



Provenance of continental blocks in the southern Scotia Sea using detrital zircon U—Pb geochronology

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ABSTRACT

Reconstructions of the opening of the Scotia Sea and the Drake Passage oceanic gateway have traditionally been based on considerations of ocean spreading and rifting between crustal blocks, and geological correlations based on sequences on islands such as South Georgia and the South Orkney Islands. Detrital zircon U—Pb geochronological data derived from dredged schists and sandstones from two submerged continental blocks in the southern Scotia Sea, Bruce Bank and Discovery Bank, provide further constraints on the origin and tectonic movement of the blocks and confirm the use of detrital geochronology for understanding the tectonic evolution of the Scotia Sea. Bruce Bank yielded greenschist facies schist with a Triassic maximum sedimentation age of 216.2 Ma, similar to schist dredged from the northern continental margin of the adjacent South Orkney microcontinent. Both schists are correlated with metamorphic rocks of an accretionary complex exposed on the South Orkney Islands. Sandstones with Permian to Triassic maximum sedimentation ages of 258–224 Ma were dredged from both the northern margin of the South Orkney microcontinent and Discovery Bank. A younger sedimentary unit with Cretaceous maximum sedimentation ages of 140–110 Ma has been recovered from both Bruce and Discovery banks. The new data are consistent with the interpretations that Bruce and Discovery banks were joined in mid-Cretaceous times and that both were proximal to the South Orkney Islands in a position on the paleo-Pacific margin of Gondwana before Late Cretaceous–Cenozoic rifting, translation of the crustal blocks, and formation of the Scotia Sea.

1. Introduction

The region of the Scotia Sea is critical for understanding southern hemisphere environmental and biological evolution during the Cenozoic era. Opening of the Drake Passage seaway ruptured a land bridge between South America and Antarctica which was a final stage of break-up of the Gondwana supercontinent. Opening of the seaway allowed development of the Antarctic Circumpolar Current, which was a contributing factor in development of Antarctic continent-wide glaciation (Kennett, 1977; Livermore et al., 2005; Lagabrielle et al., 2009; Dalziel et al., 2013a; Dalziel et al., 2013b; Maldonado et al., 2015; Martos and Catalán, 2024). Most of the Scotia Sea is underlain by the Scotia plate, most of which is oceanic lithosphere (Fig. 1). Ocean crust formed along the West Scotia Ridge between ca. 30 Ma and 6 Ma occupies most of the western part of the Scotia plate and the eastern part of the plate is formed from oceanic lithosphere formed along the active

East Scotia Ridge (Livermore et al., 2005; Eagles and Jokat, 2014; Maldonado et al., 2014; van de Lagemaat et al., 2021).

As well as oceanic crust, the Scotia plate includes shallow banks and ridges of continental origin. The northern margin of the Scotia plate trends along the North Scotia Ridge and the South Georgia microcontinent, which have South American affinities (e.g., Dalziel et al., 2013a; Carter et al., 2014; Riley et al., 2019).

The southern margin of the Scotia plate is also marked along most of its length by a submarine ridge, the South Scotia Ridge (Fig. 1). The South Orkney microcontinent is located south of the Ridge. Rising from within the microcontinent, the South Orkney Islands are the only islands within the southern Scotia Sea. North of the Ridge, the southern part of the Scotia plate is characterized by a series of blocks thought to be of continental origin and expressed as shallow banks, from west to east; Terror Rise, Pirie Bank, Bruce Bank, Discovery Bank and Herdman Bank, all separated by extensional troughs (e.g., Galindo-Zaldívar et al., 2002;

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Vuan et al., 2005; Bohoyo et al., 2007). The banks have a cover of Cenozoic sediments, and few samples have been recovered from underlying lithologies. As a result, the origin and movement of these blocks as the Scotia Sea region was extended has been poorly constrained. Reconstruction of oceanic spreading along the West Scotia Ridge and extensional rifts separating the blocks has been used to suggest origins within the Gondwana margin, and specifically along the southern margin of the South American continent (Dalziel et al., 2013a; Dalziel et al., 2013b; van de Lagemaat et al., 2021) or clustered further south within the margin, close to the South Orkney microcontinent (Galindo-Zaldívar et al., 2014; Gao et al., 2023; Riley et al., 2023; Schellart et al., 2023).

Detrital zircon U—Pb geochronology provides an opportunity to evaluate these competing models. The methodology has been used in reconstruction of origins and tectonic movements of continental elements of the North Scotia Sea (Carter et al., 2014; Riley et al., 2019). Riley et al. (2022) used U—Pb geochronology of zircon grains in three sandstones from Bruce Bank to suggest that the underlying block contains continuations of the geology of the South Orkney microcontinent. In this paper, we build on the success of this technique, using new petrological and zircon U—Pb geochronological data from metapelites and sandstones recovered by dredges from the South Orkney microcontinent, Bruce Bank and a fault-bounded continental block forming the eastern part of Discovery Bank to comment on the age, evolution and origin of the submerged continental blocks.

2. Geological setting

2.1. South Orkney microcontinent

The block has a continental character (King and Barker, 1988) and is the largest in the southern Scotia Sea, measuring 300 km east-west and 200 km north-south. A crustal thickness of up to 26.5 km has been modelled from geophysical data (Morales-Ocaña et al., 2023). It has a characteristically flat continental shelf with depths of 200–500 m, an area of 48,000 km² and has been strongly glaciated apart from the southern, deeper part of the shelf (Dickens et al., 2014). The microcontinent rifted from the northern part of the Antarctic Peninsula to form the oceanic Powell Basin at ca. 30–22 Ma (King and Barker, 1988;

Eagles and Livermore, 2002). Although the South Orkney Islands form less than 2% of the area of the microcontinent, geological interpretations of the block have inevitably heavily depended on examinations of outcrops on the islands. Stratigraphically, the South Orkney Islands consist of a late Paleozoic to Mesozoic basement complex consisting of deformed schists and lower grade metasedimentary rocks which are unconformably overlain by Mesozoic, generally coarse grained fluvialite and shallow marine clastic sequences (Matthews and Mayling, 1967; Thomson, 1973; Thomson, 1974; Thomson, 1981; Elliot and Wells, 1982; Dalziel, 1984; Trouw et al., 1997).

Basement rocks in the South Orkney Islands are included within the Scotia metamorphic complex, a group of metamorphosed rock units distributed in the southern Scotia Sea and attributed to subduction accretion (Tanner et al., 1982; Dalziel, 1984). In the western and central parts of the islands, the group comprises a Metamorphic Complex dominated by quartz-mica schists largely consisting of quartz, albite, chlorite, muscovite, biotite and garnet with subordinate marbles, quartzites and amphibolites (Matthews and Mayling, 1967; Thomson, 1968; Thomson, 1971; Storey and Meneilly, 1985). Metamorphic grade is from greenschist to epidote-amphibolite and amphibolite facies (West, 1968; Thomson, 1974; Dalziel et al., 1981; Storey and Meneilly, 1985). Structurally, the Complex is dominated by NNW-directed ductile thrusting (Meneilly and Storey, 1986; Maestro et al., 2013) and is interpreted as a series of oceanic successions deformed and metamorphosed in an accretionary complex associated with SSE-directed (present orientation) subduction at the Pacific-Gondwana margin. In the eastern part of the islands, the group consists of a Greywacke-Shale Formation consisting of stratified metasandstones, metasilts and metapelites deposited by turbidites and metamorphosed at prehnite-pumpellyite to greenschist facies (Thomson, 1973; Trouw et al., 1997). The turbidites are interpreted as dominated by continental slope successions (Trouw et al., 1997), although oceanic chert is also present (Dalziel et al., 1981). There is a structural and metamorphic transition between these turbidites and the Metamorphic Complex; folding and lineations in the Formation are similarly interpreted as resulting from south-directed subduction (Dalziel, 1984; Trouw et al., 1997).

U—Pb zircon dates from two samples of the Metamorphic Complex have Permian peaks at ca. 270 Ma, secondary Neoproterozoic-Cambrian

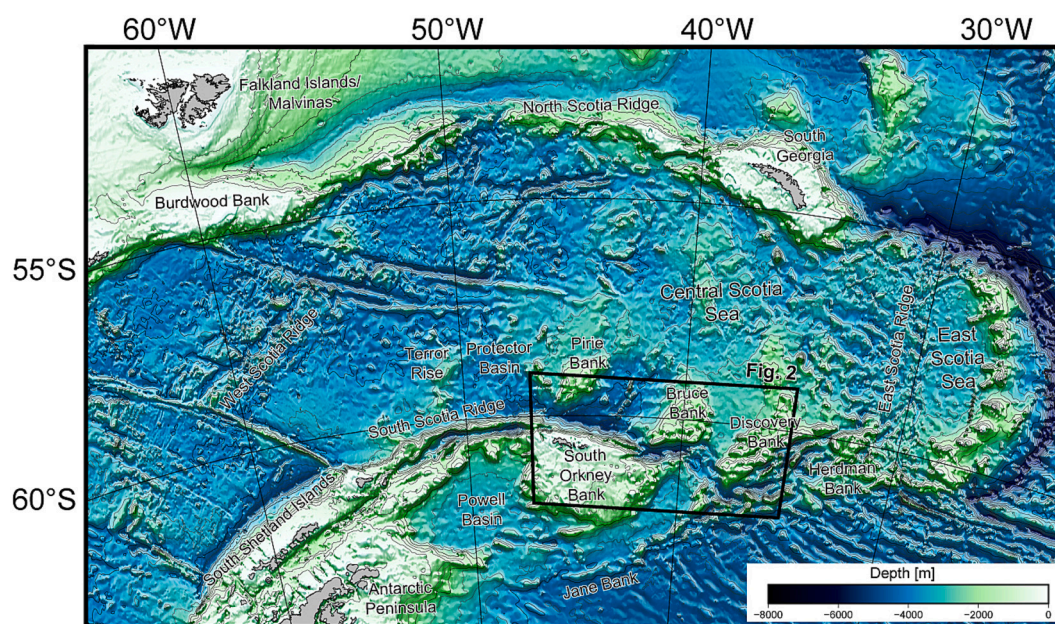


Fig. 1. Map of the Scotia Sea showing the location of the South Orkney Islands, Bruce Bank and Discovery Bank. Bathymetric data are derived from the NOAA ETOPO 2022 15 Arc-Second Global Relief model (NOAA National Centers for Environmental Information, 2022).

peaks, and youngest zircon ages of ca. 250 Ma (Carter et al., 2017), suggesting latest sedimentation was approximately Early Triassic in age. This is somewhat older than the Late Triassic sedimentation age for the Greywacke-Shale Formation derived from Radiolaria in chert (Dalziel et al., 1981). An Early Jurassic age of ca. 195–185 Ma for deformation and metamorphism of the Metamorphic Complex was interpreted from amphibole K–Ar ages on schists by Tanner et al. (1982), and Ar–Ar data produced a similar result (Grunow et al., 1992). Flowerdew et al. (2007a) produced an average muscovite mineral Rb–Sr isochron age of 190 ± 4 Ma which they suggested reliably dates the formation of the foliation and thus the subduction accretion of the Metamorphic Complex.

The accretionary complex has similar zircon age populations to those of the Trinity Peninsula Group which forms much of the northern part of the Antarctic Peninsula, and which was proximal prior to opening of Powell Basin. This Group comprises weakly metamorphosed, turbiditic, siliciclastic marine sedimentary rocks, thought to represent Carboniferous to Triassic sedimentation in a marginal basin along the Pacific margin of Gondwana with a source dominated by a late Paleozoic magmatic province (Barbeau et al., 2009a; Castillo et al., 2016).

Clastic strata unconformably overlying the metamorphic rocks in the South Orkney Islands are Jurassic to Cretaceous in age (Thomson, 1981; Cantrill, 2000). The terrestrial Powell Island Conglomerate and the younger partly marine Spence Harbour Conglomerate are up to 400 m thick, coarse-grained and interpreted as proximal alluvial fan deposits (Elliot and Wells, 1982; Wells, 1984). Previous dredges from the margins of the South Orkney microcontinent retrieved Cenozoic–Recent alkaline mafic lavas possibly related to Powell Basin rifting as well as calc-alkaline volcanic rocks of Late Cretaceous age (Barber et al., 1991).

2.2. Bruce Bank

Bruce Bank is situated north of the transform plate boundary between the Antarctic and Scotia plates, which separates it from the South Orkney microcontinent. The plate boundary south of the bank is a trough that extends to a depth of 6000 m (Fig. 2). Bruce Bank is ca. 170 km across in a N–S direction and 150 km E–W. Dove Basin, to the west and Scan Basin to the east are both oceanic (Bohoyo et al., 2007; Galindo-Zaldívar et al., 2014; Pérez et al., 2019). Bruce Bank has a

typical depth of 1000 m, forming a flat, sedimented plateau. Seismic and gravity data have been interpreted to suggest that the bank is underlain by thinned continental crust (Galindo-Zaldívar et al., 2014; Pérez et al., 2014); Morales-Ocaña et al. (2023) modelled a crustal thickness of 18 km for the crustal block. Riley et al. (2022) reported zircon U–Pb ages from two metasedimentary rock samples from the southern margin of the Bank and demonstrated that they have similar zircon age populations to metamorphic and sedimentary successions of the South Orkney Islands, characterized by similar Permian and Cambrian age peaks. They also determined zircon U–Pb ages for a silty sandstone from the eastern margin of Bruce Bank, demonstrating that it has a different detrital zircon age profile, dominated by Mesozoic age peaks of 185 and 128 Ma. Mafic igneous rocks dredged from the eastern margin of the Bank are calc-alkaline, dated at 79–53 Ma by Ar–Ar geochronology (Riley et al., 2023).

Bruce Bank is separated from Discovery Bank by the 3000 m deep Scan Basin. This strongly sedimented basin, formed by oceanic spreading, is 40 km wide in the south, widening to ca. 120 km wide in the north, and has an axial length of 250 km (Hernández-Molina et al., 2007; Pérez et al., 2014; Pérez et al., 2019). Magnetic anomalies have been modelled to indicate oceanic spreading took place along a NW–SE trending spreading center during the interval ca. 35–29 Ma (Schreider et al., 2017), which is in close agreement with an age of 30.2 Ma for basin formation derived from heat flow (Barker et al., 2013).

2.3. Discovery Bank

Discovery Bank is the largest fully submerged bank in the southern Scotia Sea, has an irregular plan elongated in a NE–SW direction, has a 350 km long NE–SW axis, is 88 km across from East to West (Fig. 2), and rises to a depth of 700 m. The northern part of the bank has subdued topography and its boundary with the adjacent crust of the Central Scotia Sea is poorly defined. On its western flank, the bank slopes gradually toward Scan Basin. By contrast, the southeastern margin of the bank is a steep fault scarp facing a transtensional bend in the Antarctic–Scotia plate boundary. A prominent horst-shaped block to the east is thought to have rifted from Discovery Bank by extension within this transtensional bend. Several smaller blocks further to the SE are thought to have had a similar origin (Lodolo et al., 2010).

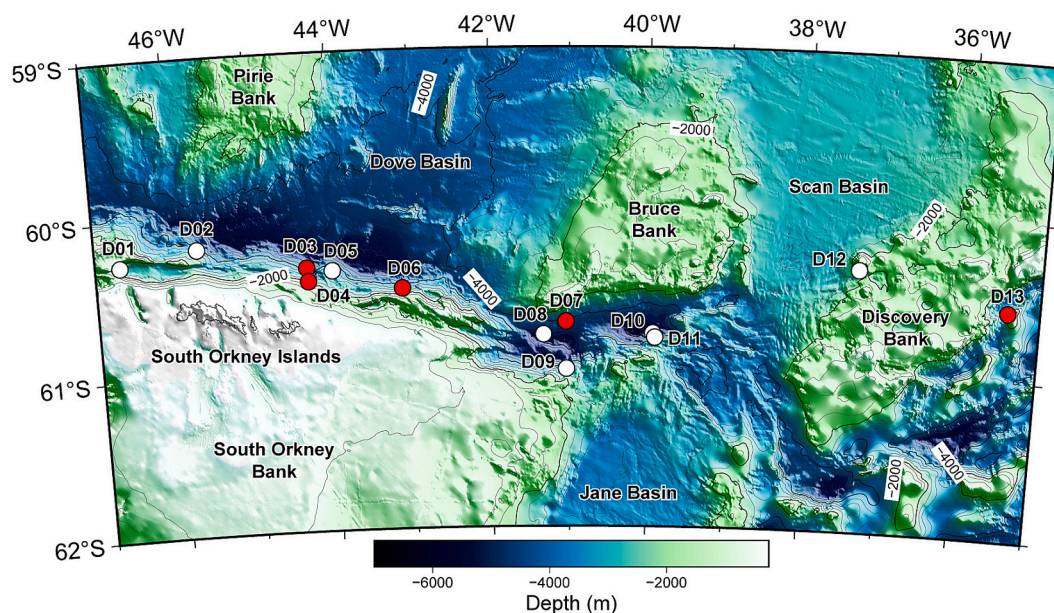


Fig. 2. Map showing dredge sites from the KH-19-6 Leg 4 cruise. Red circles indicate the locations of samples analyzed in this study. White dots are other sites sampled during the same cruise. Bathymetric data are the same as in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The bank is considered to be underlain dominantly by thinned continental crust, based on its shallow bathymetry, seismic characteristics and density derived from gravity data (Vuan et al., 2005; Galindo-Zaldívar et al., 2002; Bohoyo et al., 2007; Lodolo et al., 2010). The southeastern part of the crustal block and the faulted blocks to the SE have denser crust and are recognised as an intermediate domain interpreted as having been strongly influenced by suprasubduction magmatism (Galindo-Zaldívar et al., 2002). A crustal thickness of approximately 15 km has been modelled from gravity data for both the continental crust and intermediate domains (Galindo-Zaldívar et al., 2002; Bohoyo et al., 2007).

Dredges from the eastern scarp of Discovery Bank have yielded abundant volcanic material consisting of lavas and volcanoclastic deposits. K–Ar ages for the volcanic rocks are in the range ca. 20–12 Ma (Barker et al., 1982), but Ar–Ar geochronology yielded younger ages of ca. 14–10 Ma (Riley et al., 2021). The volcanic rocks are dominantly mafic and have incompatible trace element compositions of the island arc tholeiitic series. Tectonic considerations strongly suggest that the magmatic arc was related to subduction of oceanic plate to the NW beneath Discovery Bank, and that this arc was within the southern part of an ancestral South Sandwich volcanic arc which occupied the eastern part of the developing Scotia Sea from around 28 Ma (Dalziel et al., 2013b; Pearce et al., 2014; Riley et al., 2021). Most topographic expressions of this volcanic arc on Discovery Bank appear to have been removed by erosion to form a peneplain. No samples of continental crust that may underlie the volcanic rocks or that form the crust of the western part of Discovery Bank have previously been recovered.

3. Sampling

Samples were obtained during cruise KH-19-6 Leg 4 of RV Hakuho Maru in December 2019 and January 2020. The sites (Fig. 2) described here were sampled with a steel box dredge (Satsuki-type) which gathers detached rocks or those loosely attached to outcrops from the seafloor. It had a sharp front blade for cutting into rock and a sprung front gate to prevent sample loss. The dredge assembly was weighted by an additional 200 kg to increase pressure on the seafloor. A depth logger was installed inside the dredge to monitor its movement. A video camera was fitted to the chain approximately 3 m above the dredge to record behaviour of the assembly while on the seafloor and capture images of outcrops. All recovered rock samples were washed, weighed and measured, cut by rock saw, and described on the ship.

4. Analytical methods

4.1. Scanning Electron Microscope analysis

Examinations of the mineral contents and quantitative analysis of feldspar, garnet and compositions of other phases in the samples, were carried out using a JEOL JSM-6610 Scanning Electron Microscope (SEM) equipped with energy dispersive X-ray spectrometer (EDS) at the National Museum of Nature and Science (NMNS) at Tsukuba, Japan.

4.2. U–Pb geochronology

Zircon grains for U–Pb geochronology were separated from nine samples using a high voltage pulse power fragmentation system (SELFRAG) using a 750 µm disposable mesh at the NMNS. Heavy minerals were concentrated by panning and further purified using a Neomag 8000 hand magnet. The non-magnetic fraction was further concentrated using a heavy liquid (diiodomethane). For most samples, approximately 70–140 randomly selected zircon grains were hand-picked under a binocular stereo microscope and mounted in polished epoxy resin blocks. However, two schist samples, D06-R05 and D07-R13, had low zircon abundances and 43 and 34 zircon grains, respectively, were identified and mounted.

Sample discs were polished down to the center of the zircon grains, and cathodoluminescence (CL) and backscattered electron (BSE) images were taken using a JEOL JSM-6610 SEM at the NMNS. The U–Pb isotope dating was conducted using an NWR213 laser ablation system and an Agilent 7000× ICP–MS at the NMNS. Spot sizes for analysis had diameters of 25 µm, and laser energy was 2.41 J/cm². Zircon rims free of inclusions and cracks were selected for analysis. The sample U–Pb measurements were calibrated against zircon standard TEMORA-2 (417 Ma; Black et al., 2004) and abundances of U and Th were calibrated against the NIST SRM 610 glass standard. Experimental conditions, measurement procedures, and data reduction followed those of Tsutsumi et al. (2012). Common-Pb corrections were performed using two approaches. Pb* indicates common-lead-corrected radiogenic Pb. For zircons older than 1000 Ma, ²⁰⁷Pb*/²⁰⁶Pb* ages were corrected using the ²⁰⁸Pb-correction method (Williams, 1998). An uncorrected ²⁰⁶Pb/²³⁸U age was first used together with the measured Th/U ratio to calculate the expected radiogenic ²⁰⁸Pb*/²⁰⁶Pb* ratio, assuming concordance between the U–Pb and Th–Pb systems. The common-Pb ²⁰⁷Pb/²⁰⁶Pb and ²⁰⁸Pb/²⁰⁶Pb compositions at this age were calculated using the two-stage Pb-evolution model of Stacey and Kramers (1975). The measured ²⁰⁸Pb/²⁰⁶Pb ratio was then treated as a mixture of radiogenic and common Pb to estimate the fraction of common ²⁰⁶Pb, which was subsequently used to calculate the common-Pb-corrected ²⁰⁶Pb*/²³⁸U and ²⁰⁷Pb*/²⁰⁶Pb* ratios.

For zircons younger than 1000 Ma, ²⁰⁶Pb*/²³⁸U ages were calculated using the ²⁰⁷Pb-correction, in which the common-Pb contribution is estimated assuming concordance between the ²⁰⁶Pb/²³⁸U and ²⁰⁷Pb/²³⁵U systems. The ²⁰⁷Pb-corrected ²⁰⁶Pb*/²³⁸U ages were also used for the detrital-zircon age distributions, youngest single-grain ages, and YC1σ maximum depositional ages. Concordance was assessed from the difference between paired age estimates. For zircons dated using ²⁰⁷Pb*/²⁰⁶Pb* ages, discordance was calculated as $\{1 - (^{206}\text{Pb}^*/^{238}\text{U age}) / (^{207}\text{Pb}^*/^{206}\text{Pb}^* \text{ age})\} \times 100$, whereas for zircons dated using ²⁰⁶Pb*/²³⁸U ages, concordance was evaluated from the corresponding ²⁰⁶Pb*/²³⁸U and ²⁰⁷Pb*/²³⁵U ages in the same manner. Analyses for which the two age estimates differed by ≥15% were regarded as discordant and excluded. Concordia and kernel density diagrams were produced and weighted means were calculated using the IsoplotR program (Vermeesch, 2018). Weighted mean ²⁰⁶Pb*/²³⁸U age of the secondary zircon standard OD-3 analyzed during the analytical sessions was 32.25 ± 0.56 Ma (95% confidence interval, *n* = 34, MSWD = 1.85), which is in agreement with the reported reference age of 33.0 ± 0.1 Ma (Iwano et al., 2013). Weighted mean ²⁰⁷Pb*/²⁰⁶Pb* age of the secondary zircon standard FC-1 also analyzed during the sessions was 1098.5 ± 9.2 Ma (*n* = 59, MSWD = 0.96), in agreement with reference age of 1099.0 ± 0.6 Ma (Paces and Miller, 1993).

5. Results

Table 1 summarizes locations, youngest single zircon grain age (YSG) and the weighted mean of the youngest cluster of two or more grain ages that overlap in age within a 1σ error (YC1σ) (Dickinson and Gehrels, 2009), which is commonly used to show the older limit of deposition age. Full U–Pb data for the analyzed zircons are presented in supplementary file Table 1. CL images of the analyzed zircons are in supplementary file Fig. 2. The uncorrected Tera–Wasserburg diagrams (Fig. 3) show generally limited displacement from concordia for most samples, although a greater spread toward common-Pb compositions is observed for D13-R03. The uncorrected isotopic ratios and corresponding common-Pb-corrected values are provided in supplementary file Table 1. Kernel density estimates (KDE) and histograms displaying the full range of zircon U–Pb age distributions is presented in supplementary file Fig. 1. CL images of the zircon grains showing all analyzed spots are shown in supplementary file Fig. 2.

Images captured by the video camera indicate that most of the dredge sites were characterized by dense, poorly sorted accumulations

Table 1
Summary of dredge locations and zircon U—Pb analyses of samples from the southern Scotia Sea.

Sample No.	Location		Water Depth (mbsl)	n of analyzed grains		YSG	YC1σ	n	MSWD
	Lat (°S)	Long (°W)		All	Conc.	Age (Ma)	Age (Ma)		
D03-R16	60.349	44.326	4825–4551	93	93	217.59 ± 4.48	224.7 ± 2.5	3	1.9
D04-R02	60.433	44.311	2438–2255	101	101	230.52 ± 5.34	258.34 ± 0.79	32	6.2
D06-R05	60.496	43.124	3332–2717	43	43	221.41 ± 3.23	222.2 ± 2.6	2	0.16
D07-R12	60.719	41.045	4076–3827	70	69	106.34 ± 2.36	110.63 ± 0.84	7	1.1
D07-R13	60.719	41.045	4076–3827	34	34	214.44 ± 3.30	216.2 ± 2.1	2	0.48
D13-R02	60.565	35.412	2479–2036	75	74	113.67 ± 3.93	117.01 ± 0.75	8	2.8
D13-R03	60.565	35.412	2479–2036	101	100	126.81 ± 3.05	140.30 ± 0.45	36	8.9
D13-R04	60.565	35.412	2479–2036	74	73	228.00 ± 3.71	258.48 ± 0.93	21	14
D13-R11	60.565	35.412	2479–2036	126	126	256.29 ± 5.97	283.03 ± 0.44	105	8.8

Errors are 1σ, mbsl: meters below sea level, Conc.: concordant, YSG: The youngest single grain age.
YC1σ: the weighted mean of the youngest cluster of more than two grain ages that overlap in age within a 1σ error, MSWD: mean square weighted deviation

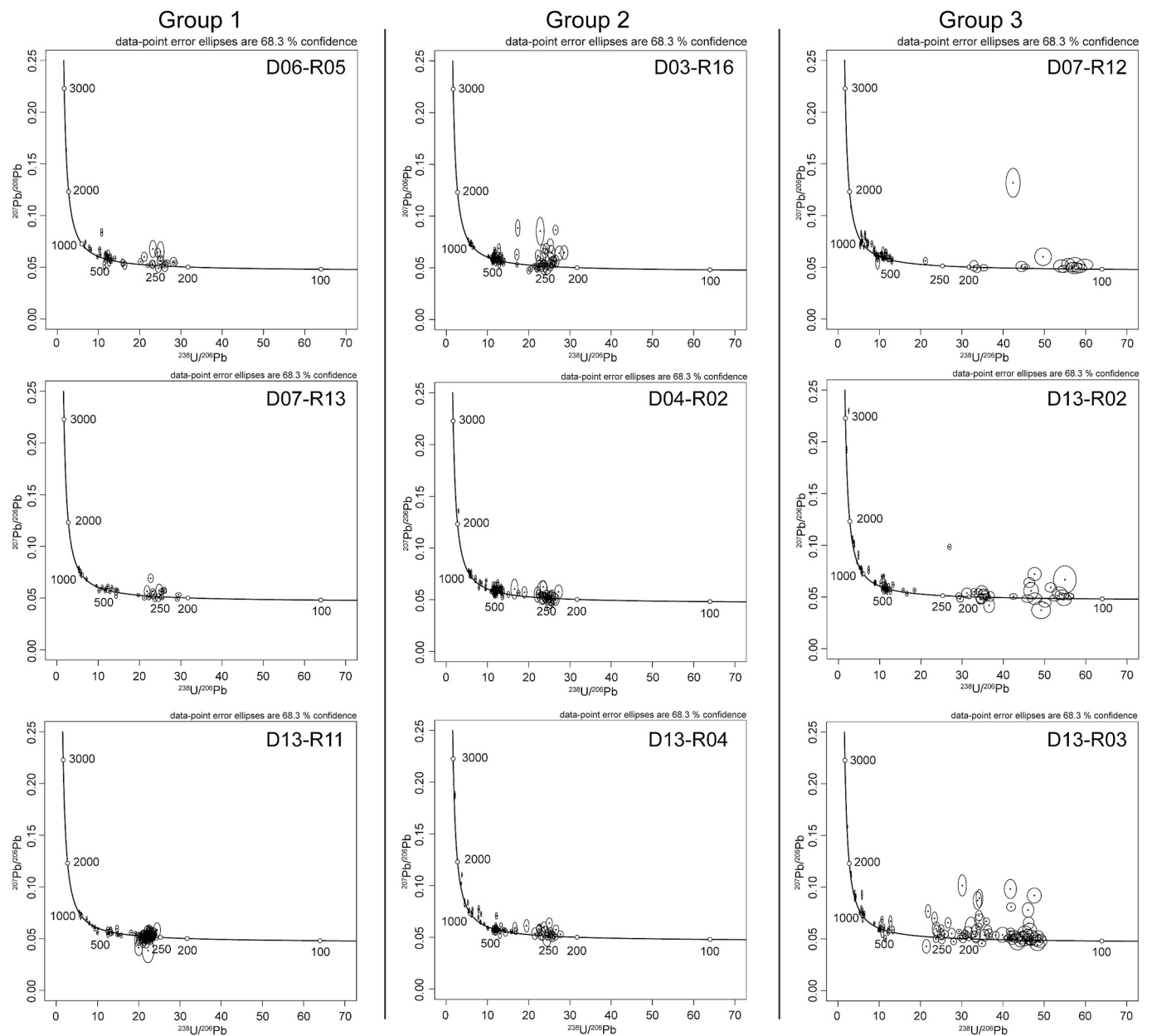


Fig. 3. Tera-Wasserburg plots for zircon samples. Samples from the South Orkney Block, Bruce Bank, and Discovery Bank (D13) are shown. Pb* indicates common-lead-corrected radiogenic portions. Error ellipses represent 68.3% confidence.

of angular rock fragments consistent with talus deposits developed on steep fault-controlled slopes (supplementary file Fig. 3). Samples chosen

for analysis were angular to subangular clasts not affected by intense alteration likely plucked from such accumulations (supplementary file Fig. 4).

5.1. Dredge D03, South Orkney microcontinent

Dredge D03 was taken from the north-facing slope of the northern

edge of the South Orkney microcontinental block. Based on the depth logger, sampling was conducted from 4836 to 4547 mbsl (meters below sea level). The dredge recovered 9.25 kg of rock including 39 samples over 4.0 cm long. Several lithologies were represented in the haul. Poorly lithified sediment was a major component (13 samples). This soft, volcanoclastic, fine sand contains lithic clasts and glass, and mineral grains including quartz, plagioclase, K-feldspar, Fe—Ti oxides,

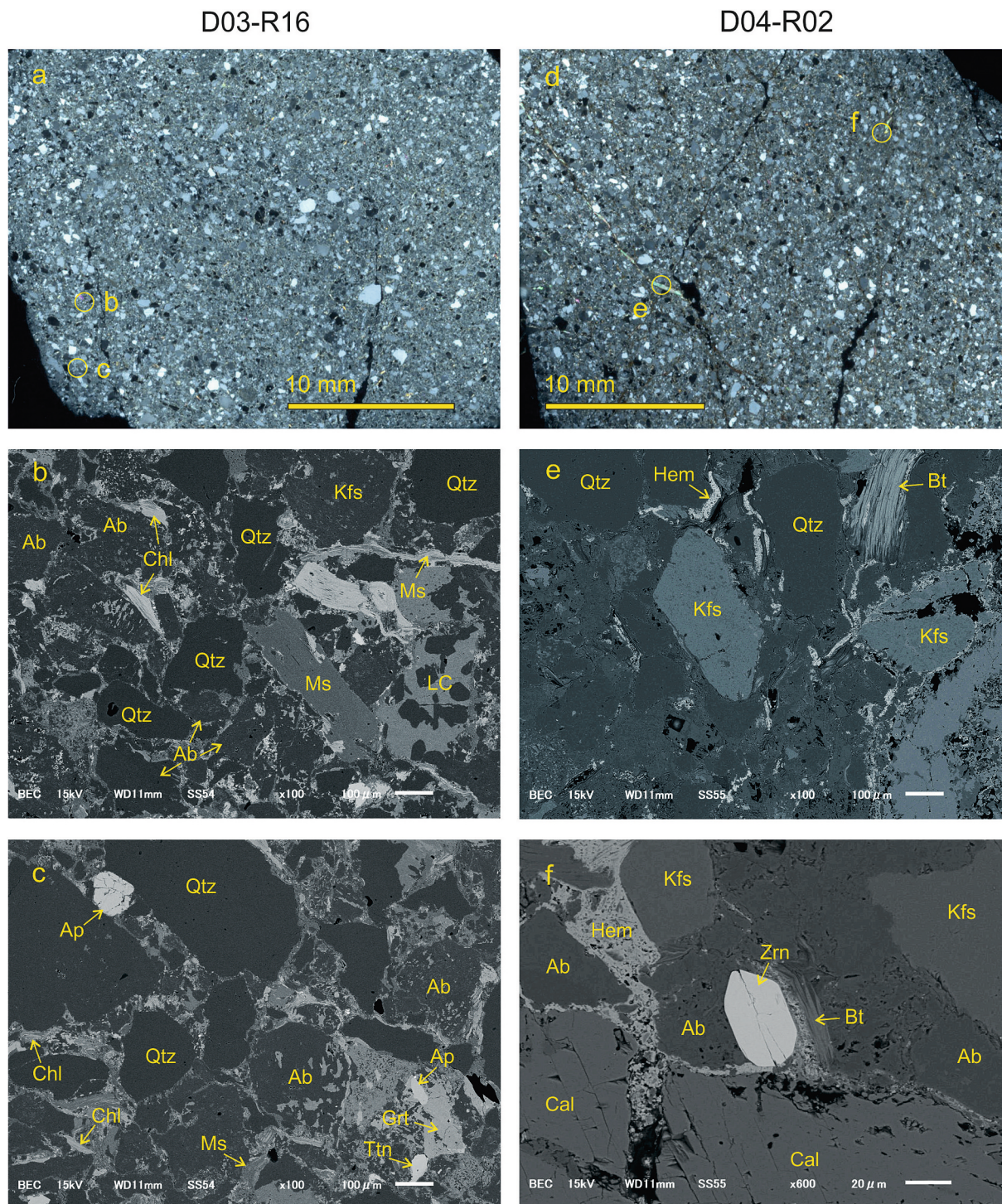


Fig. 4. Images of sandstones recovered from the South Orkney Block. **a.** Photograph of thin section of sample D03-R16, crossed polars. **b.** SEM image of part of the same sample. LC, lithic clast consisting of albite (dark shade) and K-feldspar (light shade). **c.** SEM image of part of the same sample showing rounded quartz and albite grains and grains of garnet, titanite and apatite. **d.** Photograph of thin section of sample D04-R02, crossed polars. **e.** SEM image of representative area of the sandstone showing dominance of quartz and feldspar. The biotite grain has been partially altered to chlorite. Hematite (light shade) forms veinlets between grains. **f.** SEM image of the sample at greater magnification showing calcite vein cut by hematite veinlet. Note the changes of scale.

amphibole, garnet and chlorite. The presence of probable foraminifera strongly suggests accumulation of the volcanoclastic deposit in a marine setting. Riley et al. (2022) assigned a probable Eocene age to similar sediments retrieved from Bruce Bank. Nevertheless, the dominant lithology (15 samples) in the haul was lithified sandstone occurring mainly as subangular to subrounded fragments partially or completely coated with a Mn film. Mica schists (three samples) were a minor component of the haul; most were rounded and considered likely to be ice-rafted drop stones. The dominant lithified sandstone lithology is interpreted as being in situ, and sample D03-R16 was selected as representative.

Sample D03-R16 is a well-sorted, clast-supported sandstone with rounded grains (Fig. 4a). Some mica and chlorite grains are squashed between quartz and feldspar grains, indicating compaction (Figs. 4b,c). Interstitial cement fills voids in the rock. Identified grains are lithic clasts, quartz, plagioclase, K-feldspar, muscovite, chlorite, apatite, zircon, garnet and titanite. Plagioclase is albite (Ab_{87–100}), with one more Ca rich (An₃₀) grain forming an inclusion within garnet. K-feldspar is mostly K-rich (Or_{92–98}), with one more Na-rich grain (Or₆₅). Garnet is rare. The only two garnets identified and analyzed by SEM are both rich in the grossular endmember (Gr_{79–82}). The garnets are more Ca-rich than those analyzed from Signy Island Metamorphic Complex schists and amphibolites (Storey and Meneilly, 1985) and may have been derived from metamorphism of calcareous sediments. The lithic clast in Fig. 4b consists of albite and K-feldspar. Both within the lithic clast and the matrix, albite and K-feldspar are unaltered or weakly altered. The large muscovite in the center-right of the image in Fig. 4b is also unaltered, indicating that the rock has not been subjected to more than very low-grade metamorphism. Chlorite grains possibly represent both primary grains and alteration products of biotite.

Zircon U—Pb dates from 93 concordant analyses show a large late Paleozoic to Triassic population with an age range of 313–217 Ma with a peak at 267 Ma (Fig. 5). The Th/U range of these zircons is 0.22–1.42, and they typically show oscillatory zoning (supplementary file Fig. 2), suggesting a magmatic source. There is a large population of ages between 600 and 445 Ma and a smaller cluster from 1120 to 882 Ma. The YC1σ age is 224.7 Ma indicating a Late Triassic or later sedimentation age for the sandstone.

5.2. Dredge D04, South Orkney microcontinent

Dredge D04 sampled the north-facing slope of the northern edge of the South Orkney microcontinental block close to site D03, but on a higher part of the slope. Based on the depth logger, sampling was conducted from 2445 to 2248 mbsl. A total of 10.1 kg of rock was recovered, and of twenty-two rock fragments over 4.5 cm long, the majority (18) were angular to subrounded lithified sandstones and similar sedimentary rocks with thin Mn films, and this sandstone lithology is interpreted as being in situ. One recovered sample consisting of poorly lithified fine sand contains lithic, crystal and devitrified glass grains in a mud matrix. Crystals include quartz, plagioclase, K-feldspar, clinopyroxene, amphibole and Fe—Ti oxides. This soft sediment is interpreted as a volcanoclastic marine deposit of probable Cenozoic age.

Sample D04-R02 was selected for analysis as representative of the dominant lithified sandstones. This sample, like D03-R16, is a well-sorted, clast-supported sandstone and has rounded grains (Fig. 4d). Identified grains include quartz, plagioclase, K-feldspar, apatite, zircon, ilmenite, and fibrous grains which appear to be biotite partly altered to chlorite (Fig. 4e). The plagioclase is oligoclase and albite (Ab_{80–100}). Both plagioclase and K-feldspar (Or_{88–100}) appear to be largely unaltered. No muscovite was identified in the sample. The rock contains sparse calcite veins ca. 0.3 mm wide and pervasive smaller veinlets containing hematite which cut the calcite veins (Fig. 4f).

Zircon U—Pb ages from 101 concordant analyses contain a significant late Paleozoic to Triassic population with an age range of 330–230 Ma (Fig. 5). They have Th/U ratios of 0.36–1.34 and typically show

oscillatory zoning, indicating magmatic origin. There is a large population of zircons with ages of ca. 640–415 Ma. Older ages scatter in the range 1077–627 Ma, and there is one Paleoproterozoic age of 2134 Ma. The YC1σ age is 258.3 Ma (Late Permian).

5.3. Dredge D06, South Orkney microcontinent

Dredge D06 was retrieved from the steep north-facing northern margin of the South Orkney microcontinental block to the east of the South Orkney Islands. Based on the depth logger, sampling was conducted from 3360 to 2675 mbsl. The video camera image shows a dense accumulation of poorly sorted, angular rock fragments covering the seafloor (supplementary file Fig. 3a). The recovery consisted of 207 kg of angular and subangular rocks mostly coated with Mn film. A total of 39 samples over 4 cm in length were cut and examined. Of these, the dominant lithology was a group of deformed schists and cataclasites ($n = 24$) with distinctive quartz veins and widespread minor hydrothermal mineralization. Of the remaining samples, twelve were metasediments with variable amounts of deformation, and two were lithified sandstones. There were no obvious drop stones. The dominance of the distinctive schist/cataclasite lithology means that it is highly probable that this group was retrieved from sea floor outcrop. Sample D06-R05 is typical of this group.

The sample consists of folded metapelite schist comprising muscovite, chlorite and albite with quartz and minor K-feldspar and apatite and cut by a quartz vein (Fig. 6a). The analyzed albite is entirely pure (Ab₁₀₀), and the K-feldspar is Na-rich (Or₆₉). Banding in the rock is irregular and has produced foliated zones that are composed largely of muscovite and chlorite (Fig. 6b). Other foliated zones are more leucocratic and contain albite, muscovite, chlorite and apatite (Fig. 6c). The quartz vein is up to 2 cm wide and contains minor K-feldspar (Or₉₆). A hydrothermal vein about 0.3 mm wide cuts the quartz vein and contains magnesio-carbonate, chlorite, sphalerite and Fe oxide.

The zircon-poor sample yielded only 43 zircon spots with concordant U—Pb isotopic data. There is a significant population of late Paleozoic to Triassic ages with an age range of 310–221 Ma and peaking at ca. 245 Ma (Fig. 5). There is an older population of zircons dated 542–446 Ma, with a peak at ca. 486 Ma. Further smaller clusters have ages between 914 Ma and 709 Ma. There is one grain with a Paleoproterozoic age of 2488 Ma. The YC1σ age is 222.2 Ma (Late Triassic). Th/U ratios for the late Paleozoic to Triassic grains are within the range 0.22–1.28.

5.4. Dredge D07, Bruce Bank

Dredge D07 sampled the lower part of the steep south-facing slope of the SW part of Bruce Bank. Based on the depth logger, sampling was conducted from 4095 to 3733 mbsl. The slope is part of the faulted active plate boundary between the Antarctic and Scotia plates, and the dredge site lies to the north of a deep basin along the main fault line. An image from the seafloor shows a talus deposit of angular clasts overlain by a thin layer of soft sediment (supplementary file Fig. 3b). The dredge recovered 95 kg of rock including 46 examined samples over 4.5 cm long. The range of lithologies including quartzite, granite, granodiorite and gneiss, and subrounded shapes, suggest the presence of drop stones in the recovery. The most abundant lithology consists of angular to subrounded metasediments and metapelites with Mn films which comprises 39% of the samples. The dominance of this lithology provides reasonable grounds that it represents the bedrock of the sampled seafloor slope. The second most abundant group, forming 17% of the total, consists of basalts and microgabbros which probably are examples of mafic igneous lithologies known to crop out on parts of the margin of Bruce Bank (Pérez et al., 2014; Riley et al., 2023).

Two metasediment samples were selected for zircon U—Pb analysis. Angular sample D07-R13 is a metapelite with a brecciated appearance and consists of zones with granular texture within a foliated matrix (Fig. 6d). The granular clasts are typically 1–6 mm across and generally

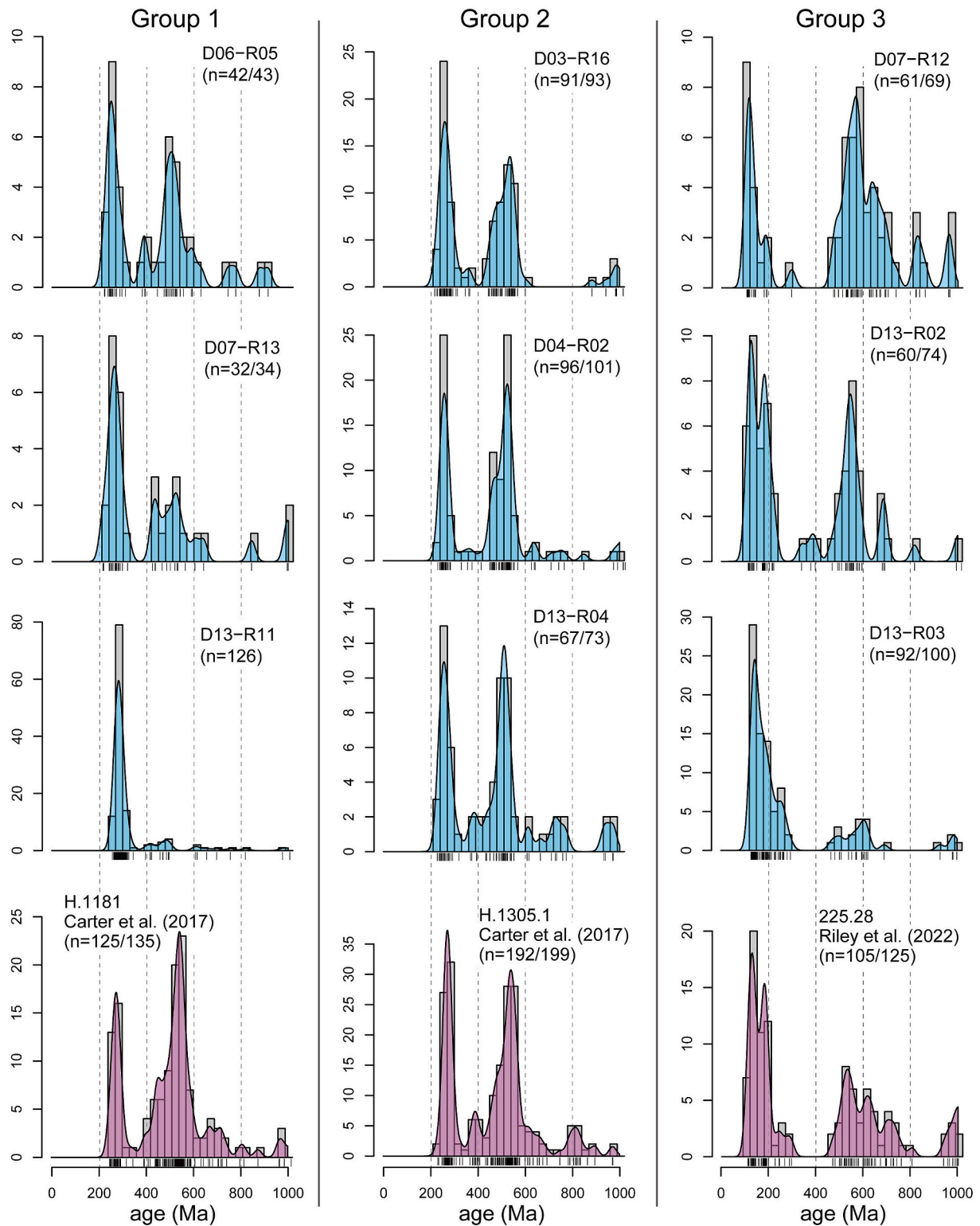


Fig. 5. Kernel density estimates (KDE) and histograms of zircon U–Pb ages for schists and sandstones recovered from the South Orkney microcontinent margin, Bruce Bank, and dredge D13 (fault scarp east of Discovery Bank) compared to data from Metamorphic Complex schist sample H.1181 and Spence Harbour Conglomerate sample H.1305.1 (Carter et al., 2017) and sandstone containing Cretaceous zircons (sample DR.225.28) from the northeastern margin of Bruce Bank (Riley et al., 2022). KDE bandwidths were selected automatically in IsoplotR. The KDEs were not normalized, and histograms were plotted using a bin width of 30 Ma. Age spectra are shown on an expanded scale for the 0–1000 Ma interval to highlight younger age populations. Analytical data are available in the supplementary file.

D06-R05

D07-R13

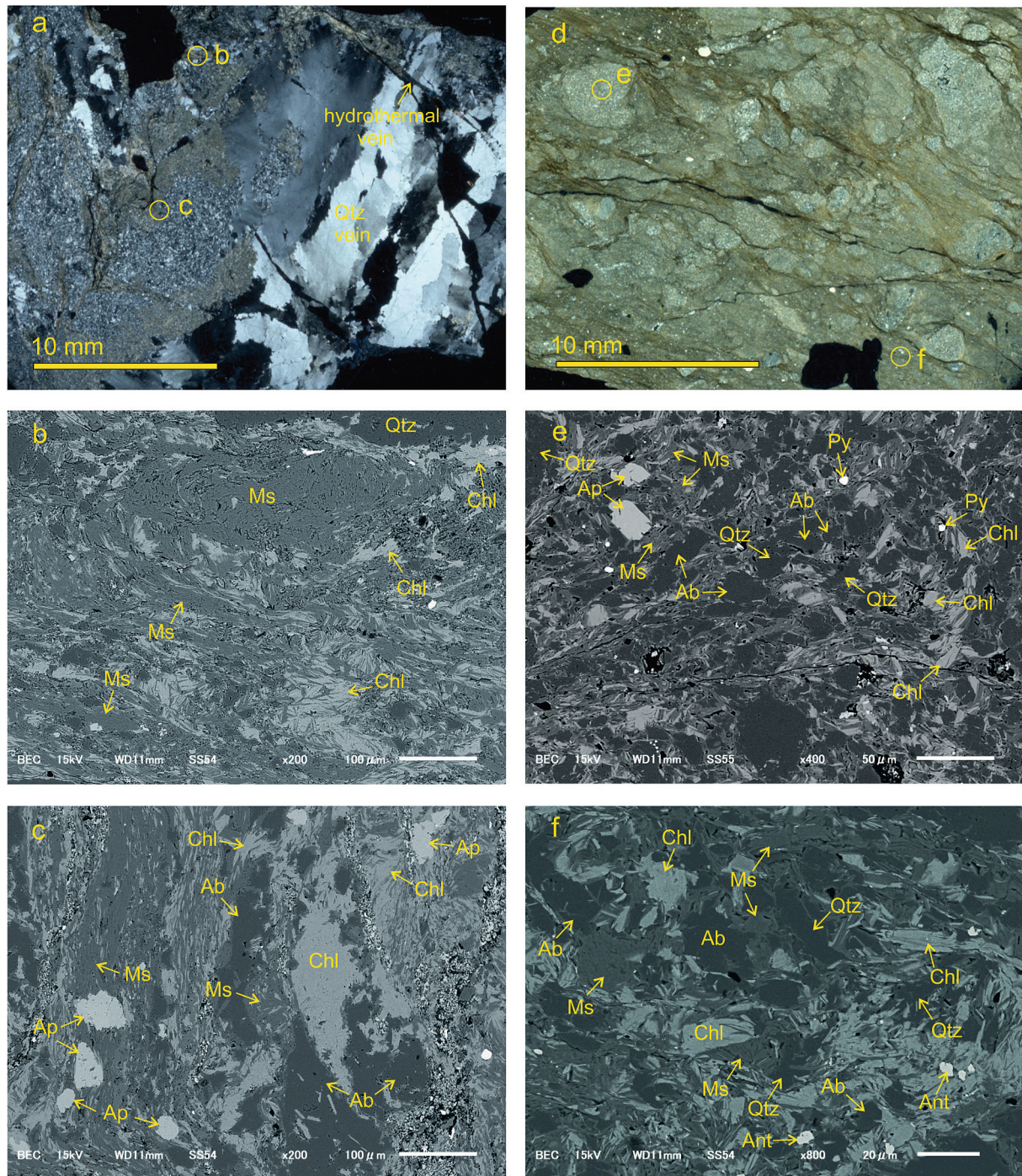


Fig. 6. Images of schists recovered from the South Orkney Block and Bruce Bank. **a.** Photograph of thin section of greenschist sample D06-R05, crossed polars. **b.** SEM image of foliated muscovite- and chlorite-rich zone of the same sample. **c.** SEM image of muscovite-chlorite-albite zone within the schist. **d.** Photograph of thin section of greenschist sample D07-R13, crossed polars. **e.** SEM image of muscovite-chlorite-albite-quartz granular zone forming a clast within the more foliated matrix. **f.** SEM image of muscovite-chlorite-albite-quartz zone forming the foliated matrix. Note the changes of scale.

more leucocratic than the foliated matrix. Internally, the clasts range from weakly to moderately foliated. The clasts consist of muscovite, chlorite, alkali feldspar, quartz, apatite and rare pyrite (Fig. 6e). The alkali feldspars range in composition from albite (Ab_{100}) to more K-rich compositions (Ab_{76}) with minor An content (up to $An_{3.3}$). The more foliated matrix (Fig. 6f) consists of a similar assemblage of muscovite, chlorite, albite (with a more restricted range of Ab_{100} – $Ab_{89.5}$), quartz, apatite and small opaque grains including a Ti oxide (anatase?).

This sample yielded only 34 zircon spots with concordant U–Pb isotopic data. Zircon ages contain a significant late Paleozoic to Triassic population with an age range of 319–214 Ma, and a peak at ca. 248 Ma (Fig. 5). There is a population with ages of ca. 565–425 (Neoproterozoic to Silurian), and older grains in the ranges 844–604 Ma and 1140–995 Ma. The YC1σ age is 216.2 Ma (Late Triassic). Most of the late Paleozoic to Triassic zircons have Th/U ratios of 0.34–1.26. One zircon with an age of 257 Ma has a Th/U ratio of 0.03 and a Th abundance of 6 ppm and

may be of metamorphic origin.

Subangular sample D07-R12 is a deformed metasediment. It yielded 70 zircon spots with concordant U—Pb isotopic data. The distribution of ages is very different to that of sample D07-R13. There is a prominent cluster at 143–106 Ma with a small group at 192–180 Ma. There is no peak in zircons of Triassic age. There is a large grouping of ages in the range 737–473 Ma. There is a cluster of ages at 862–824 and a larger one at 1108–1028 Ma. There are single Paleoproterozoic and Archean grains. The YC1 σ age is 110.6 Ma.

5.5. Dredge D13, Discovery Bank

This dredge sampled the west-facing scarp of an apparent fault block to the east of Discovery Bank (Fig. 2). Based on the depth logger, sampling was conducted from 2475 to 2062 mbsl. A video camera image shows a dense, poorly sorted accumulation of angular metasedimentary boulders (supplementary file Fig. 3c). There was a high recovery, with 92 kg of rock, mostly in the form of small rock fragments. Seventeen samples over 4 cm long were recorded. These included gabbro, gneiss, microgabbro, granite, basalt and breccia, most of which are likely to be drop stones. The most common rock type was lithified sandstone, which accounted for over half of the number (9 samples). Four of these were investigated by U—Pb zircon dating.

Angular sample D13-R02 is a fine-grained, well-sorted sandstone. It

is stratified with beds approximately 1 cm thick (Fig. 7a). SEM analysis was used to identify grains of quartz, plagioclase, K-feldspar, zircon, pyrite. Plagioclases are variably altered; analyses of least altered crystals are albite-rich (Ab_{100–88}). Relatively unaltered K-feldspars are K-rich (Or_{90–97}). All ferromagnesian minerals appear to have been altered to assemblages containing chlorite. Lithic clasts mostly appear to consist of plagioclase and altered ferromagnesian minerals. The rock is strongly cemented by calcite which fills all voids (Fig. 7b).

Zircon U—Pb dates from 75 concordant analyses contain a prominent population of Mesozoic ages in the range 221–113 Ma (Fig. 5). Within this group, there are peaks at 179 and 135 Ma. Significantly, there are no zircon ages between 339 and 221 Ma, which is the approximate range of the Carboniferous-Triassic population found in most of the analyzed South Orkney samples. There are a small number of zircons with ages of 468–339 Ma, and a larger population with ages in the range 594–468 Ma. There is a small peak at 686 Ma, older groups at ca. 1165–995 Ma and ca. 1695–1610 Ma, and two Archean grains dated at 3053 and 2763 Ma. The Mesozoic zircons have Th/U ratios of 0.19–1.65 which is within the igneous range and typically show oscillatory zoning. The YC1 σ age is 117.0 Ma.

Sample D13-R03 is another angular sandstone. Zircon U—Pb ages from 101 concordant analyses from this sample contain a large population in the range 294–126 Ma (Fig. 5). Within this group, there is a large peak at 138 Ma, a significant number of ages in the range ca.

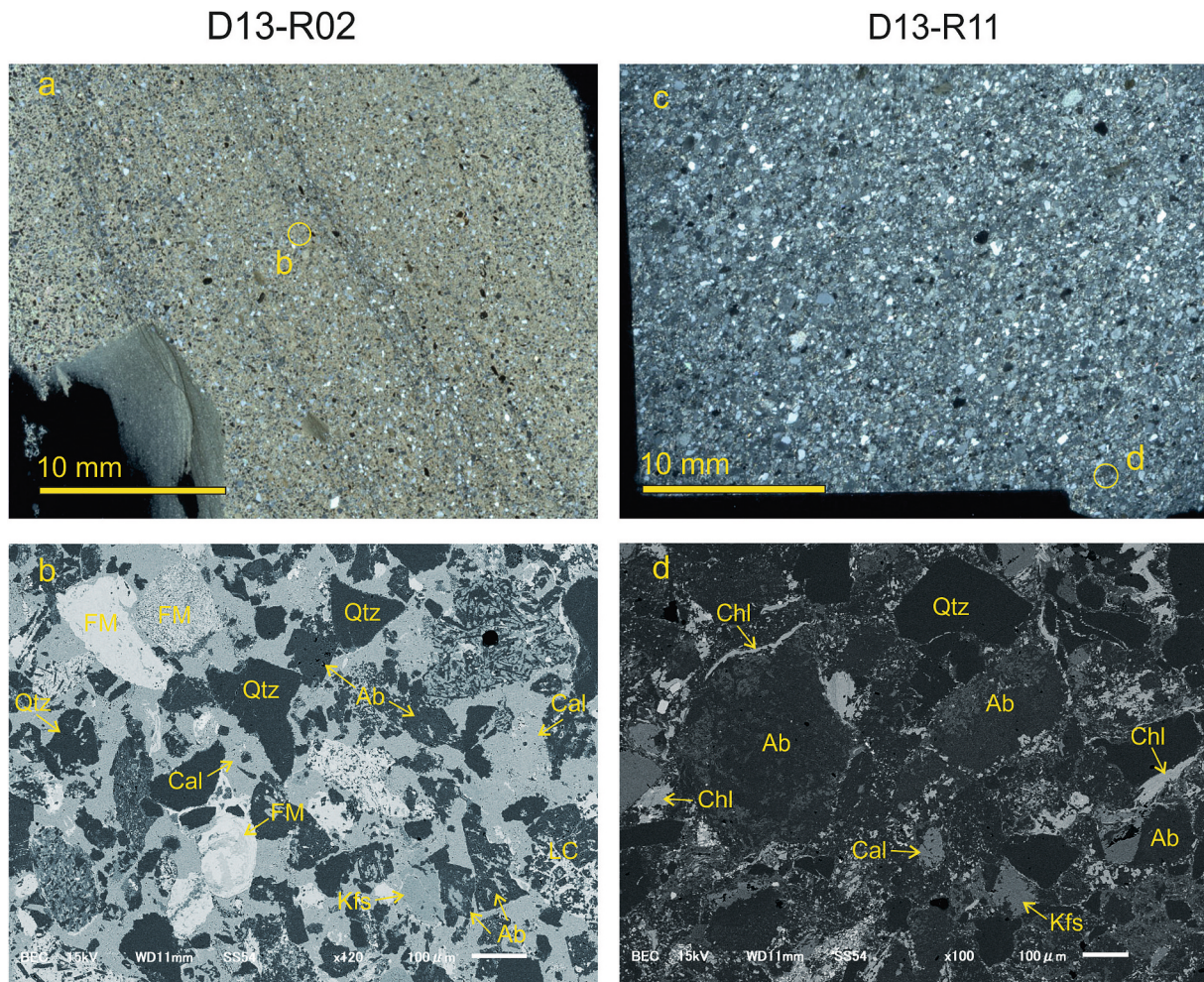


Fig. 7. Images of sandstones recovered from the fault scarp east of Discovery Bank by Dredge D13. **a.** Photograph of thin section of sample D013-R02, crossed polars. **b.** SEM image of part of the same sample. Albites and sparse K-feldspars are partially altered. Ferro-magnesian minerals (FM) are altered to assemblages containing chlorite. Lithic clast LC consists of plagioclase (dark shade) and an altered ferromagnesian mineral (light shade). The rock is strongly cemented by calcite (Cal). **c.** Photograph of thin section of sample D013-R11, crossed polars. **d.** SEM image of part of the same sample.

190–150 Ma and a possible small peak at 262 Ma. All these Permian to Cretaceous grains have Th/U ratios of 0.31–1.79, consistent with igneous origins. There is a significantly smaller population of zircons with ages between 690 Ma and 465 Ma. Most of the older, Proterozoic grains have ages of ca. 1445–930 Ma, and there are two Paleoproterozoic ages of 2442 and 1822 Ma. The YC1 σ age is 140.3 Ma.

Sample D13-R04 is a subangular metasediment. Reliable U–Pb data from 74 zircon grains consist of large populations in the ranges 319–228 Ma and 551–368 Ma. There is a significant cluster at 773–771 Ma and another at 1090–934 Ma. There are three Paleoproterozoic grains dated at 2702, 1650 and 1641 Ma. The YC1 σ age is 258.5 Ma.

Sample D13-R11 is a moderately sorted sandstone with rounded clasts (Figs. 7c). Grains include lithic clasts, quartz, plagioclase, K-feldspar, chlorite, muscovite, amphibole, zircon and a Ti oxide (rutile or anatase). The plagioclase is albite (Ab_{90–98.5}). The K-feldspar, less abundant than albite, is K-rich (Or_{79–100}). Chlorite is the most abundant ferromagnesian mineral. The single grain of amphibole that was identified is hornblende. Chlorite and muscovite appear to have been squashed between quartz and feldspar grains, indicating compaction (Fig. 7d). Lithic clasts appear to consist mainly of quartz, feldspar and ferromagnesian minerals. Some pore spaces are filled by calcite cement.

U–Pb zircon ages from 126 concordant analyses are dominated by a Carboniferous to Permian population with the age range 325–256 Ma and a peak at ca. 280 Ma, and a YC1 σ age of 283.0 Ma (Fig. 5). Most of these zircons have Th/U ratios of 0.16 to 2.0, consistent with igneous origins, although two have Th/U ratios of 2.21–2.41 with high Th abundances of 1924–2407 ppm. There are scattered early Paleozoic zircon ages of 496–396 Ma with no peak. A small population of Proterozoic ages extends from 1101 Ma to 606 Ma.

6. Discussion

The dredged samples can be divided into three groups with distinct petrographic and detrital zircon geochronological characteristics (Fig. 5).

6.1. Group 1: lithologies of the accretionary complex

Samples D06-R05 and D07-R13 are schists dredged from the north-facing margin of the South Orkney microcontinent and the southern part of Bruce Bank, respectively. We have high confidence that sample D06-R05 represents an in-situ lithology because the dredge haul was dominated by fragments of the same distinctive lithology, and reasonable confidence that sample D07-R13 represents an in-situ outcrop as well for similar reasons. Both rocks are metasediments dominated by albite, chlorite, muscovite and quartz, with complete replacement of the original granular sedimentary fabric. The presence of pure albite, chlorite and muscovite and the absence of biotite and garnet suggest that both were metamorphosed at the lower greenschist facies. The irregular foliation and fragmented quartz vein in sample D06-R05, and other similar samples from the same site, suggest a cataclastic origin, with quartz veining being broken and distributed within a foliated metapelite shear zone matrix. Sample D07-R13 consists of granular zones within a foliated matrix, suggesting intense deformation. Both the granular zones and the matrix have the same albite-chlorite-muscovite mineral composition, suggesting that the metamorphism was prograde and related to the deformation. We suggest that this rock is a sample of a *mélange*. Both cataclasite and *mélange* are characteristic products of deformation within accretionary complexes (e.g., Yamaguchi et al., 2012; Kimura et al., 2016).

These two samples may be compared to accretionary complex lithologies described from the South Orkney Islands. Schists on Coronation and Signy islands dominantly range in grade from the albite-epidote-amphibolite facies to the amphibolite facies (Thomson, 1968; Thomson, 1974; Tanner et al., 1982; Storey and Meneilly, 1985). Local greenschist facies lithologies on Coronation Island may represent a

retrograde event (Thomson, 1974). On Powell Island, greenschist facies schists containing garnet and biotite grade southward into quartz-albite-muscovite chlorite schists and then into lower-grade greywackes and shales with visible lithic clasts (Thomson, 1973; Dalziel, 1984; Trouw et al., 1997). The two dredge samples have lower metamorphic grade than Metamorphic Complex rocks on Coronation and Signy islands, but a comparable grade to the transition between higher grade metamorphic schists and the greywackes and shales on Powell Island. The South Orkney accretionary rocks are intensely deformed and contain isoclinal folds and shear zones related to thrusting, with intensities of deformation similar to those seen in the dredge samples (Meneilly and Storey, 1986; Trouw et al., 1997). Meneilly and Storey (1986) described a local occurrence of dismembered quartz layers in a micaceous matrix suggesting a cataclasite similar to sample D06-R05. The degree and style of deformation and metamorphic grade are therefore consistent with the dredged schists representing a component of the accretionary complex.

The Metamorphic Complex is characterized by prominent zircon age populations in the age ranges ca. 320–245 Ma and 650–420 Ma (e.g., sample H.1181 in Fig. 5) (Carter et al., 2017; Riley et al., 2022). Similar dominant populations of ca. 320–214 Ma and 640–420 Ma occur in the dredged schists. Moreover, maximum sedimentation ages of the dredged samples (222–216 Ma) are similar to, but a little younger than, youngest zircon ages in the Metamorphic Complex (ca. 246 Ma). Zircon age data is therefore also consistent with dredged samples D06-R05 and D07-R13 representing part of the accretionary complex.

The Late Carboniferous to Triassic population of zircons in the South Orkney accretionary complex, along with zircons of similar ages in the Trinity Peninsula Group, have been widely attributed to a Permian magmatic arc situated close to the Gondwana continental margin (Carter et al., 2017; Barbeau et al., 2009a; Castillo et al., 2016; Elliot et al., 2019). Both zircon U–Pb ages of intrusive igneous rocks in the Antarctic Peninsula, and detrital zircons in strata from the interior of Antarctica suggest that this magmatic event continued until as late as ca. 203 Ma, well into the Late Triassic (Elliot et al., 2019; Bastias et al., 2020). It is therefore likely that the youngest zircon ages recorded in the South Orkney Metamorphic Complex reflect cessation of sedimentation rather than cessation of magmatism. We therefore speculate that the younger maximum sedimentation ages of 222–216 Ma for the dredged schists relative to the Metamorphic Complex (ca. 246 Ma) is an indication that they sampled younger, and structurally lower, elements of the accretionary complex.

Sample D13-R11 from Discovery Bank is a quartz-bearing sandstone that has a similar mineral and lithic assemblage to sandstones of the Trinity Peninsula Group, which forms a significant part of the northern Antarctic Peninsula (Castillo et al., 2015). It also resembles sandstones of the Greywacke-Shale Formation on the South Orkney Islands (Thomson, 1973; Trouw et al., 1997). The zircon age distribution, with a dominant 325–256 Ma population, is similar to those of many units of the Trinity Peninsula Group (Barbeau et al., 2009a; Castillo et al., 2016), which can be considered to be an along-strike correlative of the South Orkney accretionary complex. We consider it probable that this sample was deposited as an ice-rafted drop stone derived from the Trinity Peninsula Group.

6.2. Group 2: sandstones sourced in the accretionary complex

Samples D03-R16 and D04-R02 are similar, well-sorted, clast-supported sandstones with rounded grains from the north-facing South Orkney block continental margin, from dredge sites ca. 10 km apart. The grain assemblage, including quartz, albite, K-feldspar, muscovite, chlorite, apatite, zircon and garnet are consistent with a sediment source dominated by metamorphic rocks of the accretionary complex. The sandstones are lithified, and the degree of alteration of grains is low, including alteration of biotite to chlorite and partial alteration of feldspars. It is unlikely that the sandstones correlate with the Greywacke-Shale Formation exposed in the eastern South Orkney Islands. The

latter are matrix-supported sandstones and mudstones containing clasts and mineral grains, including a wide range of feldspar compositions, reflecting derivation from igneous sources (Thomson, 1973; Trouw et al., 1997). The dredged sandstones are, however, comparable to Jurassic and Cretaceous sedimentary rocks exposed on the South Orkney Islands. These sediments are dominantly coarse-grained, unconformably overlie the Metamorphic Complex, and consist of conglomerates, sandstones, siltstones and mudstones. They contain abundant clasts derived from the Metamorphic Complex as well as an assemblage of mineral grains (quartz, plagioclase, alkali feldspar, muscovite, biotite, chlorite and heavy minerals including epidote, garnet, titanite, zircon and apatite) that is consistent with the dominant source being the Complex (Thomson, 1973; Thomson, 1974). This is a similar assemblage to that observed in the dredged sandstones. Both the non-marine Early to Middle Jurassic Powell Island Conglomerate and the marine Late Jurassic and Early Cretaceous Spence Harbour Conglomerate are proximal alluvial fan deposits which are generally coarser and less well-sorted than the dredge samples (Thomson, 1974; Thomson, 1981; Elliot and Wells, 1982).

Maximum sedimentation ages of the dredged sandstones D03-R16 and D04-R02 are ca. 225 and 258 Ma (Permian-Triassic), respectively, as determined by YC1 σ age. This closely correlates with youngest zircons in the Metamorphic Complex. It also closely correlates to youngest zircon grains in both the Powell Island Conglomerate and the Spence Harbour Conglomerate on the South Orkney Islands (231–222 Ma; Carter et al., 2017). Furthermore, the Powell Island and Spence Harbour conglomerates (e.g., sample H.1305.1, Fig. 5) have prominent clusters of zircon age peaks at ca. 330–230 Ma and 630–450 Ma (Carter et al., 2017; Riley et al., 2022), similar to those of the dredged sandstones.

Both petrography and geochronology of group 2 sandstone samples D03-R16 and D04-R02 are consistent with their deposition as parts of a sedimentary fan system that unconformably overlies the metamorphosed accreted units. They were sourced dominantly by greenschist to amphibolite facies accreted units and represent reworking of this material probably in a direction to the north (present tectonic orientation) and toward the position of the subduction zone where the accretion had taken place.

Riley et al. (2022) described similar sandstones dredged from the SW margin of Bruce Bank. These samples, DR.223.5 and DR.223.6, have similar Permian and Cambrian zircon age peaks to both the Metamorphic Complex and dredge samples D03-R16 and D04-R02 from the South Orkney microcontinent margin. The Bruce Bank sandstones were also correlated with the Powell Island and Spence Harbour conglomerates and used to suggest that Bruce Bank is a continuation of the geology of the South Orkney Islands.

Sandstone D13-R04 from Discovery Bank has a maximum sedimentation age (ca. 258 Ma) and zircon age populations that are very similar to those of the South Orkney sandstones (Fig. 5) and their equivalents on Bruce Bank. As the only known terrestrially exposed correlatives are mostly significantly coarser conglomerates and related rocks on the South Orkney Islands (Powell Island and Spence Harbour conglomerates) which are unlikely to have been sources for the sample by ice-rafted transport, it is therefore likely that this sample represents an in-situ lithology on Discovery Bank. By implication, the sedimentary fan system sourced in the South Orkney accretionary prism extended over Discovery Bank as well as Bruce Bank and the northern part of the South Orkney microcontinent.

6.3. Group 3: sandstones containing Cretaceous zircons, Bruce and Discovery banks

Four sandstone samples dredged from Bruce and Discovery banks have zircon U–Pb age distributions that are different from the South Orkney sandstones. These are D13-R02 and D13-R03 from Discovery Bank, D07-R12 from the southern margin of Bruce Bank and sample DR.225.28 described by Riley et al. (2022) from the eastern margin of

Bruce Bank (Fig. 5). Sample D13-R02, representative of the group, is a quartz-bearing, mature sandstone derived from continental sources. All these samples have Cretaceous maximum zircon deposition ages. Youngest zircons range between 106 and 113 Ma in most of the samples, with a marginally higher youngest zircon age of 126 Ma in sample D13-R03. YC1 σ ages range from 110.6 Ma in sample D07-R12 to 140.3 Ma in sample D13-R03. All the samples have few zircons in the range 330–230 Ma in contrast to South Orkney schists and sandstones which have a characteristic peak in this age range. All four samples contain Jurassic zircons in the age range 190–175 Ma, but with lower abundances than Cretaceous zircons. All four samples have significant clusters at ca. 730–470 Ma and 1200–930 Ma.

Similarities between these four samples, alongside differences from the South Orkney Islands sandstones and schists, suggests that they are representatives of a distinct and widespread sedimentation event. Age of sedimentation is likely to be Cretaceous, although all that is certain is that the maximum sedimentation age of the sediments is ca. 140–110 Ma (Early Cretaceous).

6.4. Stratigraphic and tectonic relationships

The presence of schists interpreted as parts of the South Orkney accretionary complex in both the northern margin of the South Orkney microcontinent and the southern part of Bruce Bank strongly indicates that the basement of Bruce Bank consists, at least in part, of the same accretionary complex. Moreover, clastic sediments derived from this accretionary complex with Permian-Triassic maximum sedimentation ages have been confirmed both in the northern margin of the South Orkney block and on Bruce Bank. The Bruce Bank sandstone samples of this age are from dredges retrieved from different dredge sites on the southwestern and eastern margins of the block, 136 km apart. This suggests that the sequence covers, or once covered, a significant area of the bank. These relationships confirm the view of Riley et al. (2022) that Bruce Bank is a continuation of the geology of the South Orkney microcontinent, and that the two blocks are now separated by extensional faulting along the plate boundary South Scotia Ridge fault system.

Two distinct sedimentary units, sediments derived from the accretionary complex with Permian-Triassic maximum sedimentation ages, and sediments containing Cretaceous zircons, have both been identified on both Bruce and Discovery banks. This strongly suggests that the two banks originally were parts of the same crustal block that have become separated by rifting in Scan Basin, and supports most tectonic reconstructions of the Scotia Sea (Dalziel et al., 2013b; Eagles and Jokat, 2014; Maldonado et al., 2014; Gao et al., 2023; Riley et al., 2023; Schellart et al., 2023) that indicate that Bruce and Discovery banks were joined prior to opening of Drake Passage and extension in the Scotia Sea. Rifting and ocean formation in Scan Basin is interpreted to have occurred during Eocene-Oligocene times (35–29 Ma; Schreider et al., 2017), significantly later than deposition of the sandstone units containing Cretaceous zircons.

Riley et al. (2022) suggested that ages of detrital zircons in DR.225.28, a representative of the sandstone succession containing Cretaceous zircons, most closely resembles the Fuegian Andes of southern Patagonia with similarities to the Cordillera Darwin Complex, a metamorphic core complex with Cretaceous peak metamorphism ages and which was uplifted in Cretaceous-Paleogene times (Barbeau et al., 2009b; Hervé et al., 2010a). The prominent peak in Early Cretaceous zircons in all four sandstone dredge samples is similar in age to silicic plutons of the southern Patagonian batholith (ca. 125–100 Ma; Hervé et al., 2007) and related volcanic rocks of the Divisadero Group (Echaurren et al., 2017). Zircons of age 115–100 Ma are an important component in sediments of the Magallanes foreland basin of southern Tierra del Fuego (Barbeau et al., 2009b). Clusters of Jurassic zircon ages at 172–165 Ma and 190–177 Ma in the sandstones correspond to ages of silicic volcanism of the Chon Aike Group of Patagonia (Pankhurst et al., 2000). Early Jurassic zircons are particularly abundant in samples D13-

R02 (Fig. 5) and DR.225.28 (Riley et al., 2022) where they form peaks at ca. 185 Ma. Zircon age groups in the sandstones at ca. 730–470 Ma and 1200–930 Ma are similar to age distributions in the Cordillera Darwin Complex and the Tierra del Fuego igneous and metamorphic basement complex (Hervé et al., 2010a; Hervé et al., 2010b). The presence of lithologies in the Fuegian Andes during Cretaceous times with potential zircon sources for all zircon age groups observed in the Cretaceous Bruce and Discovery banks sandstones suggests close proximity during sedimentation. It should also be noted that zircons of similar Early Cretaceous, Jurassic, early Paleozoic and Proterozoic ages could potentially have been sourced from West Antarctica (Pankhurst et al., 2000; Flowerdew et al., 2007b; Castillo et al., 2016; Riley et al., 2020).

6.5. Implications for the position of Bruce-Discovery bank in tectonic reconstructions

There have been many attempts to reconstruct the tectonic evolution of the Scotia Sea (e.g., Eagles, 2010; Dalziel et al., 2013a; Eagles and Jokat, 2014; Maldonado et al., 2014; van de Lagemaat et al., 2021; Gao et al., 2023; Riley et al., 2023; Schellart et al., 2023). All these models include movement of elements of the Scotia Sea to the east, primarily as a consequence of extension of continental crust and oceanic spreading. Nevertheless, there are significant differences between proposed models resulting from tectonic complexity, gaps in the tectonic record, and local uncertainties in crustal structure.

The position of the South Orkney microcontinent before and during opening and widening of the Scotia Sea is well-constrained. Most studies and reconstructions place the block close to the paleo-Pacific margin and attached to the northeastern tip of the Antarctic Peninsula (Fig. 8). This interpretation is consistent with the accretionary origin for the Metamorphic Complex (Dalziel et al., 1981; Tanner et al., 1982; Meneilly and Storey, 1986). Observed north-directed thrusting of units in the South Orkney accretionary complex suggests net clockwise rotation of the block to accommodate original east-directed subduction from the direction of the paleo-Pacific Ocean (Dalziel et al., 1981; Dalziel, 1984; Trouw et al., 1997). The positioning is further supported by continuity, from the Antarctic Peninsula to the South Orkney block, of a linear

magnetic anomaly, interpreted as an active margin batholith, (Martos et al., 2014; Morales-Ocaña et al., 2023), and by magnetic anomaly evidence for ocean spreading in the separating Powell Basin (Eagles and Livermore, 2002).

The location of the Bruce-Discovery block in Cretaceous times, before opening of the Scotia Sea, is more uncertain. Some tectonic reconstructions have placed it close to the pre-rifting South Georgia microcontinent, east of the eastern termination of the Fuegian Andes (Dalziel et al., 2021; van de Lagemaat et al., 2021) (position BD1 in Fig. 8). This position is difficult to reconcile with the identification of accretionary complex schist D07-R13 from Bruce Bank and differences between detrital zircon ages of sandstones from Bruce and Discovery banks and those of Cretaceous sandstones of South Georgia and the North Scotia Ridge which lack Neoproterozoic to early Paleozoic zircon age peaks (Carter et al., 2014; Riley et al., 2019). Others have placed the Bruce-Discovery block close to the paleo-Pacific margin and north of the South Orkneys (Riley et al., 2023; Gao et al., 2023) (position BD2 in Fig. 8). Martos et al. (2014) suggested that Discovery Bank was located adjacent to, and northeast of, the South Orkney block to be consistent with continuity of magnetic anomalies related to the active margin batholith. Position BD2 for the Bruce-Discovery block in mid-Cretaceous times, adjacent to, and north of, the South Orkney block, and along the active paleo-Pacific active margin, is consistent both with the schist lithology of sample D07-R13 and zircon detrital geochronology of sandstone units. For these reasons, we prefer a pre-rifting position BD2 for the block.

Sediments on the South Orkney, Bruce and Discovery blocks having Permian-Triassic maximum sedimentation ages and sources in the accretionary complex can be interpreted in modelled position BD2 to have been deposited along the continental margin or continental slope at a time when the accretionary complex was exposed to erosion. By Cretaceous times, the accretionary complex is interpreted to have been largely reduced by erosion becoming a much less significant source. Zircon sources were in southern South America, adjacent to the north, or in the Antarctic Peninsula to the south. Movement of the block from its mid-Cretaceous position to its present location is consistent with tectonic models involving clockwise rotation of the South Orkney microcontinent, sinistral transform motion of the Antarctic plate relative to South America, upper plate extension related to roll-back of the ancestral South Sandwich arc, rifting of small basins, and ocean spreading on the West Scotia Ridge (Eagles, 2010; Eagles and Jokat, 2014; van de Lagemaat et al., 2021; Gao et al., 2023; Riley et al., 2023).

7. Conclusions

Petrological and zircon U–Pb geochronological data for dredged sandstones and schists have been used to infer the origins of crustal blocks of continental origin within the southern Scotia Sea. The study confirms that such data is a powerful tool to identify origins of blocks within the Gondwana margin prior to crustal extension and ocean spreading that dispersed the blocks within the Scotia Arc.

Schists dredged from the northern margin of the South Orkney microcontinent and the southern margin of Bruce Bank are lower greenschist facies metapelites having textural characteristics of mélange and cataclasis respectively. Zircon ages for the schists from U–Pb geochronology have maximum sedimentation ages of 221.4 to 214.4 Ma and prominent zircon populations with Late Carboniferous to Triassic ages. The metamorphic grades, textures and detrital zircon ages suggest that they represent parts of the accretionary complex of the South Orkney Islands exposed in faulted margins of the South Orkney and Bruce Bank crustal blocks.

Two different sandstone units are represented in dredges from the northern margin of the South Orkney block, Bruce Bank and Discovery Bank. Sandstones with Late Permian to Triassic maximum deposition ages of 224.7 to 258.5 Ma have been identified on the South Orkney block and on Discovery Bank. These sandstones have a grain

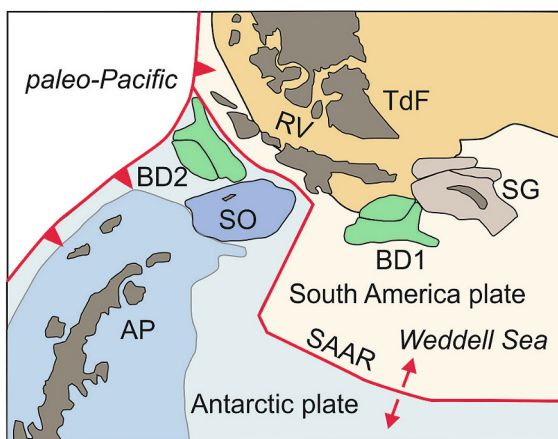


Fig. 8. Sketch tectonic reconstruction of Drake Passage at 85 Ma modified after van de Lagemaat et al. (2021) showing two possible locations for the Bruce-Discovery continental block (green). The Rocas Verdes basin has closed and ocean spreading on the South America-Antarctic Ridge (SAAR) has formed oceanic crust (pale colors) in the Weddell Sea. Position BD1 of the Bruce-Discovery continental block is to the east of the South Orkney block (SO), close to South Georgia (SG) and far from the active paleo-Pacific margin, after van de Lagemaat et al. (2021) and Dalziel et al. (2021). Alternative position BD2 for the block is close to the South Orkney block and within the active margin, after Gao et al. (2023) and Riley et al. (2023). AP, Antarctic Peninsula; TdF, Tierra del Fuego. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

assemblage, including quartz, albite, K-feldspar, muscovite, chlorite, apatite, zircon and garnet that is consistent with a sediment source dominated by metamorphic rocks of the metamorphosed accretionary complex. Riley et al. (2022) reported similar sedimentary rocks dredged from Bruce Bank. Contrasting sandstones with Cretaceous maximum deposition ages of 110.6 to 140.3 Ma have been identified on both Bruce and Discovery banks.

Identification of schist from Bruce Bank interpreted to correlate with accretionary complex metamorphic rocks of the South Orkney Islands, as well as identification of similar sandstone units on both the South Orkney block and Bruce Bank provide further support for the interpretation of Riley et al. (2022) that Bruce Bank contains a continuation of the geology of the South Orkney microcontinent.

The presence of sandstone units with both Late Permian to Triassic maximum deposition ages and Cretaceous ages on both Bruce and Discovery banks strongly suggests that the two blocks were joined before separation by Paleogene rifting of Scan Basin.

The position of the combined Bruce-Discovery block in mid-Cretaceous times is interpreted to have been adjacent to, and north of, the South Orkney microcontinent close to the active paleo-Pacific margin. Sediments deposited on the block having Late Permian to Triassic maximum deposition ages had sources dominated by exposed rocks of the accretionary complex, remnants of which now form the South Orkney Islands. By Cretaceous times, the accretionary complex was no longer a dominant source, and zircons were derived from southern South America or the Antarctic Peninsula.

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CRediT authorship contribution statement

Philip T. Leat: Methodology, Investigation, Formal analysis, Conceptualization, Writing – review & editing, Writing – original draft.
Kenichiro Tani: Methodology, Investigation, Formal analysis, Conceptualization, Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

All data is available as supplementary files.

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