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Composition and evolution of the Ancestral South Sandwich Arc: Implications for the flow of deep ocean water and mantle through the Drake Passage Gateway

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ABSTRACT

The Ancestral South Sandwich Arc (ASSA) has a short life-span of c. 20 m.y. (early Oligocene to middle–late Miocene) before slab retreat and subsequent 'resurrection' as the active South Sandwich Island Arc (SSIA). The ASSA is, however, significant because it straddled the eastern margin of the Drake Passage Gateway where it formed a potential barrier to deep ocean water and mantle flow from the Pacific to Atlantic. The ASSA may be divided into three parts, from north to south: the Central Scotia Sea (CSS), the Discovery segment, and the Jane segment. Published age data coupled with new geochemical data (major elements, trace elements, Hf–Nd–Sr–Pb isotopes) from the three ASSA segments place constraints on models for the evolution of the arc and hence gateway development. The CSS segment has two known periods of activity. The older, Oligocene, period produced basic–acidic, mostly calc-alkaline rocks, best explained in terms of subduction initiation volcanism of Andean-type (no slab rollback). The younger, middle–late Miocene period produced basic–acidic, high-K calc-alkaline rocks (lavas and pyroclastic rocks with abundant volcanigenic sediments) which, despite being erupted on oceanic crust, have continental arc characteristics best explained in terms of a large, hot subduction flux most typical of a syn- or post-collision arc setting. Early–middle Miocene volcanism in the Discovery and Jane arc segments is geochemically quite different, being typically tholeiitic and compositionally similar to many lavas from the active South Sandwich Island Arc front. There is indirect evidence for Western Pacific-type (slab rollback) subduction initiation in the southern part of the ASSA and for the back-arc basins (the Jane and Scan Basins) to have been active at the time of arc volcanism. Models for the death of the ASSA in the south following a series of ridge–trench collisions are not positively supported by any geochemical evidence of hot subduction, but cessation of subduction by approach of progressively more buoyant oceanic lithosphere is consistent with both geochemistry and geodynamics. In terms of deep ocean water flow the early stages of spreading at the East Scotia Ridge (starting at 17–15 Ma) may have been important in breaking up the ASSA barrier while the subsequent establishment of a STEP (Subduction-Transform Edge Propagator) fault east of the South Georgia microcontinent (<11 Ma) led to formation of the South Georgia Passage used by the Antarctic Circumpolar Current today. In terms of mantle flow, the subduction zone and arc root likely acted as a barrier to mantle flow in the CSS arc segment such that the ASSA itself became the Pacific–South Atlantic mantle domain boundary. This was not the case in the Discovery and Jane arc segments, however, because the northward flow of the South Atlantic mantle behind the southern part of the ASSA gave an Atlantic provenance to the whole southern ASSA.

1. Introduction

The Drake Passage Gateway (Fig. 1) is the oceanic tract that connects the southern Pacific and southern Atlantic Oceans. The opening of this gateway may have removed the last barrier to the formation of the

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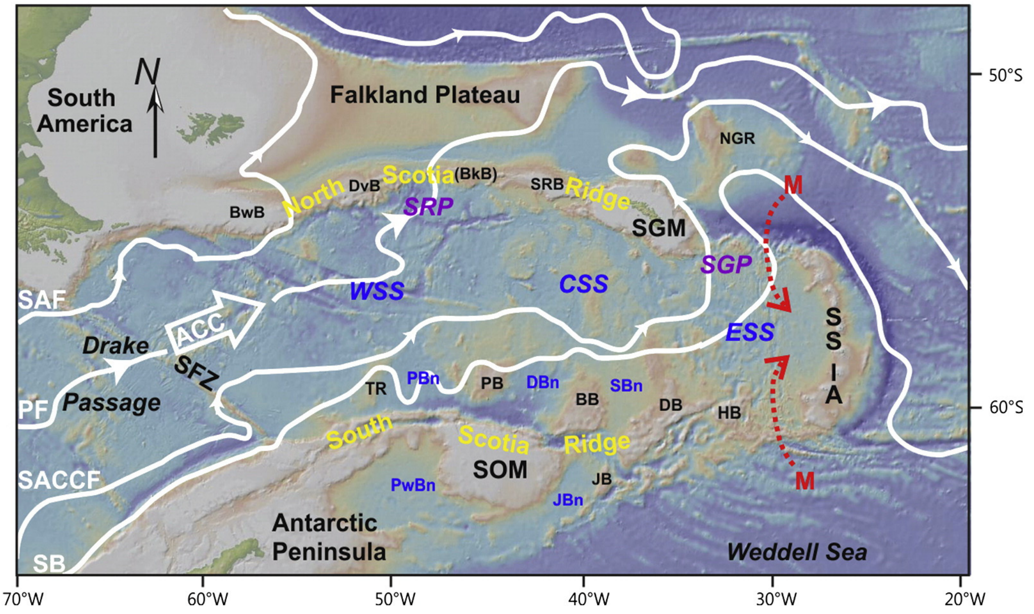

Fig. 1. Map of the Scotia Sea (modified from Dalziel et al., 2013) showing Drake Passage–Scotia arc region physiography, path of the Antarctic Circumpolar Current (white), and schematic present-day mantle flow (red). Possible barriers to flow: AB — Aurora Bank; BwB — Burdwood Bank; BB — Bruce Bank; DB — Discovery Bank; DvB — Davis Bank; H — Herdman Bank; JB — Jane Bank; NGR — Northeast Georgia Rise; PB — Pirie Bank; SFZ — Shackleton Fracture Zone; SRB — Shag Rocks Bank; SSIA — South Sandwich Island Arc; SGM — South Georgia microcontinent; SOM — South Orkneys Islands microcontinent; TR — Terror Rise. Possible channelways: CSS — Central Scotia Sea; ESS — East Scotia Sea; WSS — West Scotia Sea; DBn — Dove Basin; PBn — Protector Basin; SBn — Scan Basin; JBn — Jane Basin. Ocean currents and fronts (from Naveira Garabato et al., 2002): ACC — Antarctic Circumpolar Current; PF — Polar Front; SACCF — South Antarctic Circumpolar Current Front; SAF — Sub-Antarctic Front; SB — Southern Boundary of the ACC. Note that the Polar Front is the core of the flow of Circumpolar Deep Water of the Antarctic Circumpolar Current. White arrows show the three main pathways of the ACC.

Antarctic Circumpolar Current (ACC), one of the largest deep currents on Earth, and so the timing of its opening is critical for understanding past climate change (e.g., Kennett, 1977; Mackensen, 2004; Scher and Martin, 2006). Drake Passage itself, the body of water that lies directly between the Austral Andes of South America and the 'Antarctandes' of West Antarctica, is generally believed to have first opened at around the Oligocene–Eocene boundary, which led many to link Drake Passage opening to the abrupt change in Antarctic climate at c. 34 Ma (e.g. Zachos et al., 2001), an assertion that continues to be much-debated (e.g. DeConto and Pollard, 2003; Sijp and England, 2004). It has been apparent for some time, however, that a deep water channel in Drake Passage itself may not have been a sufficient condition for a fully-developed ACC as many continental barriers still lay to the east. Indeed, many reconstructions show connected deep-water channelways not developing until the Miocene (e.g. Barker, 1995, 2001), though others present reconstructions that allow such channelways to exist as early as the Eocene (e.g. Lawver and Gahagan, 2003). Understanding the development of the full Drake Passage Gateway from Drake Passage in the west to the South Sandwich Islands in the east is thus an important goal. A key component of this is understanding the subduction history of the gateway, though the role of subduction is not simple: subduction can create ocean basins, which provide channelways to flow, but also create island arcs, which form barriers to flow.

The Drake Passage Gateway is also potentially important in geodynamics as a gateway to mantle flow. Alvarez (1982) noted that subducting plates and continental roots act as barriers to shallow mantle flow and that the surface area of the Pacific Ocean is shrinking while that of the Atlantic is expanding. That, he argued, requires mantle flow between the two, which is only possible in the three locations without barriers to flow: the Australia–Antarctic Discordance, southern Central America and Drake Passage. Pearce et al. (2001) used isotopic fingerprinting to confirm that the Pacific mantle did flow eastwards while Drake Passage was opening, but not as far as the Atlantic as Alvarez proposed. Instead, it is the Atlantic mantle that presently flows into the East Scotia Sea in response to the retreat of the South Sandwich Trench (see also Bruguier and Livermore (2001) and Müller et al. (2008)). Helffrich et al. (2002) similarly found no evidence of present day Pacific mantle flow through Drake Passage using shear-wave splitting and Nerlich et al. (2012) independently concluded, through a study of dynamic topography, that the Drake Passage Gateway is presently not an outlet for the Pacific mantle. Nonetheless, the Drake Passage Gateway contains a major mantle domain boundary and its development is potentially significant in understanding asthenosphere flow and domain boundary development. Again, the subduction history of the gateway is important, if also potentially complex: subduction can enhance mantle flow by tectonic thinning of continental lithosphere and by driving corner or sideway flow within the mantle wedge, while arc roots and the subducting plates themselves act as major barriers to mantle flow.

The Scotia Sea is presently the main passageway within the Drake Passage Gateway (Fig. 1). Seawater flows from the Pacific into the West Scotia Sea (WSS) with one branch exiting from the WSS through the Shag Rocks Passage (SRP) in the north and the other flowing through the Central Scotia Sea (CSS) and exiting through South Georgia Passage (SGP) at the northern edge of the East Scotia Sea (ESS). However, throughout its c. 34 Ma life, the Scotia Sea has been growing faster than the rate of separation of the South American and Antarctic plates. Geometrically, therefore, there has been a need for subduction of the South Atlantic ocean floor to make room for the newly-created crust. We can thus infer on *a priori* grounds that subduction had to accompany the opening of Drake Passage and continue throughout the history of the gateway. Indeed most models for gateway evolution have a westward-dipping subduction zone active at 34 Ma or earlier (e.g. Barker, 1995, 2001; Eagles and Jokat, 2014), although some (e.g. Lagabrielle et al., 2009) do ignore subduction and its possible consequences. The main 'smoking gun' for proving the presence, precise location and tectonic setting of this subduction zone is the presence and composition of arc volcanics of Oligocene and younger age, and that is the subject of this paper.

A recent cruise (NBP0805) using the U.S. Polar Research vessel *Nathaniel B. Palmer* recovered the first *in situ* samples from the Central Scotia Sea and imaged some of the sample sites (Dalziel et al., 2013). Notably, it provided the first information on the geology of the Central

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