M. 1982. Models for the deposition and simple shear deformation of a turbidite sequence in the South Georgia portion of the southern Andes back-arc basin. *Journal of the Geological Society, London*, **139**, 739-754.

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.

TANNER, P W G, STOREY, B C, and MACDONALD, D I M. 1981. Geology of an Upper Jurrasic–Lower Cretaceous island-arc assemblage in Hauge Reef, the Pickersgill Islands and adjoining areas of South Georgia. *British Antarctic Survey Bulletin*, **53**, 77-117.

THOMSON, M R A. 1977. An annotated bibliography of the paleontology of Lesser Antarctica and the Scotia Ridge. *New Zealand Journal of Geology and Geophysics*, **20**, 865-904.

THOMSON, M R A., TANNER, P W G, and REX, D C. 1982. Fossil and Radiometric Evidence for Ages of Deposition and Metamorphism of Sedimentary Sequences on South Georgia. In: Craddock, C. (ed.) *Antarctic Geoscience*. The University of Wisconsin Press, Madison. 177-184.

THÜRACH, H. 1890. Geognostische Bewchriebung der Insel Sud-Georgien. Die *Internationale Polarforschung 1882-1883. Die deutschen Expeditionen und ihre Ergebnisse*. **2**: *Beschreibende Naturwissenschaften in einzelnen Abhandlung*. Hamburg. 107-164.

TRENDALL, A F. 1953. The Geology of South Georgia: I. *Falkland Islands Dependencies Survey Scientific Reports*, No. 7, 26 pp, 2 plates, fold-out map.

TRENDALL, A F. 1959. The Geology of South Georgia: II. *Falkland Islands Dependencies Survey Scientific Reports*, No. 19, 47 pp, 5 plates, fold-out map.

TRENDALL, A F. 2011. *Putting South Georgia on the map. Duncan Carse's South Georgia Surveys of 1951-56*. Published by the author, Albany, Western Australia. 216 pp.

TURNBULL, I M, and Craw, D. 1988. Relationships between the Cumberland Bay and Sandebugten Formations, South Georgia, and some tectonic implications. *Journal of the Geological Society, London*, **145**, 591-602.

TYRRELL, G W. 1915. The Petrology of South Georgia. *Transactions of the Royal Society of Edinburgh*, **50**, 823-836, 1 plate.

TYRRELL, G W. 1916. Further notes on the petrography of South Georgia. *Geological Magazine*, Decade 6, **3**, 435-441.

TYRRELL, G W. 1918. Additional notes on the petrography of South Georgia. *Geological Magazine*, Decade 6, **5**, 483-489.

TYRRELL, G W. 1930. The petrography and geology of South Georgia. *British Museum (Natural History) Report on the Geological Collections made during the voyage of the* "Quest" *on the Shackleton-Rowett Expedition to the South Atlantic and Weddell Sea in 1921-22*. London: Trustees of the British Museum. 28-54.

TYRRELL, G W. 1945. Report on rocks from West Antarctica and the Scotia Arc. *Discovery Reports*, **23**, 37-102. Cambridge.

VINE, F J, and MATTHEWS, D H. 1963. Magnetic anomalies over oceanic ridges. *Nature, London*, **199**, 947-949.

WEGENER, A. 1912. Die Entstehung der Kontinente. *Geologische Rundschau*, **3**, 276-292.

WEGENER, A. 1915. *Die Entstehung der Kontinente und Ozeane*. Friedrich Vieweg and Sohn, Braunschweig.

WEGENER, A. 1929. *Die Ehtstehung der Kontinente und Ozeane* (4th edition). Friedrich Vieweg and Sohn, Braunschweig. English translations as *The Origin of Continents and Oceans* were published in the USA by Dover Publications Inc. (1966) and in the UK by Methuen and Co., London (1967).

WILCKENS, O. 1932. Fossilien und Gesteine von Süd Georgien. *Scientific Results of the Norwegian Antarctic Expedition 1927–1928*, **8**. I Kommisjon Hos Jacob Dybwad, Oslo.

WILCKENS, O. 1933. Der Südantillen-Bogen. *Geologische Rundschau*, **24**, 320-335.

WILCKENS, O. 1937. Geologische Ergebnisse der Deutschen Süd Georgien Expedition Dr Kohl-Larsen 1928–29. *Geologische Rundschau*, **28**, 127-128.

WILCKENS, O. 1947. Paläontologische und geologische Ergebnisse der Reise von Kohl-Larsen (1928–29) nach Süd Georgien. *Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft*, **474**, 66 pp.

WINN, R D. 1978. Upper Mesozoic flysch of Tierra del Fuego and South Georgia Island: A sedimentological approach to lithosphere plate restoration. *Geological Society of America Bulletin*, **89**, 533-547.

WOOD, R M. 1985. *The Dark Side of the Earth*. George Allen and Unwin, London. 246 pp.

WORDIE, J M. 1921. Shackleton Antarctic Expedition 1914-1917: geological observations in the Weddell Sea area. *Transactions of the Royal Society of Edinburgh*, **53**, 17-27.

Appendix 1

South Georgia place names celebrating geologists and geological contributions

(Unless otherwise noted, the dates given are those when fieldwork was undertaken)

Andersson Passhöhe: 54° 10’S, 36° 32’W.

J. G. Andersson, geologist with the Swedish Antarctic Expedition 1901-04. The name is currently regarded as redundant.

Clayton Glacier: 54° 04’S, 37° 27’W:

R. A. S. Clayton, BAS geologist 1972-74

Douglas Crag: 54° 46’S, 36° 00’W.

G. V. Douglas, geologist with the *Quest* Expedition 1921-22.

Ferguson Peak: 54° 47’S, 35° 50’W.

D. Ferguson, mineral exploration geologist employed by the Salvesen Whaling Company, 1912.

Klutschak Point: 54° 16’S, 37° 41’W.

H. W. Klutschak, a visitor in 1877, provided the first (inaccurate) geological description.

Kohl Plateau: 54° 14’S, 36° 58’W.

L. Kohl-Larsen, Leader of the German South Georgia Expedition 1928-29.

Macdonald Cove: 54° 00’S, 37° 29’W.

D. I. M. Macdonald, BAS geologist 1975-1976.

Mount Mair: 54° 50’S, 36° 02’W:

B. F. Mair, BAS geologist 1974-75 and 1976-77.

Pettigrew Scarp (Annenkov Island): 54° 30’S, 37° 04’W.

T. H. Pettigrew, BAS geologist 1972-73.

Quensel Glacier: 54° 46’S, 35° 51’W.

P. D. Quensel, geologist with the Swedish Magellanic Expedition which visited South Georgia in 1909.

Salomon Glacier: 54° 46’S, 35° 56’W.

W. Salomon, Professor of Geology at the University of Heidelberg, was one of the scientific mentors of the German Antarctic Expedition 1911-12, commented on specimens and arranged publication of the results from South Georgia.

Storey Glacier: 54° 47’S, 36° 01’W.

B. C. Storey, BAS geologist 1974-76.

Tanner Island (one of the Pickersgill Islands): 54° 38’S, 36° 46’W.

P. W. G. Tanner, BAS geologist 1973-1974 and 1975-76.

Trendall Crag: 54° 48’S, 35° 59’W.

A. F. Trendall, geologist with the first two of the South Georgia Survey Expeditions 1951-52 and 1953-54

Tyrrell Glacier: 54° 24’S, 36° 32’W.

G. W. Tyrrell, Glasgow University petrologist, published a series of descriptions of South Georgia rocks between 1915 and 1945.

Wilckens Peaks: 54° 12’S, 36° 56’W.

O. Wilckens, German palaeontologist who described most of the early fossil collections from South Georgia, publishing descriptions between 1932 and 1947.

In addition to the above, the following eminent geologists have been celebrated with South Georgia place-names, although they made no direct, personal contribution.

Geikie Glacier: 54° 18’S, 36° 42’W.

Sir Archibald Geikie (1835-1942). Director of the Geological Survey of Great Britain.

Harker Glacier: 54° 22’S, 36° 32’W.

Alfred Harker (1859-1939). Professor of Geology at the University of Cambridge.

Lyell Glacier: 54° 19’S, 36° 37’W.

Sir Charles Lyell (1795-1875). Author of *Principles of Geology*, the three volumes of which greatly influenced his friend Charles Darwin.

Nordenskjöld Glacier: 54° 25’S, 36° 24’W.

Nordenskjöld Peak: 54° 29’S, 36° 21’W.

Nils Otto Gustaf Nordenskjöld (1869-1928). Leader of the Swedish Antarctic Expedition 1901-04.

Philippi Glacier: 54° 49’S, 36° 05’W.

Emil Philippi. Geologist/glaciologist with the 1901-03 German Antarctic Expedition (which did not visit South Georgia) and later Professor of Geology at the University of Jena.