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Geochronology and geochemistry of the northern Scotia Sea: A revised interpretation of the North and West Scotia ridge junction

Teal R. Riley [a,*], Andrew Carter [b], Philip T. Leat [a,c], Alex Burton-Johnson [a], Joaquin Bastias [d], Richard A. Spikings [d], Alex J. Tate [a], Charlie S. Bristow [b]

[a] British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK
[b] Department of Earth and Planetary Sciences, Birkbeck, University of London, Malet Street, London WC1E 7HX, UK
[c] School of Geography, Geology and the Environment, University of Leicester, University Road, Leicester, LE1 7RH, UK
[d] Department of Earth Sciences, University of Geneva, 3, Rue des Maraichers, Geneva 1205, Switzerland

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ABSTRACT

Understanding the tectonic evolution of the Scotia Sea is critical to interpreting how ocean gateways developed during the Cenozoic and their influence on ocean circulation patterns and water exchange between the Atlantic and Southern oceans. We examine the geochronology and detrital age history of lithologies from the prominent, submerged Barker Plateau of the North Scotia Ridge. Metasedimentary rocks of the North Scotia Ridge share a strong geological affinity with the Fuegian Andes and South Georgia, indicating a common geological history and no direct affinity to the Antarctic Peninsula. The detrital zircon geochronology indicates that deposition was likely to have taken place during the mid – Late Cretaceous. A tonalite intrusion from the Barker Plateau has been dated at 49.6 ± 0.3 Ma and indicates that magmatism of the Patagonian–Fuegian batholith continued into the Eocene. This was coincident with the very early stages of Drake Passage opening, the expansion of the proto Scotia Sea and reorganization of the Fuegian Andes. The West Scotia Ridge is an extinct spreading center that shaped the Scotia Sea and consists of seven spreading segments separated by prominent transform faults. Spreading was active from 30–6 Ma and ceased with activity on the W7 segment at the junction with the North Scotia Ridge. Reinterpretation of the gravity and magnetic anomalies indicate that the architecture of the W7 spreading segment is distinct to the other segments of the West Scotia Ridge. Basaltic lava samples from the eastern flank of the W7 segment have been dated as Early – mid Cretaceous in age (137–93 Ma) and have a prominent arc geochemical signature indicating that seafloor spreading did not occur on the W7 segment. Instead the W7 segment is likely to represent a downfaulted block of the North Scotia Ridge of the Fuegian Andes continental margin arc, or is potentially related to the putative Cretaceous Central Scotia Sea.

1. Introduction

The expansion of the Scotia Sea and the opening of Drake Passage between the Antarctic Peninsula and South America (Fig. 1) has long been considered to be the critical tectonic event that lead to the thermal isolation of Antarctica and the onset of widespread glaciation (Kennett, 1977; Barker, 2001). However, recent work has emphasized the role of declining global atmospheric CO_2 concentrations, as occurred during the late Eocene (DeConto et al., 2008). This does not mean that changes in the configuration of ocean gateways in the Southern Ocean were unimportant; coupled climate models used by Elsworth et al. (2017) demonstrated how tectonic movements in the floor of the Southern Ocean would have changed ocean circulation patterns and water-heat exchange between the Atlantic and Southern Oceans.

Initial development of the Scotia Sea was strongly controlled by spreading on the West Scotia Ridge (Barker and Burrell, 1977), which was active from at least 29 Ma until ∼6 Ma, when spreading completely translated to the East Scotia Ridge (Fig. 1). The junction between the northernmost W7 segment of the West Scotia Ridge and the Barker Plateau of the North Scotia Ridge (Fig. 2) is the subject of this paper. We examine the age and detrital geochronology of samples from the North Scotia Ridge and investigate the age and geochemistry of basaltic rocks from the W7 segment of the West Scotia Ridge. The W7 segment was investigated in view of its distinct seafloor architecture in comparison to the other six

* Corresponding author.
E-mail address: trr@bas.ac.uk (T.R. Riley).

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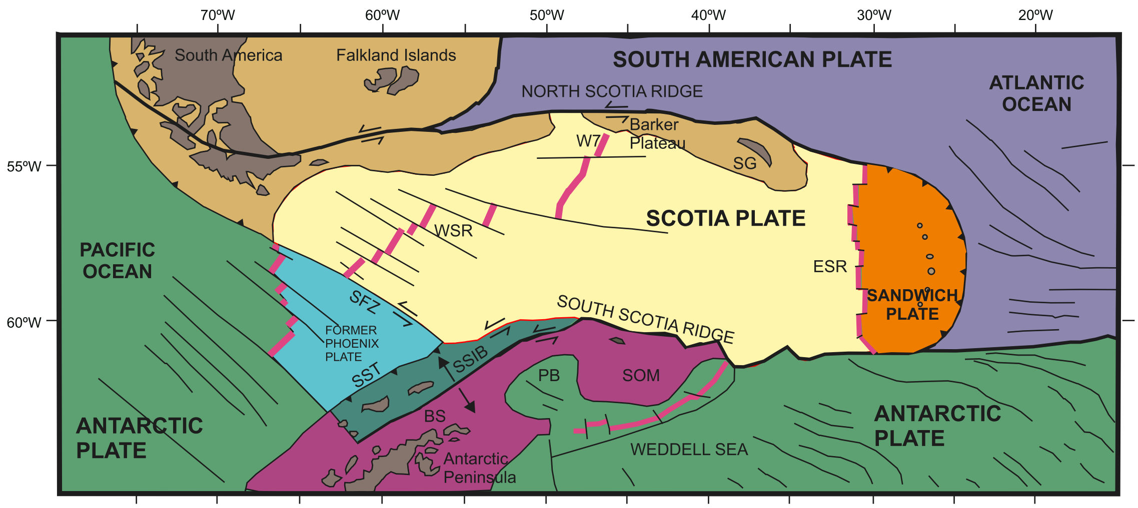

Fig. 1. Tectonic setting of the Scotia Plate. WSR: West Scotia Ridge; ESR: East Scotia Ridge; SOM: South Orkney microcontinent; PB: Powell Basin; SST: South Shetland trough; BS: Bransfield Strait; SFZ: Shackleton fracture zone; SSIB: South Shetland Islands Block; SG: South Georgia. Adapted from Maldonado et al. (2006).

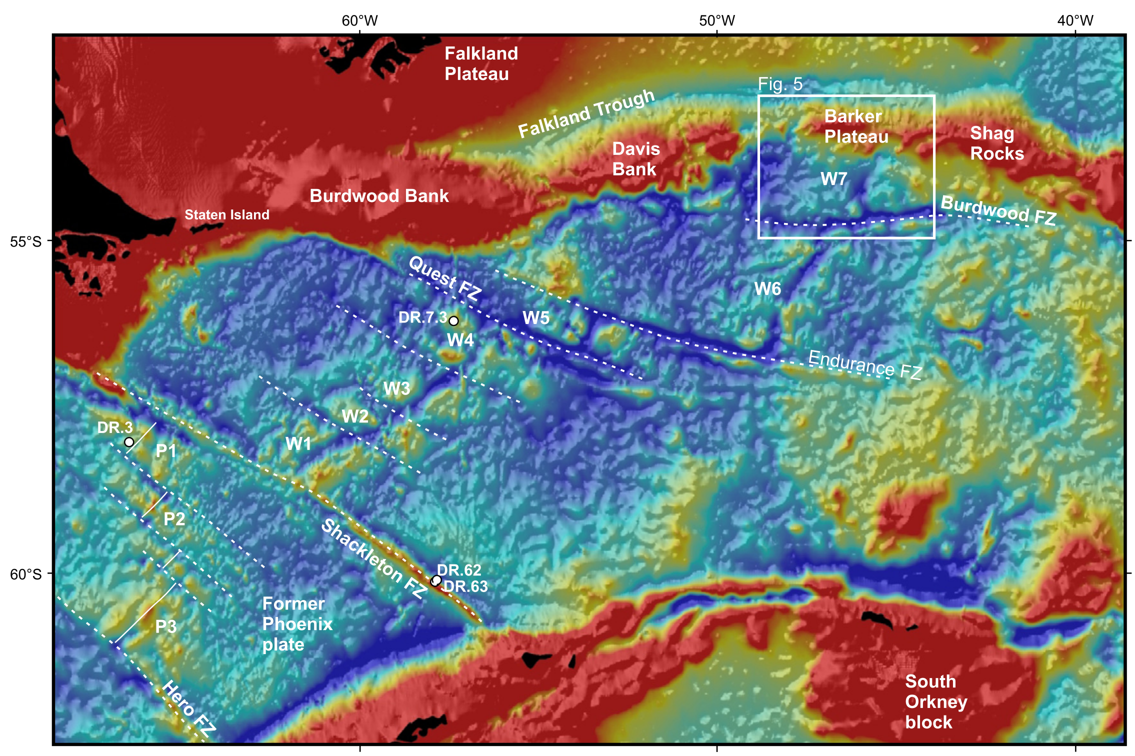

Fig. 2. Bathymetric map of the West Scotia Sea highlighting the spreading segments of the West Scotia Ridge and associated fracture zones. The banks of the North Scotia Ridge are shown. Dredge sites from Pearce et al. (2001) are highlighted. FZ: fracture zone.

identified segments of the West Scotia Ridge. The W7 segment is characterized by a different magnetic anomaly architecture to the neighboring segments, with irregular magnetic highs and the absence of a clear magnetic anomaly lineation pattern (Fig. 3). This is also apparent in the free air gravity anomaly map where the features on either flank of the W7 segment are distinct to segments W1–W6 (Fig. 4). The free air gravity is not symmetrical either side of the central rift, but rather declines rapidly to the west and forms a series of irregular highs to the east (Fig. 4; Livermore et al., 1994; Eagles et al., 2005). Furthermore, the orientation of the Burdwood Fracture Zone, the northernmost fracture zone of the West Scotia Ridge which marks the junction between W6 and W7 (Fig. 2), is also distinct, with an E-W orientation as opposed to a WNW-ESE orientation of the Shackleton, Quest and Endurance fracture zones (Fig. 2).

The origins of the North Scotia Ridge are discussed in the context of the geology of the Fuegian Andes (South America) and South Georgia (Fig. 1) and the age and geochemistry of the W7 basalts are discussed in the context of their affinity to basaltic rocks from elsewhere in the Scotia Sea in an attempt to understand their petrogenesis and tectonic setting.

2. Geological setting

The Scotia Plate is bounded by the East Scotia Ridge, the North Scotia Ridge, the South Scotia Ridge, and the Shackleton Fracture Zone (Fig. 1). The Scotia Plate is predominantly formed of ocean

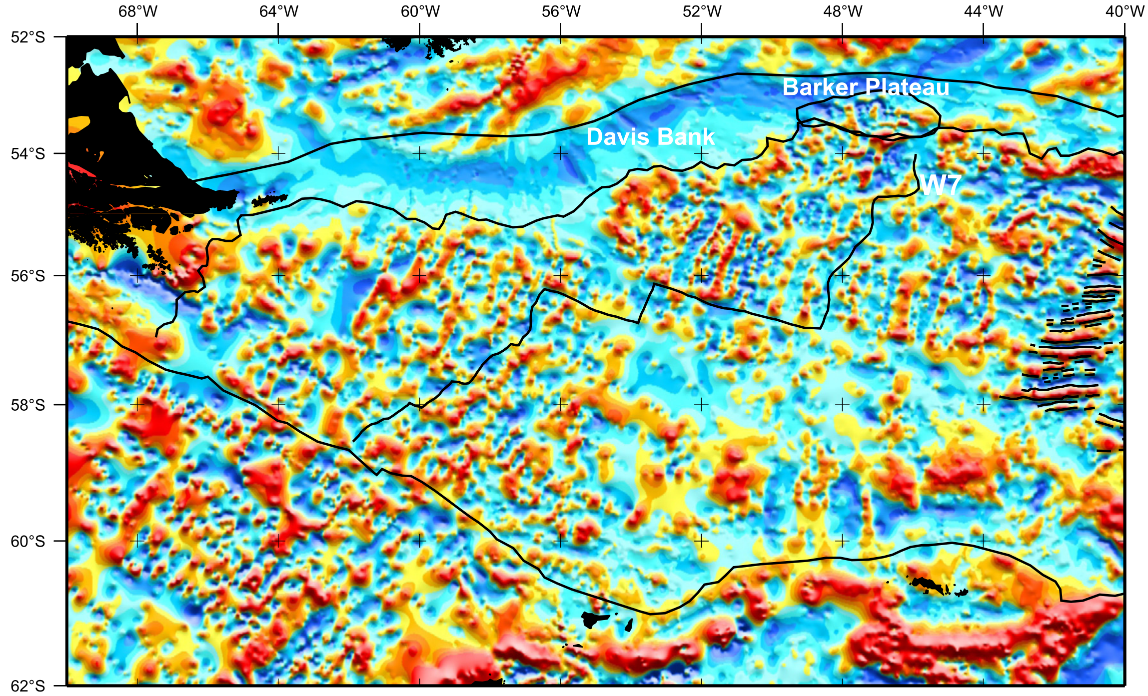

Fig. 3. Total magnetic field anomaly grid for the Scotia Sea (from Eagles et al., 2005).

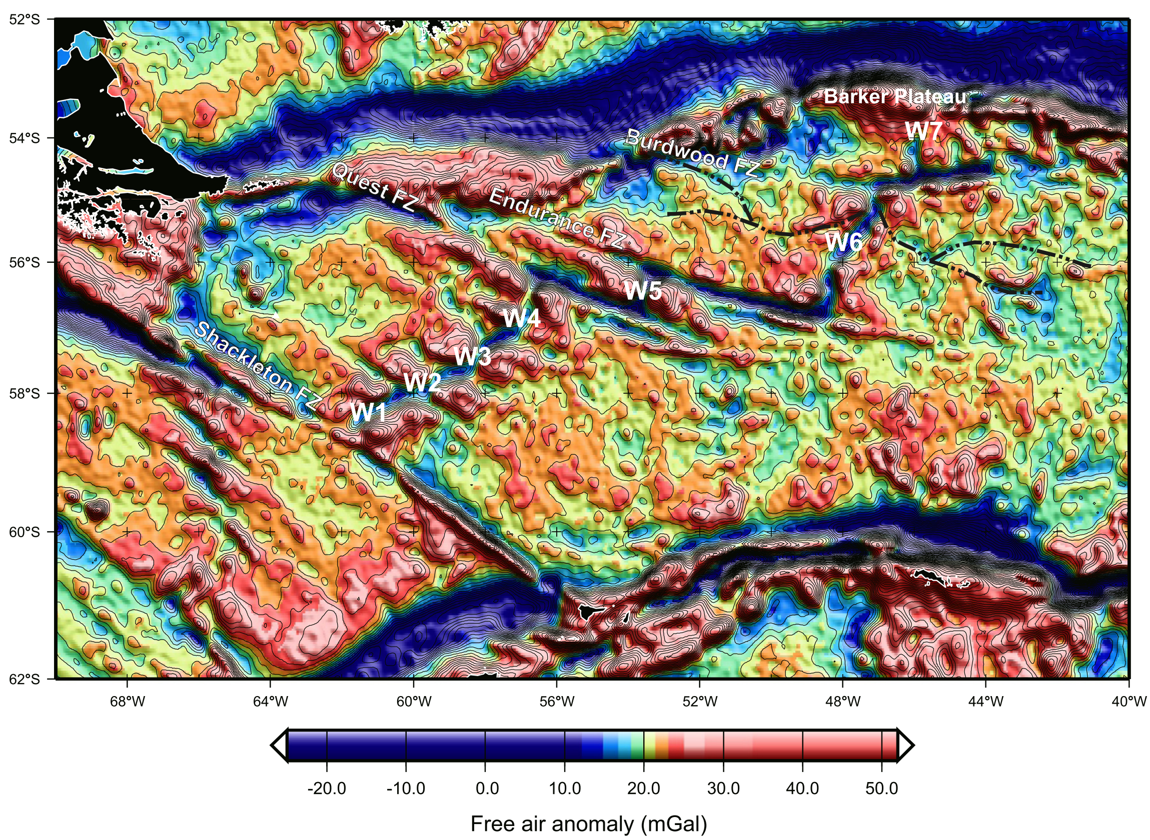

Fig. 4. Satellite-derived free-air gravity anomalies from Eagles et al. (2005). Areas marked W1–W7 indicate spreading corridors described in text. Black dash-dotted lines indicate possible offset traces in W6. Contour interval is 20 mGal. Data grid from Sandwell and Smith (1997).

crust created on the West Scotia Ridge and on the west side of the East Scotia Ridge, as well as a central zone probably consisting of oceanic crust of potentially Cretaceous age (Eagles, 2010) which is overlain by the ancestral South Sandwich arc (Dalziel et al., 2013a; Eagles and Jokat, 2014; Pearce et al., 2014). Formation of oceanic crust of the Scotia Plate led to the opening of the oceanic and mantle gateway, the Drake Passage (Fig. 1). A model for the opening of the Scotia Sea in four separate phases has been proposed by Maldonado et al. (2014). The initial Eocene/Oligocene phase (50–30 Ma) marked the transition from eastward oriented subduction of the Phoenix Plate beneath the South America-Antarctic Peninsula Pacific margin to the severance of the land bridge and rifting and dispersal of continental fragments, combined with westward dipping subduction at the Weddell Sea front (Fig. 1). It is the final phase of tectonic activity during the latest Oligocene to latest Miocene (24–6 Ma) that shaped the Scotia Sea that is recognizable today, with West Scotia Ridge oceanic spreading and continental block dispersal along the North and South Scotia ridges.

2.1. West Scotia Ridge

The West Scotia Ridge was an actively spreading ocean ridge from ∼30 Ma until it became extinct at ∼6 Ma (Livermore et al., 2005). Maldonado et al. (2014) interpreted that West Scotia Ridge spreading initiated after chron C11n (30 Ma), although other workers (Barker, 2001; Eagles, 2010) suggest there is only reliable evidence that spreading commenced at chron C8 (26.5 Ma). The extinction of the West Scotia Ridge is interpreted to have occurred at chron C3A (6.6–5.9 Ma), and magmatism on the W7 segment was thought to have ceased at this time (Eagles et al., 2005; Maldonado et al., 2014). Eagles et al. (2005) modeled fracture zone shapes from the West Scotia Ridge to demonstrate five distinct rotations during its ∼23 Myr history.

There are seven separate spreading segments of the West Scotia Ridge, separated by WNW-ESE transform faults (Fig. 2), characterized by spreading rates of 12–26 km/Myr (Eagles and Jokat, 2014), which slowed as the West Scotia Ridge propagated northwards. Eagles et al. (2005) interpreted that spreading rates slowed by chron 5C (∼17 Ma) and were probably related to the onset of back-arc spreading in the East Scotia Sea (Vanneste et al., 2002). W7, the most northerly segment, intersects the North Scotia Ridge, which is an active E-W strike-slip fault (Smalley et al., 2007) and marks the plate boundary (Livermore et al., 1994; Barker, 2001; Eagles and Jokat, 2014).

The onset of sea floor spreading at the north-south oriented East Scotia Ridge (Fig. 1) at ∼17 Ma (Eagles and Jokat, 2014) would have overlapped with spreading on the West Scotia Ridge for approximately 11 Myr, until cessation of spreading on the West Scotia Ridge at ∼6 Ma. Spreading on the East Scotia Ridge continues until the present day.

2.2. North Scotia Ridge

The North Scotia Ridge marks the location of the plate boundary between the South American and Scotia plates Livermore et al., 1994). It is a long-lived strike-slip system that accommodated oceanic spreading in the Scotia Sea and potentially eastward movement of the South Georgia continental block (Barker, 2001; Dalziel et al., 2013b; Eagles and Jokat, 2014). It consists of several submerged continental blocks, which based on their bathymetry have been termed banks or plateaus, which form an almost continuous linear belt from Tierra del Fuego to South Georgia (Fig. 1). The main banks/plateaus from west to east are Burdwood, Davis, Barker (previously referred to as Aurora) and Shag Rocks (Fig. 2). The Shag Rocks Bank has isolated exposed pinnacles forming Shag Rocks, to the west of South Georgia (Fig. 1). Seafloor imaging reveals highly faulted crust with faults approximately parallel to the plate boundary and that are likely to have accommodated strike-slip movement (Cunningham et al., 1998). The North Scotia Ridge terminates at South Georgia, which forms the only major exposed section of the Ridge.

The geology of South Georgia is dominated by Cretaceous volcaniclastic turbidites and arc volcanic rocks, and they have been correlated with the successions of the Tierra del Fuegian Andes of southern Patagonia (Dalziel et al., 1975; Barbeau et al., 2009a). Jurassic granitoids and basaltic rocks are more widespread in the southeastern region of South Georgia, alongside pre-Jurassic metasedimentary rocks (Curtis, 2011). Combined with the geological observations (e.g. Dalziel and Palmer, 1979) of Staten Island/Isla de los Estados (Fig. 2) many workers (e.g. Barker, 2001; Dalziel et al., 2013b) have suggested that the North Scotia Ridge is a submerged mountain belt of continental crust of Patagonian affinity that was deformed into the present day elongated ridge as a result of sea floor spreading in the Scotia Sea. A detrital zircon U–Pb geochronology and apatite thermochronometry study of bedrock from South Georgia by Carter et al. (2014) confirmed that the Cretaceous successions of South Georgia shared a stratigraphic connection to the Rocas Verdes back-arc basin of the South American plate and also experienced the same thermotectonic event that took place between 45–40 Ma. Thus, the separation of South Georgia from Patagonia could not have taken place until after 40 Ma and prior to 40 Ma was still part of the South American plate (Carter et al., 2014).

Geological constraints on the nature of the submerged sections of the North Scotia Ridge are very limited; Pandey et al. (2010) investigated several dredged samples from the Davis Bank and Barker (Aurora) Plateau (Fig. 2). Despite the strong alteration of the samples (LOI ≤7.79, ≤CaO 29.6 wt%), they suggested that the rocks were calc-alkaline and are similar to continental margin volcanic arc rocks of the Cretaceous Hardy Formation volcanic arc rocks of Patagonia, which are in turn correlated with the Early Cretaceous Cumberland Bay Formation on South Georgia (Curtis, 2011). Pandey et al. (2010) interpreted these similarities to indicate a continuous continental link between Tierra del Fuego and South Georgia and a similar tectonic history. However, their interpretations did not include any geochronological control, and were based on broad geochemical characteristics indicating an 'arc affinity'.

3. Geological sampling and bathymetry

To gain new insights into the nature of the submerged parts of the North and West Scotia ridges rock samples were dredged during British Antarctic Survey cruise *JR*16003 on *RRS James Clark Ross* (November 2016–January 2017). Several sites with steep topography, to reduce the risk of sampling glacial dropstones, were targeted along the North Scotia Ridge on Davis Bank and Barker Plateau (Fig. 2, 5) at water depths between 2800 and 800 m. Dredge sites were also sampled on the eastern flank of segment W7 of the West Scotia Ridge (Fig. 5) and were at water depths between 4200 m and 3300 m (Supplementary Table S1).

Bathymetric data were acquired using the onboard EM122 multibeam echo sounder. Across the W7 segment, where previous coverage was incomplete, almost 1000 km of line coverage was newly acquired to produce complete coverage of the segment and adjacent area to characterize the ridge margins at its truncation at the North Scotia Ridge (Fig. 5).

3.1. Sample descriptions and methodology

3.1.1. West Scotia Ridge

Three of the four dredge sites (DR.206–DR.209; Fig. 5) on the West Scotia Ridge yielded a significant return of mostly basaltic volcanic rocks (lavas, hyaloclastites). The abundance of samples of similar lithology from three separate dredge sites allow confidence in interpreting the basaltic samples as having been sampled in situ. A small subset of non-volcanic rocks were also recovered, including granitoids, metasedimentary rocks and granitic gneiss, which were interpreted to be either glacially derived dropstone material or locally derived from the adjacent North Scotia Ridge. Sample sites DR.206–DR.209 yielded mostly fine-medium grained basaltic lavas, which are weakly plagioclase phyric to aphyric. They are typically

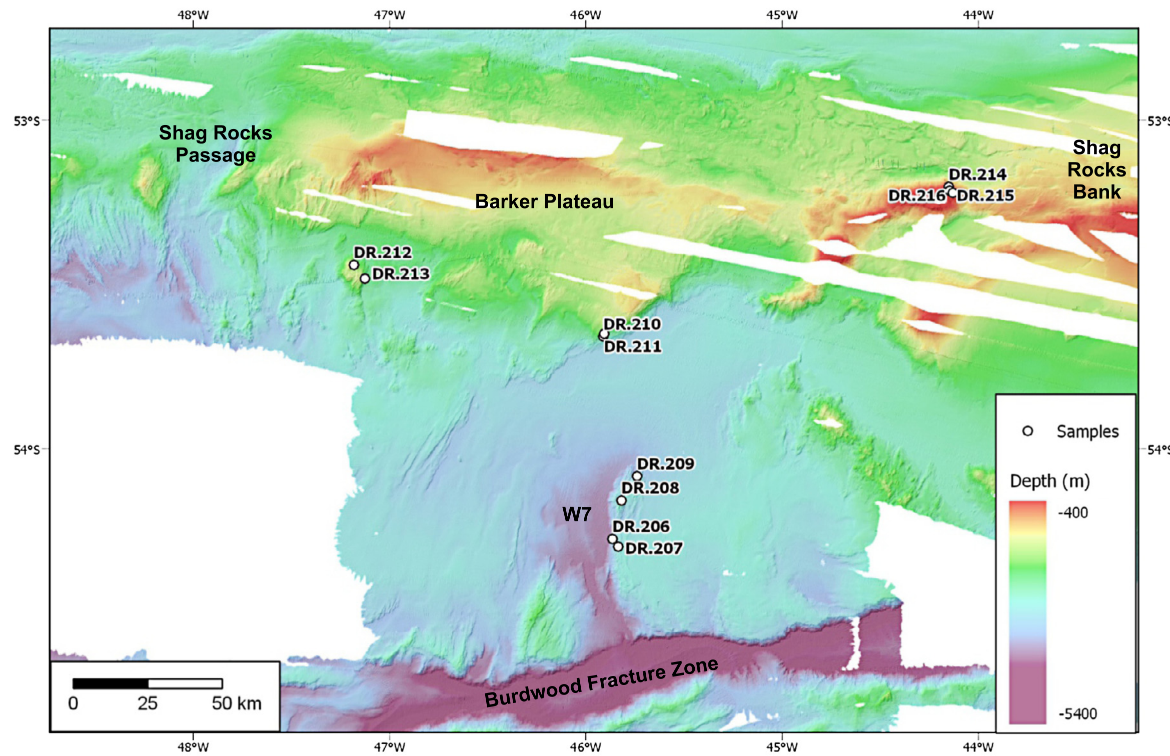

Fig. 5. Bathymetric data of the Barker Plateau-W7 junction highlighting the relief of the Barker Plateau and the prominent Burdwood Fracture Zone. The diffuse median valley of segment W7 is apparent. The dredge sites of the West Scotia Ridge (DR.206–209) and the North Scotia Ridge (DR.210–216) are highlighted.

rounded, vesicular blocks, with a pronounced (∼1 cm) nodular Fe-Mn crust and may represent pillow lavas. A subset of samples are more vitreous and have a glassy 'rind' beneath the Fe–Mn crust.

3.1.2. North Scotia Ridge

The recovered material from the North Scotia Ridge (Fig. 5) was more varied in composition and is dominated by lithologies that were interpreted to be glacially derived based on their diverse compositions and occasionally glacial striations. These included pelitic-psammitic metasedimentary blocks, paragneiss, granitoids, biotite-quartz schists and porphyritic lithologies. Those samples that were interpreted to have been sampled directly from the North Scotia Ridge are of interest here. These include granitoids, mudstone and volcaniclastic lithologies which have fractured surfaces, and are relatively abundant and are therefore interpreted to have been sampled from in situ outcrops. A subset of two samples from the North Scotia Ridge have been selected for analysis; sample DR.212.2 is a block of medium grained tonalite (quartz-plagioclase-biotite) and DR.212.3 is a fractured block of fine grained, weakly metamorphosed mudstone with extensive Fe staining on fractured surfaces.

3.2. Analytical methods

Detailed analytical procedures are provided in a supplementary file.

4. Results

Whole rock geochronological, geochemical and petrographical analyses of basalts from the West Scotia Ridge and geochronological analyses of samples from the North Scotia Ridge are presented here and are used to understand the latter stages of spreading history of the West Scotia Ridge, the petrogenesis of the oceanic basalts and the tectonic history of the North Scotia Ridge.

4.1. West Scotia Ridge

4.1.1. $^{40}Ar/^{39}Ar$ geochronology

Two samples from the eastern flank of the W7 segment were selected for Ar-Ar geochronology (Supplementary uncertainties reported at the 2σ-level. All initial interpolated $^{40}Ar/^{36}Ar$ ratios overlap with the atmospheric value of 298.6 (Lee et al., 2006).

Samples DR.206.6 and DR.209.3 are both fine grained, melanocratic, plagioclase phyric, vesicular basaltic lavas, characterized by thick (∼1 cm) nodular Fe-Mn crusts.

Mafic groundmass from the magnetic (<2.5 V) aliquot of the samples DR.206.6 and DR.209.3 yield disturbed age spectra, that show evidence for ^{40}Ar loss in the initial heating steps, which is probably due to secondary alteration of the groundmass. The remaining heating steps show evidence for ^{39}Ar recoil. The oldest and youngest steps range between 115–93 Ma for DR.206.6 (Fig. 6a), and 137–119 Ma for DR.209.3 (Fig. 6b), and we consider these to be the maximum and minimum $^{40}Ar/^{39}Ar$ dates for each sample. Therefore, although there is some degree of uncertainty, the basaltic lavas on the eastern flank of the W7 segment are interpreted to have a crystallization age from the Early – mid Cretaceous.

4.1.2. Petrography and geochemistry

The nine basaltic rocks analyzed from the eastern flank of segment W7 on the West Scotia Ridge are transitional tholeiitic – calc-alkaline basalts; they are generally fine grained. The primary mineral phases are plagioclase and clinopyroxene, with compositions of An_{60-70} and augite respectively. The samples are characterized by Mg# values (Mg/(Mg+Fe) $*$ 100) of 44–64 and SiO_2 values of 49.8–54.9 wt% (Supplementary Table S3) and range in composition from basalt to basaltic andesite, but will be broadly referred to as basaltic in this paper.

The W7 basalts have FeO_T/MgO ratios >1 and modest Ni (<80 ppm) and Cr (<250 ppm) contents indicating that none of

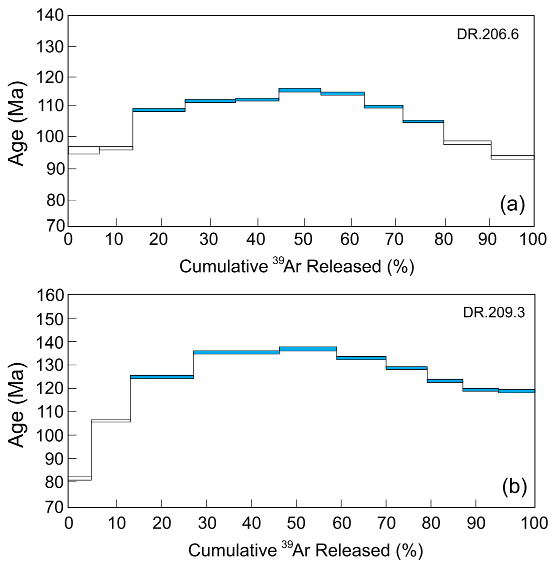

Fig. 6. ^{39}Ar release spectra for samples DR.206.6 (a) and DR.209.3 (b). Both samples generate a plateau, but do not reach the criteria of 3 release steps comprising 50% of the total release. The shading is considered to highlight the steps most affected by ^{39}Ar recoil.

the mafic rocks are primitive in composition. The chondrite normalized (Sun and McDonough, 1989) rare earth element (REE) abundances of the W7 basaltic rocks are weakly enriched in the light REE relative to the heavy REE, with La_N/Yb_N = 1.5–6.4 (Fig. 7a). Also plotted (Fig. 7b) are the REE abundances of a selection of basaltic rocks from the Scotia Sea region (Pearce et al., 2001). The comparative samples are dredged material from the Phoenix Plate, the East Scotia Ridge and also one sample from the W4 segment of the West Scotia Ridge (Fig. 2). The two more enriched samples with La_N/Yb_N values of ∼11 are from the Shackleton Fracture Zone (Fig. 1), whilst all other basaltic samples have La_N/Yb_N values of 1–2 and have MORB-like chemistry. The sample from the W4 segment of the West Scotia Ridge is highlighted in Fig. 7b and is seen to have a relatively flat REE profile in comparison to the basaltic rocks of the W7 segment. Four basaltic – basaltic andesite rocks from the Davis Bank and Barker Plateau reported by Pandey et al. (2010) are plotted in Fig. 7c and are light REE enriched with La_N/Yb_N = 6.0–7.9, akin to mafic lavas from an arc setting and partially overlapping with the basaltic rocks from W7.

The multi-element abundance plot, normalized to N-MORB (Sun and McDonough, 1989) is shown in Fig. 7d and the W7 samples have a pronounced trough at Nb–Ta and a minor trough at Zr–Hf. These features are generally typical of calc-alkaline magmas from island arc/continental margin settings. These same characteristics are observed in the basaltic andesites of the Davis Bank and Barker Plateau (Fig. 7e) and supports the conclusions of Pandey et al. (2010) that the basalts were emplaced in an active continental margin setting. Fig. 7f shows the multi-element variations for basaltic rocks from elsewhere in the Scotia Sea region (Pearce et al., 2001) including the highlighted sample from the W4 segment of the West Scotia Ridge. The majority of the basaltic rocks exhibit MORB-like chemistry with the exception of the two enriched samples from the Drake Passage margin (DR.62, DR.63; Fig. 2). One sample from the East Scotia Sea margin (DR.12.19) has a moderate trough at Nb–Ta, akin to the basaltic rocks from the W7 segment (this study). The basalt from the W4 segment (DR.7.3: Fig. 2) has MORB-like chemistry and is distinct to the basalts from the more northerly W7 segment.

One of the most useful diagrams to interpret basaltic rocks with 'arc-like' chemistry is the Th/Yb vs Nb/Yb plot (Fig. 8). The West Scotia Ridge basaltic rocks of the W7 segment are plotted alongside the MORB-OIB array of Pearce and Peate (1995) and the field of South Sandwich Island intra-oceanic arc lavas (Pearce and Peate, 1995) which can be assumed to have formed from an asthenospheric source because no pre-existing continental lithosphere is known to exist beneath the arc (Leat et al., 2002). Also plotted are the basaltic rocks from several localities across the Scotia Sea region (Pearce et al., 2001; Fig. 2). The samples of the Scotia Plate generally fall within the MORB-OIB array of Pearce and Peate (1995) including the sample from the W4 segment of the West Scotia Ridge. However, all nine samples from the W7 segment plot above the MORB-OIB array indicating a subduction modified component in their source. The basaltic rocks from the Davis Bank and Barker Plateau (Pandey et al., 2010) are also plotted in Fig. 8 and have trace element ratios typical of volcanic rocks from an arc setting and partially overlap with the most enriched W7 basalts.

4.2. North Scotia Ridge

The geochemical identity of some of the submarine sections of the North Scotia Ridge has been discussed by Pandey et al. (2010) who identified calc-alkaline volcanic rocks of basalt-rhyolite composition, typical of convergent plate margin settings. Although they had no direct geochronological control, they interpreted the dredged material to have formed during the Cretaceous arc volcanism of the Tierra del Fuegian Andes. They provided no information on any sedimentary or plutonic sections of the North Scotia Ridge.

Two samples from Barker Plateau (Fig. 5) have been selected here for geochronological analysis (Supplementary Table S4); a medium grained tonalite (DR.212.2) and a fine grained metasedimentary rock (DR.212.3) that are both interpreted to have been sampled in situ based on their fractured surfaces, the absence of any dropstone features such as striations and the occurrence of similar lithologies in the same dredge. The tonalite (DR.212.2) was dated using laser ablation U-Pb zircon geochronology and nine separate grains were analyzed, which yielded a concordia age of 49.6 ± 0.3 Ma (Fig. 9; MSWD = 0.23). Sample DR.212.3 is a fine grained metasedimentary rock and was investigated for its detrital zircon age profile. The age structure of DR.212.3 is shown in Fig. 10a and is characterized by two prominent Mesozoic peaks, of mid-Cretaceous and Early – Middle Jurassic age. The detrital zircon age profile of sample DR.212.3 is compared (Fig. 10) to the age structure of samples from South Georgia, Tierra del Fuego and a dredge sample of an in situ sandstone at Shag Rocks Passage (Fig. 10b–d) to examine any similarities along the entire length of the North Scotia Ridge. To assess the potential input from continental sources around the margins of the Weddell Sea (see supplementary Fig. S1), a composite age structure from several samples from the northern Antarctic Peninsula (Fig. 10e) are plotted, as are representative samples to examine the potential input from East Antarctica (Dronning Maud Land, Filchner Ice Shelf; Fig. 10f–g).

5. Discussion

5.1. West Scotia Ridge

The main phase of Scotia Plate oceanic lithosphere evolution took place in the interval, 30–6 Ma as a result of sea floor spreading on the West Scotia Ridge. Spreading on the most northerly segment W7 has been interpreted to have been active between magnetic anomalies C6 and C3A (ca. 20–6 Ma), with spreading on the entire West Scotia Ridge having ceased at approximately 6 Ma (Eagles et al., 2005).

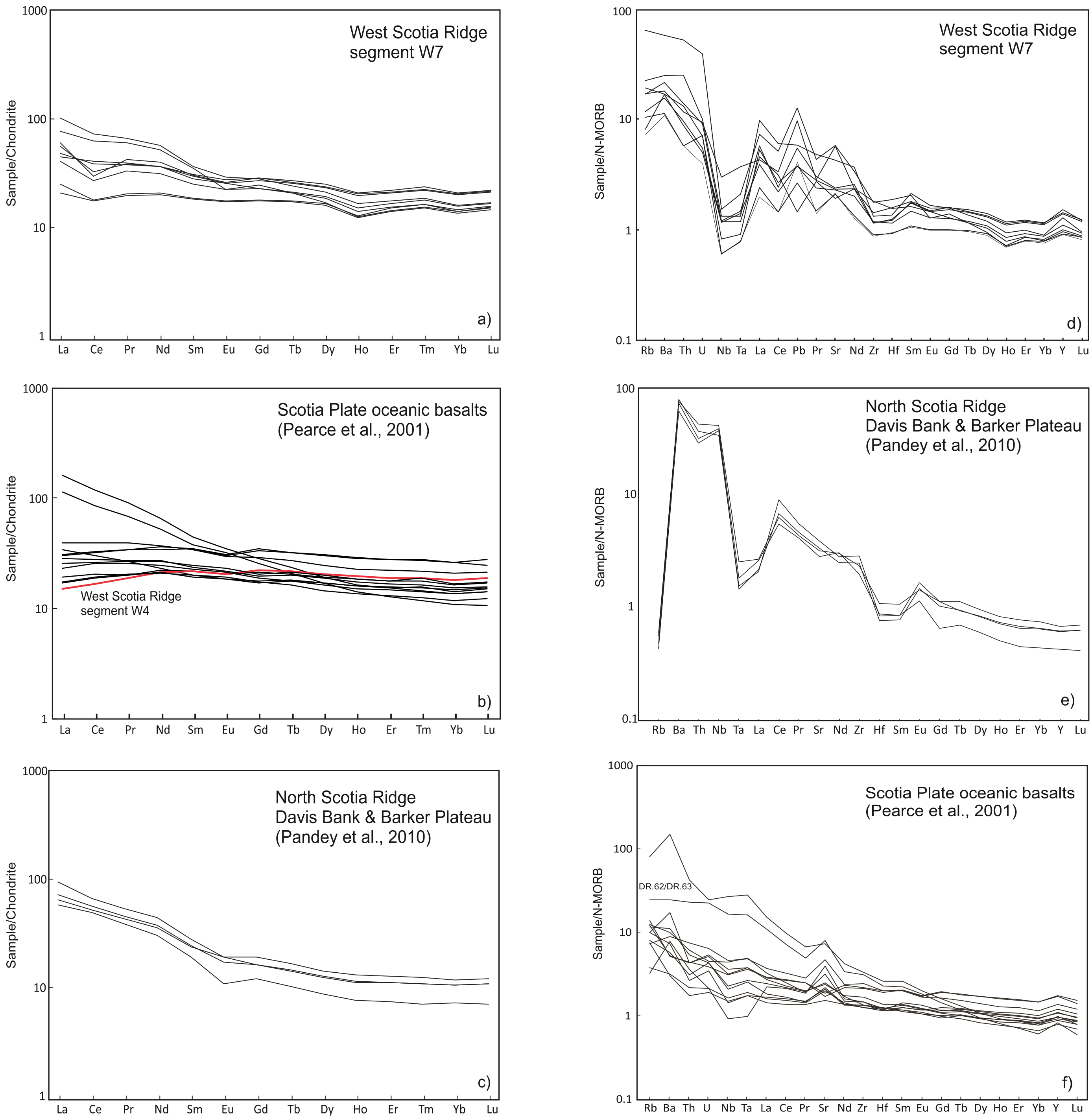

Fig. 7. Chondrite (Sun and McDonough, 1989) normalized REE diagrams for basaltic rocks from: (a) West Scotia Ridge W7 (this study); (b) Scotia Plate basalts (Pearce et al., 2001); (c) North Scotia Ridge (Pandey et al., 2010). Multi-element N-MORB (Sun and McDonough, 1989) normalized plots for basaltic rocks from: (d) West Scotia Ridge W7 (this study); (e) North Scotia Ridge (Pandey et al., 2010); (f) Scotia Plate basalts (Pearce et al., 2001).

The ages acquired as part of this study demonstrate that the geological history of the W7 segment of the West Scotia Ridge requires significant revision. Based on previous interpretations of the magnetic anomaly data (Eagles, 2010), ages of ∼6 Ma would be anticipated close to the W7 segment median valley and a maximum age of ∼17 Ma at ∼100 km from the segment axis based on even the slowest spreading rates (∼9 km/Myr). The sample sites described here are <20 km from W7 median valley (Fig. 5).

The ubiquity of basaltic samples from three separate dredge sites (DR.206, DR.207, DR.209), combined with their uniform geochemistry strongly indicates that the Early – mid Cretaceous ages reported here represent the age of basaltic lava crystallization on the eastern margin of segment W7. Combined with the distinct magnetic and free air gravity anomaly architecture of the W7 segment, there is a strong indication that the W7 segment does not represent a normal spreading segment of the West Scotia Ridge, and may be unrelated to ridge processes. Also, a re-examination of the sparse magnetic anomaly profiles across segment W7 suggest that they do not strongly correlate with either modeled profiles or anomaly data across segments to the south, indicating a distinct origin for the W7 segment.

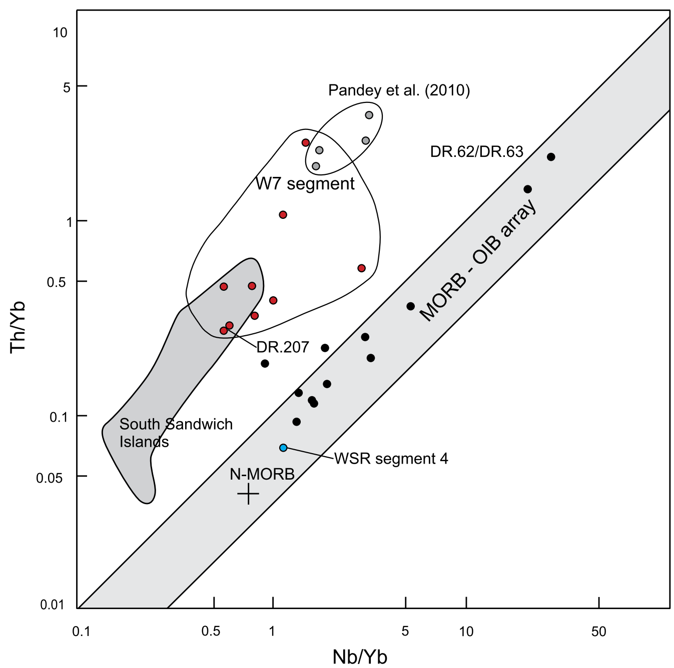

Fig. 8. Variations in Th/Yb vs. Nb/Yb showing the composition of mafic rocks from the Scotia Sea region relative to the MORB-OIB array (Pearce and Peate, 1995).

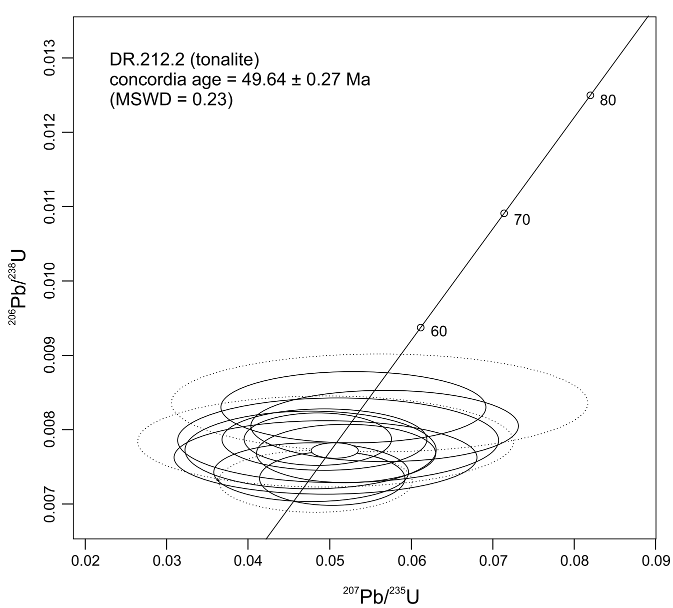

Fig. 9. Concordia diagram for tonalite sample, DR.212.2 from the Barker Plateau, North Scotia Ridge.

The likely interpretation of the newly presented geochronology and geochemistry is that the crust assigned to the W7 segment forms a tectonic part of the North Scotia Ridge, such that the Burdwood Fracture Zone represents the boundary between the oceanic plate formed at the West Scotia Ridge and the continental crust of the southern margin of the North Scotia Ridge (Fig. 5). A Cretaceous age for basaltic rocks of this region would be consistent with the interpretations of Pandey et al. (2010) who suggested the calc-alkaline basaltic andesite rocks of Davis Bank and Barker Plateau were akin to the Cretaceous Hardy Formation arc volcanic rocks of the Fuegian Andes. As the depth of the basaltic samples from the eastern flank of W7 are far greater (4200–3300 m) than the adjacent North Scotia Ridge (<2000 m depth), the W7 crust is considered to be a down-faulted and possibly extended part of the North Scotia Ridge lithosphere, as opposed to a Miocene spreading ridge.

To evaluate this, the newly acquired geochronology and geochemistry of the W7 region must be interpreted with respect to a potential active continental margin setting, as well as an ocean ridge spreading segment. There is very limited published geochemical data from the West Scotia Ridge with Pearce et al. (2001) analyzing a single sea floor basaltic sample from the W4 segment (Fig. 2) which was active from 24–10 Ma (Eagles et al., 2005). Pearce et al. (2001) reported N-MORB geochemical characteristics for the basalt from the W4 segment, consistent with its tectonic setting.

The basaltic rocks analyzed as part of this study are all from the eastern margin of the W7 segment of the West Scotia Ridge and are ∼50 km south of the southern escarpment of the east-west trending bathymetric North Scotia Ridge (Fig. 5). The two most primitive samples (MgO ∼7 wt%; Mg# ∼63; Cr ∼250 ppm) are from dredge site DR.207, which is the southernmost sample site on segment W7 (Fig. 5) and have flatter REE profiles than the more northerly samples. All other analyzed samples from the W7 segment have more enriched REE signatures relative to MORB (Fig. 7a–c), a characteristic that is also evident in the multi-element diagram and the Th/Yb vs Nb/Yb plot (Fig. 8). The multi-element plot (Fig. 7d–f) illustrates that the W7 segment basalts have trace element characteristics typical of island arc basalts, with pronounced negative anomalies in the high field strength elements at Nb–Ta and Zr–Hf, combined with enrichment in the large ion lithophile elements (Rb, Ba, Th, U). This is also evident in Fig. 8, which shows all of the W7 basaltic rocks are significantly displaced from the MORB-OIB array with Th values up to 6 ppm. Th-enriched compositions relative to the MORB-OIB array are typically indicative of a subduction component, as Th is mobile in subduction zone settings. The enrichment of Th relative to the similarly incompatible Nb is an effective proxy of the input of subduction modified crust into the magma source (Pearce, 2008). The West Scotia Ridge basalts of segment W7 have 'arc-like' Hf/Th ratios of 2–3, with those from site DR.207 having the highest values, but still considerably less than N-MORB values of ∼15 (Karsten et al., 1996).

Although subduction zone geochemical characteristics in ocean ridge basalts have been recognized from other sites where sea floor spreading is proximal to a continental margin (e.g. southern Chile Ridge; Karsten et al., 1996), in the case of the W7 segment, the geochemistry is likely to reflect a Cretaceous continental margin setting and not a hybrid magma between MORB and arc basalt.

Pearce (2008) investigated oceanic basalts from a range of global settings and demonstrated that almost all fall within the MORB-OIB array, reflecting N-MORB, E-MORB and OIB sources in the oceanic mantle. Pearce (2008) recognized that basalts erupted at rifting continental margins are similar to those in subduction zone settings are displaced to higher Th/Nb relative to the MORB-OIB array. Most basalts of the East Scotia Ridge and W4 segment of the West Scotia Ridge (Pearce et al., 2001) fall within the center of the MORB-OIB array which indicates a high degree of melting of relatively fertile mantle (E-MORB) or low degree melting of more depleted MORB mantle. However the mantle source for the W7 basalts is clearly distinct to the source for the W4 segment oceanic basalts and the more recent basalts of the East Scotia Ridge (Pearce et al., 2001). Combined with the newly acquired ages from the W7 region, which indicate magmatism occurred at ∼115 Ma and not 17–6 Ma as previously thought, it is clear that magmatism to the east of the W7 segment is not related to Miocene ocean spreading.

The age and origin of the crust of the northern part of the central Scotia Sea has been considered by several authors (e.g. Eagles, 2010) who, based on geophysical evidence, suggested it has a distinct history to the otherwise Eocene – Recent Scotia Plate.

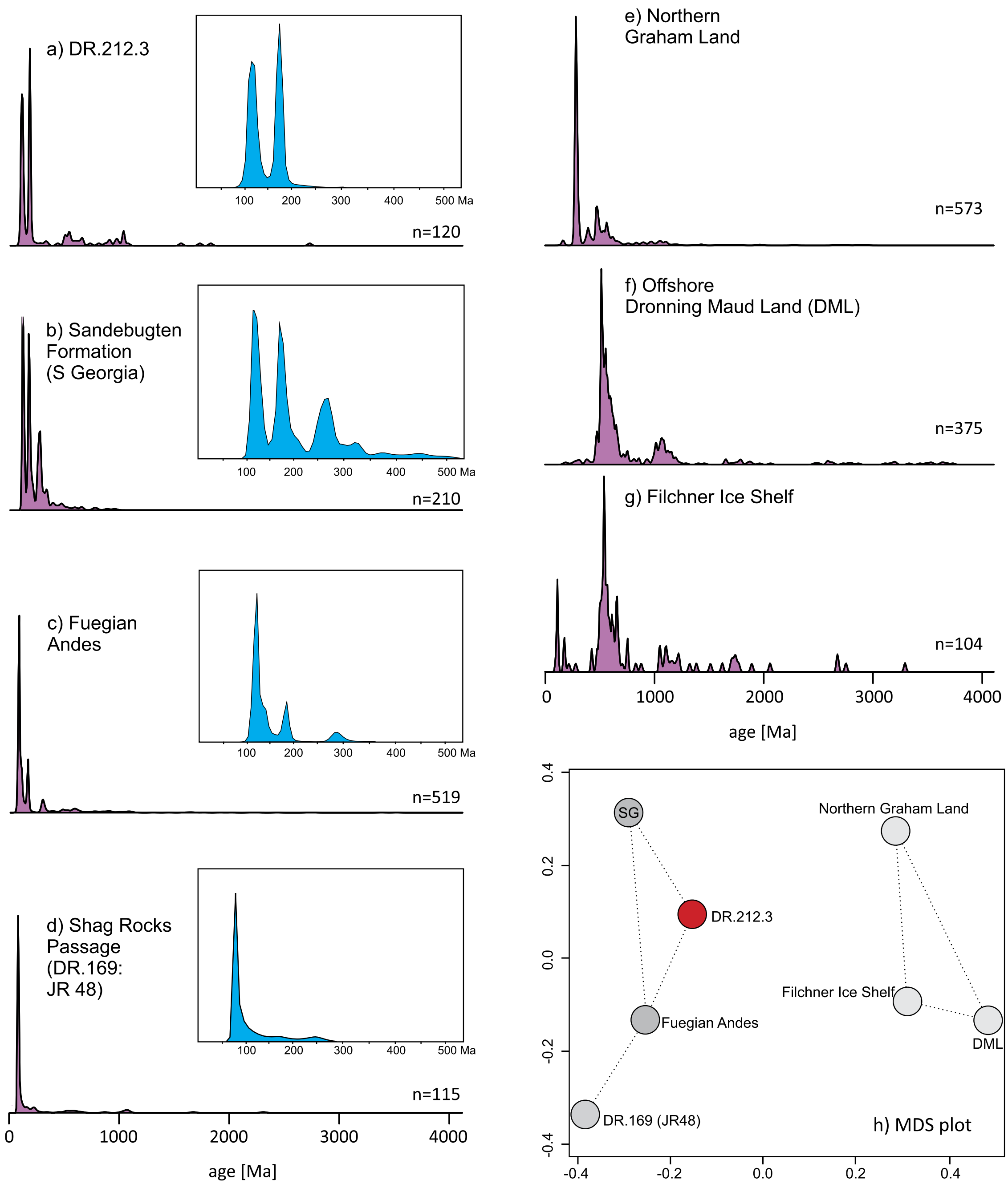

Fig. 10. Kernel density plots of detrital zircon ages for samples analyzed from (a) DR.212.3 Barker Plateau (this study Table S4); (b) Sandebeguten Formation, South Georgia (Carter et al., 2014); (c) Fuegian Andes (Barbeau et al., 2009b); (d) Shag Rocks Passage, JR48-DR.169 (unpublished data, see supplementary Table S4); (e) Northern Graham Land (Carter et al., 2017); (f) Offshore Dronning Maud Land (ODP 693; Carter et al., 2017); (g) Filchner Ice Shelf (Carter et al., 2017); (h) Multidimensional Scaling Maps (Vermeesch, 2013) comparing the age spectra in dissimilar samples from Fig. 10a–g; SG: Sandebugten Formation, South Georgia.

Eagles (2010) and Eagles and Jokat (2014) interpreted the central Scotia Sea as Cretaceous oceanic crust, whilst Dalziel et al. (2013b) and Pearce et al. (2014) suggested that it could represent Cretaceous oceanic crust overlain by a Cenozoic volcanic arc. Dubinin et al. (2016) interpreted the central Scotia Sea as extended continental crust. If part of the central Scotia Sea is Cretaceous oceanic crust, it is therefore older than the onset of West Scotia Ridge spreading and would have been tectonically 'captured' during Scotia Plate evolution (Eagles, 2010). The extent and origin of such 'captured' crust is uncertain, and an alternative suggestion for the W7 crust is that it represents a fragment of Cretaceous crust akin to the central Scotia Sea. The volcanic arc compositions of the dredge samples of W7 would suggest that they represent a previously unknown Cretaceous volcanic arc built on such oceanic crust.

5.2. North Scotia Ridge

The Fuegian Andes are the southern terminus of the 8000 km long Andean continental margin mountain belt (Fig. 1). The continental margin is interpreted to have extended for greater than 1000 km into the Antarctic Peninsula throughout the Mesozoic and early Cenozoic until the opening of the Drake Passage severed the continental land bridge and led to the development of the deep oceanic gateway.

The Patagonian-Fuegian magmatic arc is dominated by tonalities and gabbros of the Patagonian-Fuegian batholith and coeval volcanic arc rocks (Hervé et al., 2007). The magmatic arc is characterized by rocks of Late Jurassic to Neogene age with major pulses of magmatism at 150, 105 and 85 Ma (Hervé et al., 2007). Although magmatism of the Patagonian-Fuegian batholith was prominent during the Late Jurassic and Cretaceous, Cenozoic magmatism is also recorded (Poblete et al., 2016). During the Eocene, magmatism continued, but was coeval with a significant tectonic reorganization in southern South America and Drake Passage (Barbeau et al., 2009a; Poblete et al., 2016). This reconfiguration was associated with a significant shift in provenance for sediment input to the Magallanes foreland basin from the Patagonian-Fuegian batholith to the Cordilleran Darwin metamorphic complex (Barbeau et al., 2009a).

The age of the in situ tonalite (49.6 ± 0.3 Ma) recovered from site DR.212.2 on Barker Plateau supports the inference of Hervé et al. (2007) that Eocene magmatism was still ongoing at the time of reorganization of the Fuegian Andes and potentially the very early stages of Drake Passage opening and the expansion of the proto Scotia Sea at ∼50 Ma (Eagles et al., 2006; Lagabrielle et al., 2009). Eocene age granitoid magmatism has been reported by Poblete et al. (2016) from the Fuegian Andes and also from the adjacent South Shetland Island block where Paleocene – Eocene magmatism has been identified (Willan and Armstrong, 2002; Wang et al., 2009; Gao et al., 2017). Magmatism in this interval was coincident with the earliest stages of separation of the Antarctic Peninsula and South America.

U-Pb detrital zircon geochronology was carried out on sample DR.212.3, a fine grained metasedimentary rock from Barker Plateau (Fig. 10a). The detrital zircon age structure is plotted in Fig. 10a and exhibits a prominent mid-Cretaceous peak, which actually reflects two separate age populations at ∼105 Ma and ∼115 Ma. These two mid-Cretaceous age peaks are consistent with the identification of a Cretaceous magmatic flare-up event in the Antarctic Peninsula and Patagonia (Riley et al., 2018) with three distinct episodes of granitoid magmatism at 125, 115 and 105 Ma, leading to a significant increase in Cretaceous detrital material. The second prominent peak is Early – Middle Jurassic in age (182–170 Ma) and is likely to reflect detrital input from the Jurassic Chon Aike Province silicic volcanic rocks, which are widespread in Patagonia (Pankhurst et al., 2000) and West Antarctica (Riley et al., 2010).

This age structure of DR.212.3 is very close to that of the age structure from samples SG.389 and SG.394, volcaniclastic turbidite lithologies, from the Sandebugten Formation (Fig. 10b) on South Georgia (Carter et al., 2014). The Sandebugten Formation age profile also has prominent mid-Cretaceous and Early Jurassic peaks (Tobífera Formation), but is also characterized by a third major peak at ∼275 Ma, which is not present in the Barker Plateau dredge sample (DR.212.3). This Permian peak is likely to be related to detrital input from the Duque de York Complex (or offshore equivalents), a metasedimentary unit widely exposed in southern South America (Barbeau et al., 2009a). The detrital age structure from the Fuegian Andes (Barbeau et al., 2009a) is also characterized by two prominent Mesozoic peaks, which is particularly pronounced at ∼105 Ma (Fig. 10c). The Jurassic peak (∼170 Ma) from the Fuegian Andes is less pronounced but is likely to be associated with detrital input from the extensive rhyolitic ignimbrites of the Tobífera Formation of the broader Chon Aike Province (Pankhurst et al., 2000).

The dredge sample from Shag Rocks Passage (DR.169; British Antarctic Survey cruise JR48) is a sandstone lithology and is dominated by Late Cretaceous ages that peak at ∼72 Ma (Fig. 10d), but generally lacks a secondary mid-Cretaceous peak identified elsewhere along the North Scotia Ridge. Other minor ages span the Jurassic to late Triassic as well as a subset of Proterozoic ages. Late Cretaceous ages have been reported in the Dorotea Formation of the Magallanes foreland basin (Romans et al., 2010) and demonstrate that material from the magmatic arc was being transferred to the east at that time. Similarly, Late Cretaceous zircon ages have been reported in Rocas Verdes strata (Barbeau et al., 2009b).

All samples from the Fuegian Andes-North Scotia Ridge-South Georgia region are also characterized by a broad age profile through the Phanerozoic and Neoproterozoic likely reflecting a diverse range of recycled lithologies from metamorphic complexes in southern South America.

The prominent sources for the turbiditic and volcaniclastic sequences of the Fuegian Andes-North Scotia Ridge-South Georgia region are likely to be derived from either the Fuegian Andes region, Burdwood Bank, the northern Antarctic Peninsula or, less likely, sources from East Antarctica. Age profiles from the northern Antarctic Peninsula, offshore Dronning Maud Land and recovered sediment from the Filchner Ice Shelf are plotted in Fig. 10 alongside the North Scotia Ridge age profiles. The northern Antarctic Peninsula sample is a compiled age profile (Fig. 10e) from two volcaniclastic samples from the eastern coast (Carter et al., 2017). The combined profile has a dominant Permian age peak at 280 Ma, which is likely to be sourced from Permo-Carboniferous Trinity Peninsula Group of the northern and eastern Antarctic Peninsula (Fig. 1; Riley et al., 2011). The Trinity Peninsula Group of the Antarctic Peninsula is considered to be closely related to the Duque de York Complex of Patagonia (Barbeau et al., 2009a). However, the northern Antarctic Peninsula age profile lacks the prominent mid-Cretaceous peaks that are evident along the North Scotia Ridge, suggesting the northern and eastern Antarctic Peninsula are unlikely to be the detrital source for sedimentary rocks of the North Scotia Ridge.

The East Antarctic (offshore Dronning Maud Land and Filchner Ice Shelf; Carter et al., 2017) age profiles (Fig. 10f-g) are significantly different to the age structure of the Fuegian Andes-North Scotia Ridge region. They are characterized by prominent Pan African/Ross Orogeny age peaks (∼550 Ma) and a broad signal of Proterozoic – Archean ages reflecting the cratonic geology of East Antarctica (Pierce et al., 2014). A multidimensional scaling map (MDS; Vermeesch, 2013) is shown in Fig. 10h and compares the age spectra of those samples displayed in Fig. 10a–g. This approach provides a robust test of the relationship between sample areas and identifies those areas that are likely to share a common detrital source region. The MDS map (Fig. 10h) interrogates samples from across the Weddell-Scotia Sea region and identifies a close similarity between the dredge sample from the Barker Plateau (DR.212.3) and the samples from South Georgia (SG) and the Fuegian Andes, whilst the dredge sample DR.169 from Shag Rocks Passage exhibits a weaker similarity. However, there is a clear dissimilarity to the circum-Weddell Sea lithologies from the northern Antarctic Peninsula and those from East Antarctica, which makes any detrital contribution from these more distal sources unlikely, although there is close internal similarity between the Filchner Ice Shelf and offshore Dronning Maud Land samples. The data therefore overwhelmingly indicate a detrital source from the Fuegian Andes/Burdwood Bank region of southern South America.

Barbeau et al. (2009a) divided the Fuegian Andes region into five tectonstratigraphic units as distinct source regions for detrital zircon: i) Southern Andean metamorphic complexes; ii) Gondwana dispersal magmatic rocks; iii) Rocas Verdes Basin; iv) Patagonian-Fuegian magmatic arc; v) Magallanes foreland basin and thrust belt. The primary sources of detrital zircon for the North Scotia Ridge lithologies are likely to come from the Patagonian-Fuegian magmatic arc, which was active from the Late Jurassic to the Neogene (Hervé et al., 2007), with a magmatic 'flare-up' during the mid-Cretaceous (Riley et al., 2018). A secondary source for Cretaceous detrital material would be the Magallanes foreland basin and thrust belt, which accumulated a thick succession of Cretaceous – Paleogene sediments in a deltaic fan-shallow marine setting. Detrital zircons recovered from Upper Cretaceous sediments of the Magallanes Basin are dominated by a 150–90 Ma population (Barbeau et al., 2009a).

The Early – Middle Jurassic detrital zircon population can be attributed to the Gondwana dispersal tectonostratigraphic unit of silicic volcanic rocks and granitoids. This unit includes silicic volcanic rocks of the extensive Chon Aike Province (Pankhurst et al., 2000) and the Darwin intrusive suite (Barbeau et al., 2009a). The volcanic rocks of the Chon Aike Province are locally represented by the Tobífera Formation (∼174 Ma; Pankhurst et al., 2000), but the age span of the entire province ranges from 185–155 Ma with three distinct magmatic peaks at 184, 170 and 155 Ma (Pankhurst et al., 2000).

The Permian signal identified from South Georgia, but which is far less significant elsewhere along the North Scotia Ridge can be attributed to the Southern Andean metamorphic complexes, particularly the contribution from the Permian Duque de York metasedimentary rocks of southern Patagonia.

6. Conclusions

i) U–Pb detrital geochronology provides strong evidence that the submerged sections of the North Scotia Ridge share a geological affinity with South Georgia and the Fuegian Andes and not with the Antarctic Peninsula or East Antarctica. The detrital zircon geochronology indicates that deposition was likely to have been during the Late Cretaceous given the age of the youngest zircon grains.

ii) An in situ tonalite intrusion on the Barker Plateau has been dated at 49.6 ± 0.3 Ma and supports the continued magmatism of the Patagonian-Fuegian batholith into the Eocene. This granitoid intrusion was likely to have been emplaced shortly before the initial stages of opening of the Drake Passage.

iii) $^{40}Ar/^{39}Ar$ dating of basaltic rocks from the eastern flank of the W7 segment of the West Scotia Ridge yield Early – mid-Cretaceous ages demonstrating that previous models of Miocene seafloor spreading on the W7 segment need to be reassessed.

iv) Basalts from the W7 segment of the West Scotia Ridge have geochemical signatures typical of arc-like basalts, as opposed to MORB, which is in agreement with the new age data and supports a non-spreading center origin. The basalts of W7 are likely to be related to the Cretaceous arc of the Fuegian Andes, which is consistent with similar lithologies reported from the Davis Bank and Barker Plateau (Pandey et al., 2010). This suggests that segment W7 is a down-faulted crustal block of the North Scotia Ridge.

v) A potential alternative hypothesis is that the Cretaceous basaltic rocks of the W7 segment represent a previously unknown volcanic arc built on an extension of the adjacent Cretaceous oceanic crust of the Central Scotia Sea (Eagles, 2010). This is consistent with their depth at up to 4200 m.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2019.04.031.

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