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Notes

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ABSTRACT

Cenozoic opening of the central Scotia Sea involved the tectonic translation of crustal blocks to form the North Scotia Ridge, which today is a major topographic constriction to the flow of the deep Antarctic Circumpolar Current that keeps Antarctica thermally isolated from warmer ocean waters. How this ridge developed and whether it was a topographic barrier in the past are unknown. To address this we investigated the Cenozoic history of the South Georgia microcontinental block, the exposed part of the ridge. Detrital zircon U-Pb geochronology data confirm that the Cretaceous succession of turbidites exposed on South Georgia was stratigraphically connected to the Rocas Verdes backarc basin, part of the South America plate. Apatite thermochronometry results show that South Georgia had remained connected to South America until ca. 45–40 Ma; both record a distinct rapid cooling event at that time. Subsequent separation from South America was accompanied by kilometer-scale reburial until inversion ca. 10 Ma, coeval with the cessation of spreading at the West Scotia Ridge and collision between the South Georgia block and the Northeast Georgia Rise. Our results show that the South Georgia microcontinental block could not have been an emergent feature from ca. 40 Ma until 10 Ma.

INTRODUCTION

Considerable effort has been directed at understanding the geological evolution of the Scotia Sea region as seafloor spreading in the West Scotia Sea caused the opening of the deep Drake Passage oceanic gateway that paved the way for the thermal isolation of Antarctica by the deep Antarctic Circumpolar Current (ACC) (Dalziel et al., 2013a, 2013b). Because models of the evolution of the ACC are tied to the tectonic reconstructions that restore microcontinental blocks and volcanic arcs to pre–seafloor spreading locations, it is essential that pre-drift locations are well defined. Furthermore, because the three main fronts to the modern ACC are steered by regional bathymetry (Fig. 1), models of the ancient ACC need to incorporate constraints as to where and when crustal blocks were barriers to ocean currents. Today the Subantarctic Front and the Polar Front follow gaps in the North Scotia Ridge while the Southern Antarctic Circumpolar Current Front takes an eastward path before heading north, turning around the eastern end of South Georgia; however, how much of a barrier these ridges were in the past is unknown due in part to uncertainty about their pre-breakup location and subsequent drift history.

The conventional view (Dalziel et al., 1975, 2013a; Livermore et al., 2007), based on interpretations that match the geology of the South Georgia microcontinent with South America, is that originally South Georgia occupied a position to the immediate southeast of Tierra del Fuego from the Jurassic until the Cenozoic, when seafloor spreading created the west Scotia Sea. Late Cretaceous compressional deformation structures in the Andean Cordillera, that drove inversion of the marginal basins, and the obduction of the Rocas Verdes ophiolitic basement onto the continental margin can be followed along strike from Tierra del Fuego into South Georgia (Dalziel et al., 2013a). This phase of deformation is believed to have caused uplift of the North Scotia Ridge and may have also initiated eastward translation of the South Georgia microcontinent by left-lateral ductile shearing.

However, plate kinematic data have, controversially, been used to suggest that the pre–seafloor spreading location was at the eastern end of the North Scotia Ridge and that South Georgia once belonged to part of an extended continental margin along the Falkland Plateau that formed as Gondwana broke up in Jurassic time (Eagles, 2010a). The motivation for this model was driven by the need to explain an apparent deficit in the translation of South Georgia accounted for by seafloor spreading based on a South American origin. Restoration using plate kinematic evidence can only account for approximately half of the ~1600 km displacement (Eagles et al., 2005). A position for South Georgia on the Pacific margin of Gondwana would require less transport to the east during opening of the Scotia Sea; it would mean that the South Georgia block could not have served as an early proximal barrier to deep Pacific-Atlantic flow. To resolve these issues we examined the provenance of Cretaceous turbidites exposed on South Georgia using detrital zircon U-Pb geochronology and studied the island's bedrock exhumation history using apatite thermochronometry.

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The geology of South Georgia (Fig. 2) is central to the debate about the original location of this microcontinental block and its role

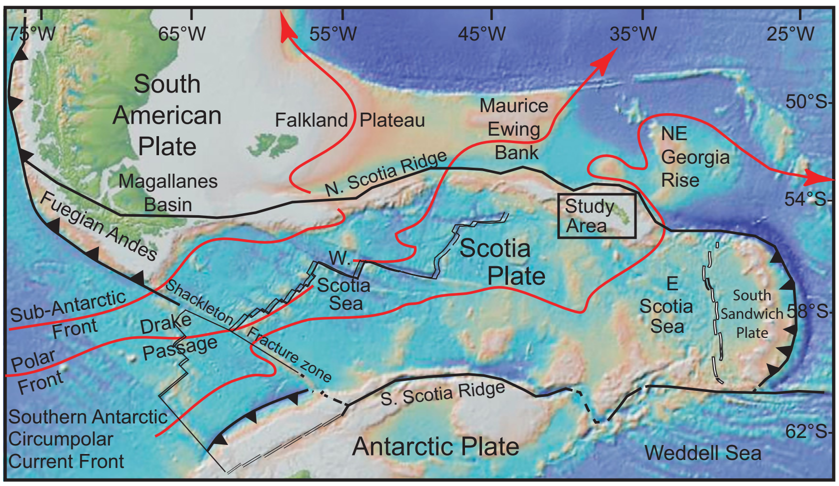

Figure 1. Scotia Arc region; study area (Fig. 2), principal topographic features, and main fronts of Antarctic Circumpolar Current are indicated (generated by GeoMapApp; www.geomapapp.org). Red lines show positions of Sub-Antarctic Front and Southern Antarctic Circumpolar Current Front (Orsi et al., 1995) and Polar Front (Moore et al., 1997).

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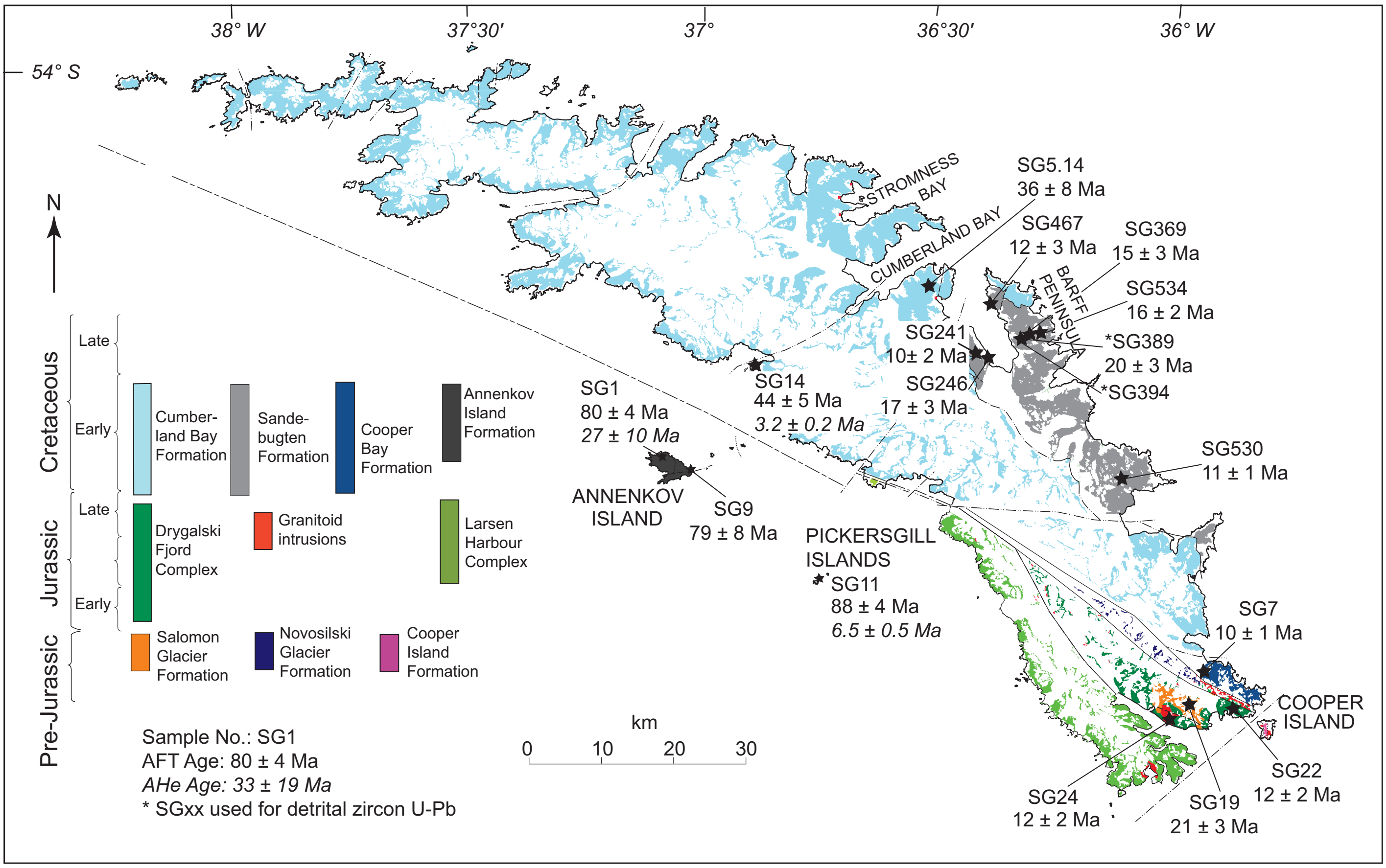

Figure 2. Geological map of South Georgia Island; locations and apatite fission track (AFT) central ages and ejection-corrected (U-Th)/He ages (AHe) of sampled rocks are indicated; map based on Curtis and Riley (2011). Age uncertainties are 1σ.

during the opening of the Drake Passage. The majority of the rock exposure is formed by two laterally equivalent turbidite sequences deposited by deep-sea fans in an Early Cretaceous backarc basin. The 8-km-thick Cumberland Bay Formation, which crops out over half of the island, is a classic turbidite succession composed of andesitic volcaniclastic graywackes derived from a volcanic island arc (Tanner and MacDonald, 1982). The Sandebugten Formation is also composed of turbiditic facies rocks that are distinguished by their siliciclastic composition and the presence of trachytic and dacitic fragments and felsitic and granitic clasts sourced from the continental margin of a backarc basin (MacDonald et al., 1987).

The conventional view considers that the geology of South Georgia represents a missing part of the Fuegian Andes once located to the south of Isla de los Estados and Burwood Bank (Dalziel et al., 1975). Both areas share common rock types, depositional ages, and structures that fit with a once-extended Rocas Verdes basin that dates back to the breakup of Gondwana when the Patagonian Andes underwent extension. By the Early Cretaceous, this extension had led to the formation of the quasi-oceanic rift basin filled by large volumes of silicic volcaniclastic sediments, including turbidites that thicken to the south. The Rocas Verdes basin and continental margin arc rocks terminate along the strike of the mid-Cretaceous structures at the continental margin immediately to the east of Isla Navarino, leaving oceanic lithosphere to the south of Isla de los Estados and Burdwood Bank. The turbidite sequences that crop out on South Georgia are therefore viewed as the missing part of the Fuegian Andes. By contrast, the alternative model for South Georgia, based on a passive margin setting on the southern edge of the Falkland Plateau, suggests that other volcanic centers, such as the Polarstern Bank near the southeast margin of the Weddell Sea, could account for the silicic volcanic detritus (Eagles, 2010a).

RESULTS AND INTERPRETATION

To discriminate between competing plate reconstruction models and remove uncertainty surrounding the pre-breakup location of the South Georgia microcontinental block, we compared detrital zircon U-Pb age signatures of the Cretaceous turbidite sequences exposed on South Georgia with potential source areas; namely, the Cordillera. These are the Cordillera Darwin complex and the eastern Magallanes foreland basin of South America (Barbeau et al., 2009; Hervé et al., 2010; Klepeis et al., 2010), and an East Gondwana passive margin setting on the edge of the Falkland Plateau, represented by a Permian sample from the Falkland Islands (see the GSA Data Repository[1] for analytical details). The results (Fig. 3) show a remarkable match to sources from the South Patagonian batholith, Jurassic volcanics, and the south Andean metamorphic basement. The data do not fit with an East Gondwana provenance (Eagles, 2010a) because Proterozoic to Cambrian age zircons are largely absent. Our detrital zircon data thus support a connection to the Rocas Verdes backarc basin during the Early Cretaceous, as originally suggested by Dalziel et al. (1975).

Apatite and zircon fission track and apatite (U-Th)/He thermochronometry (AHe) results from bedrock samples (for analytical details, see the Data Repository; see Fig. 2 for locations and summary ages) lend additional support to this interpretation. On the northeastern side of South Georgia, a compilation of the results from the Cretaceous Sandebugten Formation from the Barff Peninsula identifies two distinct phases

[1]GSA Data Repository item 2014112, analytical methods, Figures DR1 and DR2, Table DR1 (AFT data), Table DR2 (AHe data), and Table DR3 (U-Pb ages for detrital zircon grains), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

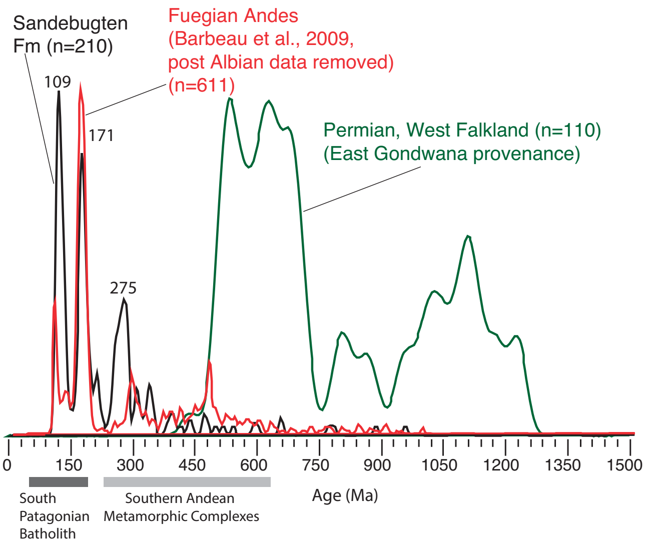

Figure 3. Kernel density plots of detrital zircon U-Pb ages from Sandebugten Formation of South Georgia Island compared with data from rocks in Fuegian Andes that include Cordillera Darwin complex and eastern Magallanes foreland basin (Barbeau et al., 2009) and Permian sandstone from West Falkland representative of typical provenance of eastern Gondwana.

of cooling (Fig. DR1 in the Data Repository) constrained by zircon fission track data (ZFT) and differential fission track annealing kinetics arising from variations in apatite composition. Petrography shows that these rocks were buried to low-grade metamorphic temperatures within the prehnite-pumpellyite facies (Stone, 1980) and the ZFT data record the end of this metamorphism as ca. 45 Ma, marked by rapid exhumation to shallow (<2 km) crustal levels; apatite grains with more resistant compositions form a distinct population of ca. 40 Ma. Although reburial followed soon after, it was not sufficient to reset fission tracks across the entire range of apatite compositions (Fig. DR1), so maximum burial temperatures could not have been much above ~100 °C. Peak burial-related heating in the late Miocene was followed by inversion ca. 10–7 Ma, constrained by the youngest population of FT grain ages (least resistant to FT resetting) and apatite AHe ages.

The southwestern side of South Georgia also records post-Eocene reburial, but the depth of burial is less. A west coast sample from the mostly apatite-barren Cumberland Bay Formation has an FT central age of 44 Ma, diagnostic of the Eocene cooling event, but the accompanying AHe age of 3.2 ± 0.2 Ma requires some small-scale reburial and recent exhumation in this region. Sampled 90–105 Ma igneous rocks from the Annekov and Pickersgill Islands yielded apatite FT (AFT) ages with long (>14 μm) mean track lengths, close to the rock formation ages, that testify to long-term residence at near surface temperatures, although the 6.5 ± 0.2 Ma AHe age from the Pickersgill Islands also shows that there must have been some burial. Thermal history models (Fig. DR1) confirm this and show that burial from ca. 40 Ma reached peak temperatures of ~70 °C prior to the initiation of final inversion ca. 10–7 Ma. Figure 4 summarizes the thermal histories.

DISCUSSION

Our provenance and exhumation history results confirm that the South Georgia block was once connected to the Rocas Verdes backarc basin, most likely east of Navarino Island and south of the Burdwood Bank (Dalziel et al., 1975). Evidence from South America shows that this basin was inverted and obducted onto the continental margin of South America, metamorphosed (upper amphibolite grade), and the equivalents of the Early Cretaceous turbidites of South Georgia folded before intrusion of the Late Cretaceous Beagle Suite granitoids (Mukasa and Dalziel, 2009); therefore, South Georgia was likely a topographic feature by the Late Cretaceous. This is supported by nearly

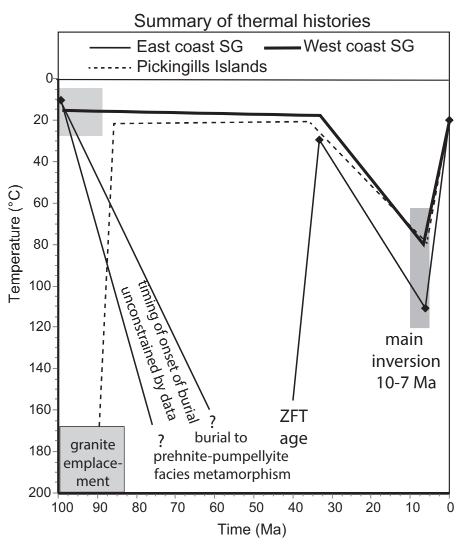

Figure 4. Plot summarizing thermal histories of sampled rocks from South Georgia Island (SG) and Annekov and Pickersgill Islands. Timings for inversion and burial events are similar, although magnitudes of burial vary with east to west location. ZFT—zircon fission track.

contemporaneous AFT ages from 90–105 Ma granitoids on the Annekov and Pickersgill Islands that show that these rocks were exhumed to shallow crustal levels (<1 km) soon after their emplacement.

Between the Late Cretaceous and early Eocene, the South Georgia block must have been reburied to low-grade metamorphic temperatures as the exhumation data require cooling from ~250 °C close to 45 Ma. This is coincident with exhumation data from the Fuegian Andes that record rapid cooling ca. 45–40 Ma (Gombosi et al., 2009) and a dramatic sediment provenance shift ca. 39 Ma in the Magallanes foreland basin, interpreted as evidence of rock and surface uplift of the Cordillera Darwin complex and adjacent hinterland thrust sheets (Barbeau et al., 2009). A shared exhumation history thus requires final separation from South America to postdate 45 Ma. The contractional regime that drove this exhumation and development of the Patagonian orocline by counterclockwise rotation of the Fuegian Andes (Gombosi et al., 2009) may have contributed to the final breakup.

The thermochronometry data from South Georgia require a second period of kilometer-scale reburial following Eocene exhumation, a period that extended through the Oligocene as seafloor spreading took place in the West Scotia Sea. The final phase of exhumation recorded by both AFT and AHe data initiated ca. 10 Ma and was likely related to the effects of collision with the Northeast Georgia Rise ca. 12–9 Ma (Kristoffersen and LaBrecque, 1991; Dalziel et al., 2013a). Thrust earthquakes are recorded from both sides of the South Georgia microcontinent, but the main thrusting appears to be onto the central Scotia Sea floor (Eagles, 2010b), consistent with deeper, more recent exhumation in the northeastern section of the island. To the southwest, the Annekov and Pickersgill Islands appear to have been much more stable, and record lower levels of reburial and exhumation compared to mainland South Georgia to the east. This markedly different thermal history may be related to movement on some of the major structures in the region that trend northeast-southwest. A possible structural candidate is the mid-Late Cretaceous Cooper Bay shear zone (Curtis et al., 2010), the largest exposed structural feature in South Georgia. However, exhumation data collected from both sides of the onshore parts of this structure in the Cooper Bay–Drygalski Fjord region give ages similar to those from South Georgia. Alternatively, the inferred offshore contact between the ophiolitic Larsen Harbour Complex and the arc assemblage of the Annekov and Pickersgill Islands (Simpson and Griffiths, 1982) provides a likely structural boundary that is consistent with the exhumation data.

A common provenance and exhumation history requires South Georgia to be placed much closer to Tierra del Fuego during the early

Cenozoic than shown by recent reconstructions, which acknowledge the lack of previous constraints (Lawver et al., 2011). What took place after separation is important to help understand the development of the deep ACC. Our results show that following breakup, during its drift eastward South Georgia could not have been an elevated block, as the thermal history models require increased levels of heating due to kilometer-scale reburial throughout the Oligocene and early Miocene. This reheating must be due to burial, because (1) elevated geotherms associated with seafloor spreading are constrained by slow rates of conductive transfer which are unlikely to have much impact on the adjacent continental crust; and (2) more important, our data from the Annekov and Pickersgill Islands (closest to oceanic crust) show no evidence of Oligocene reheating. At geothermal gradients in the range of 20–30 °C/km, the thermal history models require between 2 and 4 km of burial. Therefore, during the opening of the Scotia Sea and Drake Passage, South Georgia would have been submerged; however, whether it was a major barrier to Pacific to Atlantic through flow would depend on the bathymetry at that time. Submerged features such as the Campbell Plateau south of New Zealand (bathymetry ≤500 m) can deflect the ACC, but such plateaus have low sedimentation rates, and they would need to subside further in order to accommodate the several kilometers of sediment indicated by the apatite thermochronometry data.

CONCLUSIONS

We have confirmed that the South Georgia microcontinent was originally connected to the Rocas Verdes backarc basin of South America until the Eocene. As part of the South America plate it would have been a topographic feature during the two main regional deformation events in the Late Cretaceous and Eocene. Kilometer-scale reburial after the Eocene is required by the thermochronometry data, so South Georgia must have been submerged until the final stage of surface uplift that initiated ca. 10 Ma, linked to the collision between the South Georgia microcontinent and the Northeast Georgia Rise.

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