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Provenance and correlation of Permian successions from the Falkland/Malvinas Islands with West Gondwana: implications for a Natal Embayment palaeo-location

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Abstract: Detrital zircon U–Pb and Lu–Hf data from the youngest (late Permian) sedimentary succession of the Falkland/Malvinas Islands are used to constrain the depositional age, provenance and palaeogeography, and to test the Natal Embayment model for the Falkland/Malvinas Islands microplate. The late Permian was a period of extensive magmatism and sediment recycling along the accretionary margin of West Gondwana. Deposition into retro-arc foreland basins was widespread across South Africa, Antarctica, South America and the Falklands Islands, forming thick successions of fluvial, deltaic and shallow marine units. Our analysis links the late Permian (*c.* 260 Ma) Bay of Harbours Formation of the Falkland/Malvinas Islands with deltaic/fluvial volcaniclastic units from the Karoo Basin of South Africa, the Theron Mountains of East Antarctica and the sandstones of the Ellsworth Mountains and southern Antarctic Peninsula. These units all have a shared provenance from the Antarctic sector of the West Gondwana margin. Although the detrital zircon age profiles of the Falkland/Malvinas Islands sedimentary units overlap with those from the accretionary and volcanic complexes of Patagonia, the Lu–Hf isotope compositions are clearly distinct, indicating that there was no direct link between the late Permian successions of the Falkland/Malvinas Islands (ε_{Hf} −3 to +3) to the volcano-sedimentary successions of southern South America (ε_{Hf} less than −5).

Supplementary material: U–Pb and Lu–Hf datasets are available at https://doi.org/10.6084/m9.figshare.c.7765296

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The geological and tectonic history of the Falkland/Malvinas Islands has been the subject of considerable debate for over 100 years (Stone 2016), with multiple investigations (e.g. Halle 1912; Du Toit 1927; Adie 1952; Borrello 1963; Mitchell *et al.* 1986; Marshall 1994; Storey *et al.* 1999; Stone *et al.* 2009; Ramos *et al.* 2017) attempting to resolve whether the Falkland/Malvinas Islands had a Paleozoic geological history aligned with Africa or South America.

The overwhelming consensus is that the Falkland/Malvinas Islands had a Paleozoic origin in the Natal Embayment adjacent to the Eastern Cape of SE Africa and the Ellsworth–Whitmore Mountains crustal block of present-day West Antarctica (Fig. 1). However, a palaeo-position in the Natal Embayment requires a rotation of 180° from its current orientation to satisfy lithostratigraphic correlations with the Cape Fold Belt and Karoo Basin of SE Africa (Adie 1952). Other workers (e.g. Ramos *et al.* 2017; Eagles and Eisermann 2020) therefore favour either a South American affinity for the Falkland/Malvinas Islands or their being part of an allochthonous Deseado Massif microcontinent (Schilling *et al.* 2017). These alternative models negate the requirement for crustal block rotation (Richards *et al.* 1996), which these workers interpreted as being consistent with the seafloor architecture. However, more recent structural and seismic analyses by Stanca *et al.* (2019, 2022) from the western margin of the Falkland Plateau lend support to the rotation of the Falkland/Malvinas Islands microplate in an extensional setting in the Natal Embayment.

The lithostratigraphy (e.g. Trewin *et al.* 2002; Hunter and Lomas 2003), glacial geology (e.g. Stone *et al.* 2012), structural geology (e.g. Curtis and Hyam 1998), palaeomagnetism (Mitchell *et al.* 1986), geochemistry (e.g. Hole *et al.* 2016) and geochronology (e.g. Mussett and Taylor 1994) of the Falkland/Malvinas Islands have all been used to establish their geological history and position within Gondwana, prior to break-up, and all have been unable to provide a consensus. A more recent approach is the application of detrital zircon U–Pb geochronology combined with Lu–Hf zircon geochemistry to help resolve the age, provenance and correlation of sedimentary successions of the Falkland/Malvinas Islands. This methodology was applied by Ramos *et al.* (2017) and Malone *et al.* (2023) to investigate wider links to South Africa, South America and East Antarctica. Although there was no clear consensus to resolve the palaeo-location of the Falkland/Malvinas Islands, Malone *et al.* (2023) determined that their results were most readily accommodated with the Falkland/Malvinas Islands as a rotated crustal block originating in the Natal Embayment.

Detrital zircon analysis of the sedimentary successions of the Falkland/Malvinas Islands have thus far focused on the lower parts of the stratigraphy (Fig. 2), with both Ramos *et al.* (2017) and Malone *et al.* (2023) investigating the units of the West Falkland Group and the lower parts of the Lafonia Group succession (Fig. 3). The late Permian sequences of the Falkland/Malvinas Islands are part of an extensive belt of volcano-sedimentary successions across

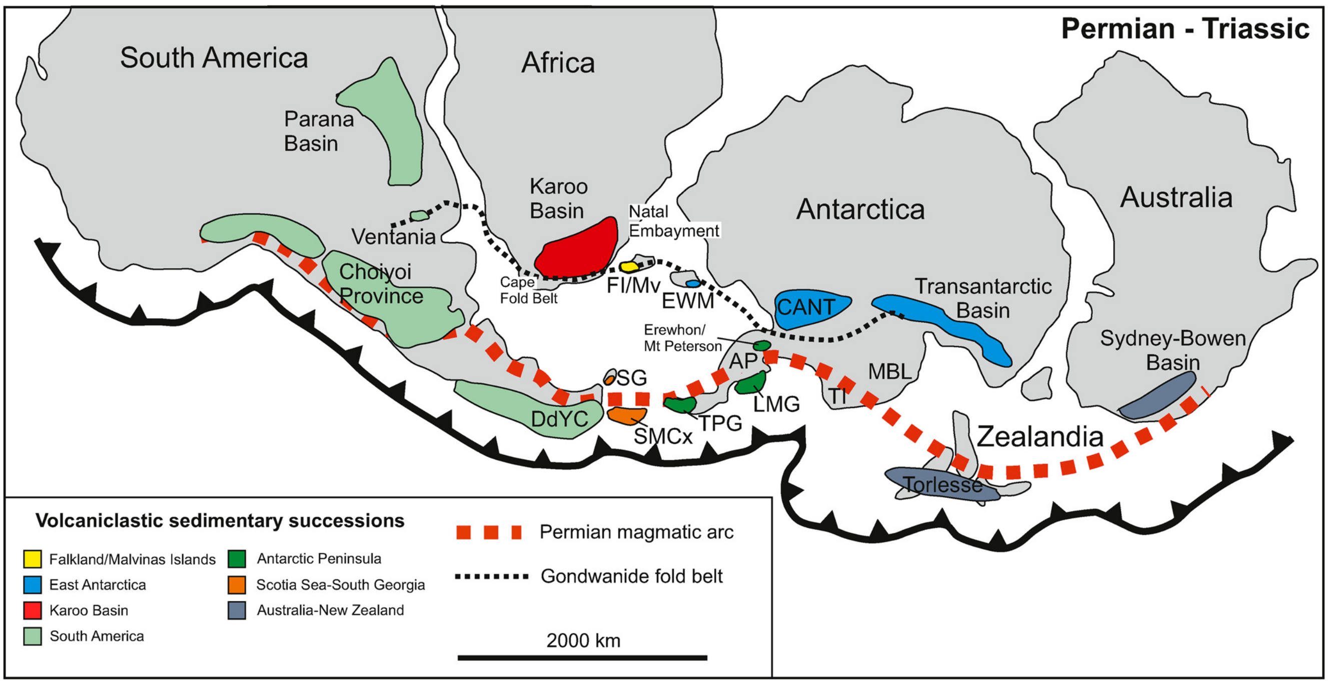

Fig. 1. Late Permian palaeogeographical reconstruction of West Gondwana showing the location of volcano-sedimentary successions along the proto-Pacific margin and hinterland basins. FI/MV, Falkland/Malvinas Islands; EWM, Ellsworth–Whitmore Mountains; CANT, Central Antarctica; AP, Antarctic Peninsula; MBL, Marie Byrd Land; TI, Thurston Island; LMG, LeMay Group; TPG, Trinity Peninsula Group; SMCx, Scotia metamorphic complex; DdYC, Duque de York Complex; SG, South Georgia. Source: adapted from Nelson and Cottle (2019).

West Gondwana (Fig. 1), which, although disparate, have, in part, been correlated (e.g. Nelson and Cottle 2019).

This study examined, for the first time, the detrital zircon population of deltaic sandstones from the upper part of the Carboniferous–Permian Lafonia Group (Bay of Harbours Formation; Fig. 2). Using U–Pb data combined with Lu–Hf zircon analysis, the maximum likely age (MLA) of deposition and provenance constraints from the Bay of Harbours Formation were compared with middle to upper Permian successions from across West Gondwana. This allowed a comprehensive analysis of the potential correlations across the extensive distribution of Permian sedimentary and volcaniclastic successions of West Gondwana (Fig. 1). Sequences from South Africa, South America, the Antarctic Peninsula, the Ellsworth Mountains, East Antarctica and South Georgia were all evaluated; these are successions that were deposited during a dynamic period of subduction, volcanism, basin inversion and the recycling of detrital material. Evaluation of these units with respect to the late Permian succession of the Falkland/Malvinas Islands allowed us to test contrasting models.

Geological setting

The geological history of the Falkland/Malvinas Islands has been described in detail by Aldiss and Edwards (1999) and summarized by Stone (2016). The geology of the islands is shown in Figure 2, with the stratigraphy summarized in Figure 3. The geology is almost entirely Paleozoic in age, with the exception being a Mesoproterozoic basement complex at Cape Meredith (Fig. 2) and a suite of Early Jurassic and Mid-Cretaceous mafic dykes that cross-cut the entire succession (Stone *et al.* 2008). The basement complex consists of amphibolite, paragneiss, orthogneiss and granite (Thistlewood *et al.* 1997). The complex has been dated to the interval *c.* 1120–1000 Ma (Jacobs *et al.* 1999) and has been correlated with a network of Mesoproterozoic arc terranes in the Natal–Maud Belt of South Africa and western Dronning Maud Land of East Antarctica (Jacobs *et al.* 1999; Riley *et al.* 2020) and the adjacent Maurice Ewing Bank (Chemale *et al.* 2018).

The basement complex at Cape Meredith is unconformably overlain by the West Falkland Group, which forms a >7 km thick succession of fluvial–marine quartz sandstone, quartzo-feldspathic sandstone and mudstone units (Aldiss and Edwards 1999). The West Falkland Group has an outcrop extent across West Falkland and the northern sector of East Falkland (Fig. 2). It is dominated by the *c.* 4500 m thick Port Stephens Formation (Fig. 3) of fluvial–shallow marine sandstone (Hunter and Lomas 2003), which has been correlated with the Table Mountain Group in South Africa (Vorster *et al.* 2021). The Port Stephens Formation is overlain by the Devonian Fox Bay, Port Philomel and Port Stanley formations (Fig. 3), which outcrop extensively across both West and East Falkland. The Fox Bay Formation has a well-defined invertebrate fauna consistent with an Early Devonian depositional age (Marshall 1994). The Port Stanley Formation, which conformably overlies the fine-grained sandstone of the Port Philomel Formation, is up to 1100 m thick and consists of medium-grained quartz sandstone that forms a broad belt of characteristic rocky ridges across the northern sector of West Falkland (Aldiss and Edwards 1999).

The West Falkland Group is overlain by the Carboniferous–Permian Lafonia Group (Aldiss and Edwards 1999), which crops out across Lafonia and north of Choiseul Sound (Fig. 2). The base of the Lafonia Group is marked by the *c.* 200 m thick Bluff Cove Formation (Fig. 3) of fine-grained sandstone and localized shale beds and has been interpreted as a glacio-marine unit (Aldiss and Edwards 1999). This unit is overlain by the distinctive Fitzroy Tillite Formation, a massive sandy diamictite up to 750 m thick (Fig. 3). The Fitzroy Tillite Formation is a late Carboniferous to early Permian glaciogenic diamictite that forms part of a succession recognized across Gondwana and is inferred to represent widespread glaciation at *c.* 290 Ma (Visser *et al.* 1997; Stone 2016). Correlations have been made with the Dwyka Group tillite of South Africa, the Sauce Grande Formation of the Ventania System (Argentina) and the Whiteout Conglomerate of the Ellsworth Mountains (Antarctica), with these correlations supported by detrital zircon analyses (e.g. Craddock *et al.* 2017; Malone *et al.* 2023). The glaciogenic

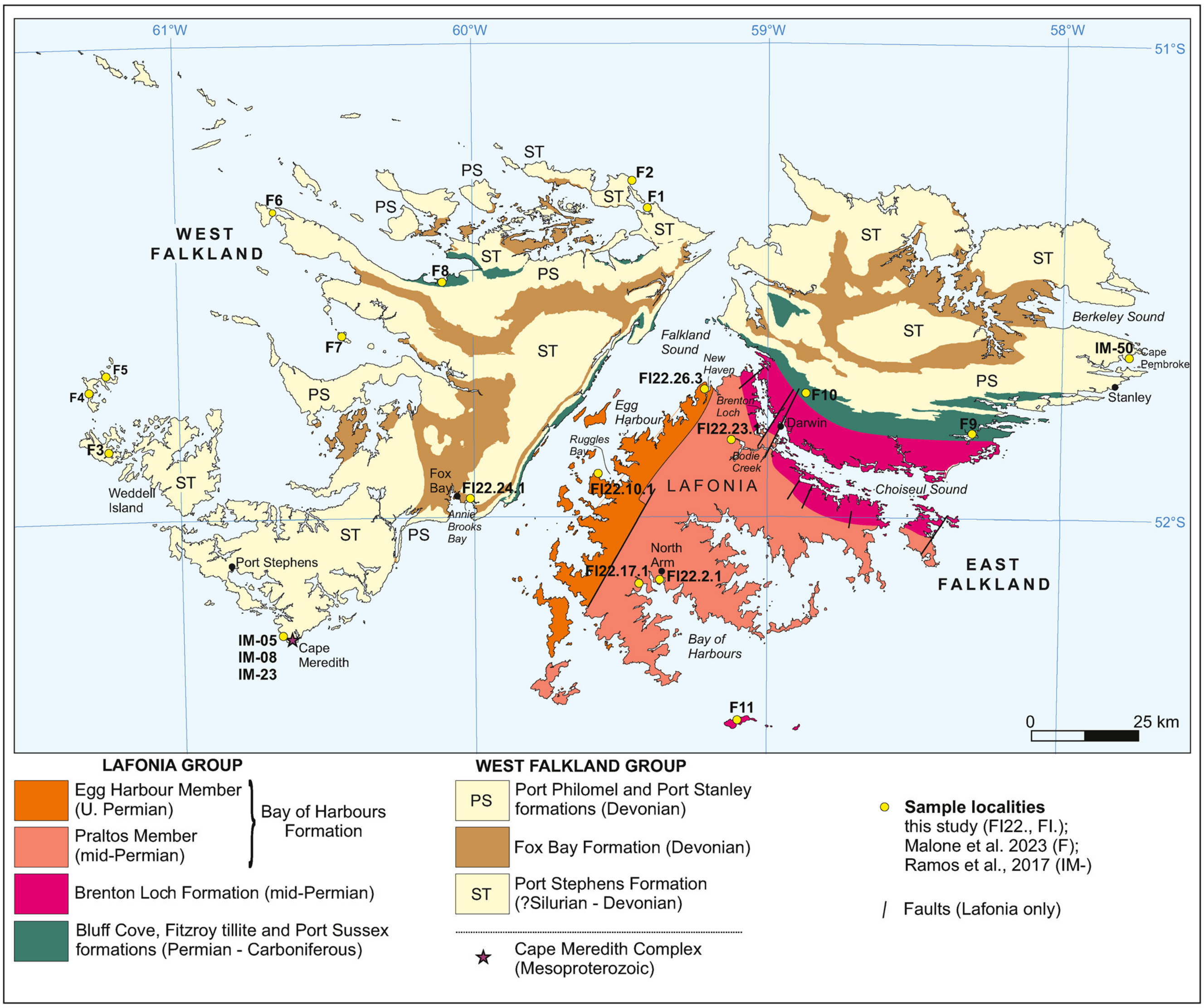

Fig. 2. Geological map of the Falkland/Malvinas Islands. Sample sites are from Ramos *et al.* (2017) (IM-), Malone *et al.* (2023) (F) and this study (FI22). Sample locations: FI22.2.1 (52.13436° S, 059.37044° W); FI22.10.1 (51.91092° S, 059.58036° W); FI22.17.1 (52.13647° S, 059.44292° W); FI22.23.1 (51.83928° S, 059.12181° W); FI22.24.1 (51.96306° S, 060.01497° W); FI22.26.3 (51.73306° S, 059.21972° W). Source: modified from Aldiss and Edwards (1999).

succession is widely inferred to have had an Antarctic source, supported by fossil-bearing clasts within the diamictite, linked with Paleozoic successions in Antarctica (Craddock *et al.* 2019).

The diamictite is conformably overlain by the Port Sussex Formation (Fig. 3), which is dominated by black mudstone with minor amounts of diamictite at its base. The Port Sussex Formation reaches a maximum thickness of *c.* 250 m (Aldiss and Edwards 1999) and crops out in a narrow band in central East Falkland (Fig. 2).

The mid-Permian Brenton Loch Formation crops out either side of Choiseul Sound (Fig. 2) and forms a *c.* 3 km thick succession of mudstone, siltstone and fine-grained sandstone deposited in a pro-deltaic setting (Aldiss and Edwards 1999). The Brenton Loch Formation is host to non-marine bivalves and *Glossopteris* flora introduced into the basin by proximal fluvial systems (Simões *et al.* 2012); it forms part of the upper Lafonia Group. The succession has been correlated with the Ecca Group of the Karoo Basin and the Polarstar Formation of the Ellsworth Mountains of Antarctica (Malone *et al.* 2023).

The uppermost section of the Lafonia Group – the youngest sedimentary succession exposed in the Falkland/Malvinas Islands – is the Bay of Harbours Formation, which has an outcrop extent across almost all of Lafonia (Fig. 2) and is the primary focus of this study. The Bay of Harbours Formation has been subdivided into the stratigraphically older Praltos Member (Trewin *et al.* 2002) and the younger Egg Harbour Member (Aldiss and Edwards 1999). The Praltos Member records a transition from a delta slope to a delta top environment and forms a *c.* 2500 m succession (Trewin *et al.* 2002) of gently dipping mudstone and sandstone channel beds (Fig. 2). Conformably overlying the Praltos Member is the Egg Harbour Member that crops out along the western margin of Lafonia (Fig. 2) and forms an up to 1700 m thick succession (Fig. 3) of sandstone and shale with a *Glossopteris* flora (Aldiss and Edwards 1999). The Egg Harbour Member was deposited in a delta top environment and has been correlated with the lower part of the Beaufort Group in the Karoo Basin (Trewin *et al.* 2002).

Trewin *et al.* (2002) investigated the sedimentology and petrography of the Bay of Harbours Formation and described the sandstone beds as a moderately well-sorted, medium-grained, feldspar-rich lithic arenite with a significant volcaniclastic component. The petrography of the sandstone beds indicate a provenance typical of a dissected magmatic arc (Dickinson *et al.* 1983). Palaeocurrent evidence from Trewin *et al.* (2002) indicate transport from the NE sector, which would represent a broadly SW vector in a 180° rotated reconstruction.

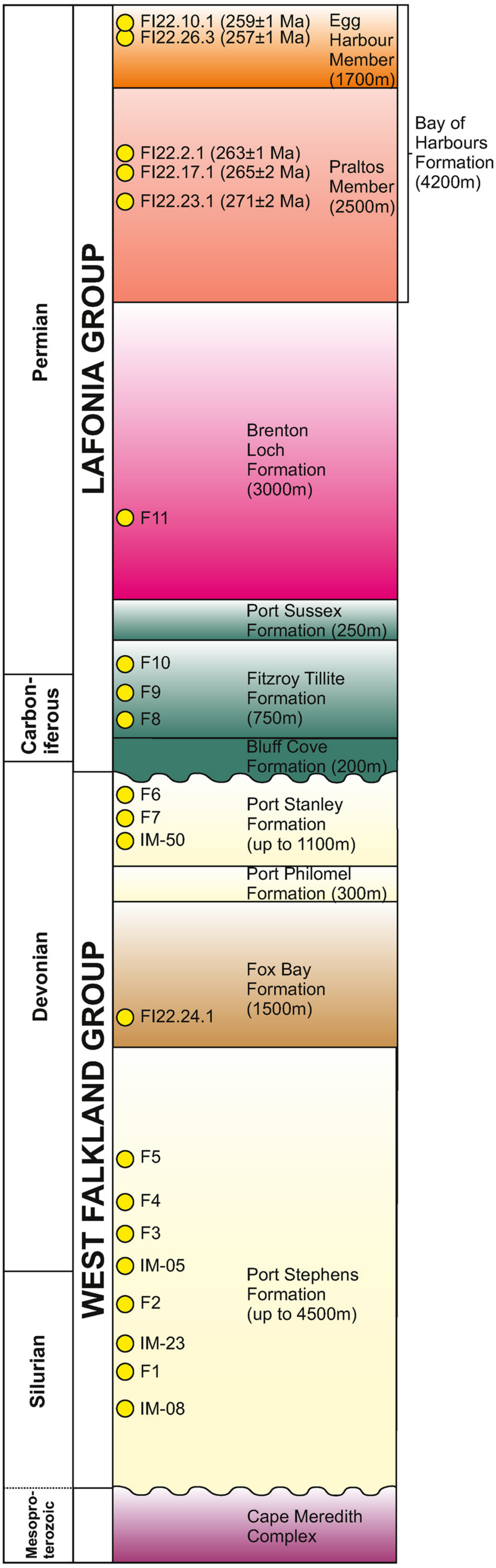

Fig. 3. Stratigraphy of the geological history of the Falkland/Malvinas Islands. The estimated maximum likely depositional ages are from Supplementary Figure S1. Source: adapted from Malone *et al.* (2023); sample sites from Ramos *et al.* (2017), Malone *et al.* (2023) and this study.

The entire sedimentary succession of the Falkland/Malvinas Islands is cut by a swarm of Early Jurassic (Hole *et al.* 2016) and mid-Cretaceous (Stone *et al.* 2008) mafic dykes. The Early Jurassic dykes have been correlated with extensive basaltic magmatism associated with the Karoo–Ferrar large igneous provinces at *c.* 183 Ma (Svensen *et al.* 2012).

Sample selection

Six samples (Supplementary Table S1) from across the Falkland Islands were selected for detrital zircon provenance analysis (Fig. 2). The primary focus of this study was the late Permian Bay of Harbours Formation, from where five samples were selected for analysis. A single sample (FI22.24.1) was also analysed from the West Falkland Group to complement the detrital zircon analysis of Ramos *et al.* (2017) and Malone *et al.* (2023). The selected sample was from the Fox Bay Formation because no provenance data has previously been recorded for this unit.

Two samples were selected from the uppermost Egg Harbour Member (Fig. 3); sample FI22.10.1 is from the upper part of the stratigraphy and is a massive medium-grained sandstone from a cliff section at White Cliff Point at Ruggles Bay (Fig. 2). Sample FI22.26.3 is a coarse-grained massive sandstone, also from the upper part of the Egg Harbour Member, which crops out in a narrow coastal exposure at New Haven (Fig. 2).

Three samples were selected from the Praltos Member of the lower Bay of Harbours Formation (Fig. 3). Samples FI22.17.1 and FI22.2.1 are medium-grained massive sandstones from gently dipping units adjacent to the Bay of Harbours shoreline (Fig. 2). Sample FI22.23.1 is a fine-grained laminated sandstone from the northern extent of the Praltos Member at Bodie Creek (Fig. 2).

Analytical methods

U–Pb zircon geochronology

Heavy minerals were separated from bulk sieved (<250 µm) sediment using standard density liquid and magnetic separation procedures. Zircon-enriched extracts were mounted in hard epoxy resin on glass slides and polished for analysis. The zircon crystals were typically in the size range 100–170 µm, with a range of grain sizes analysed for all samples. Zircon U–Pb geochronology on all six samples (FI22.2.1, FI22.10.1, FI22.17.1, FI22.23.1, FI22.24.1 and FI22.26.3) was carried out at the at the London Geochronology Centre, University College London in November 2023 using a Agilent 7700 inductively coupled plasma mass spectrometer coupled to a New Wave Research 193 nm excimer laser. Typical laser spot sizes of 25 µm were used with a 7–10 Hz repetition rate and a fluence of 2.5 J cm^{-2} and the outer parts of the grain were analysed. The background measurements before ablation lasted 15 s and the laser ablation dwell time was 25 s.

The external zircon standard was Plešovice, which has a thermal ionization mass spectrometry reference age of 337.13 ± 0.37 Ma (Sláma *et al.* 2008). The standard errors on the isotope ratios and ages include the standard deviation of the $^{206}Pb/^{238}U$ ages of the Plešovice standard zircon. The time-resolved signals that record isotopic ratios with depth in each crystal were processed using GLITTER 4.5 data reduction software, which was developed by the ARC National Key Centre for Geochemical Evolution and Metallogeny of Continents at Macquarie University and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Exploration and Mining. Processing enabled filtering to remove spurious signals due to overgrowth boundaries, weathering, inclusions or fractures. The ages were calculated using the $^{206}Pb/^{238}U$ ratios for samples dated <1.1 Ga and the $^{207}Pb/^{206}Pb$ ratios for older grains. Discordance was determined using $((^{207}Pb/^{235}U–^{206}Pb/^{238}U)/^{206}Pb/^{238}U)$ and similar for the

$^{207}Pb/^{206}Pb$ ages. The full analyses and full analytical methods are provided in the Supplementary Files and Supplementary Table S2.

Lu–Hf isotope analysis

Lu–Hf isotopes were determined on a subset of two of the samples from the Egg Harbour (FI22.10.1) and Praltos (FI22.2.1) members using the same spot location as for the U–Pb dating. Due to spot size parameters (25 µm), the Lu–Hf isotopes for sample FI22.2.1 were determined on zircon grains larger than 150 µm (see Supplementary Tables S2 and S3), which have an age distribution overlapping with zircon grains <150 µm (Supplementary Figure S1). The grain sizes for sample FI22.10.1 were all generally in the range 130–160 µm. All the grains >150 µm (46 total) in sample FI22.2.1 analysed for U–Pb geochronology were also analysed for Lu–Hf isotopes. In sample FI22.10.1, a total of 96 Lu–Hf isotope analyses were determined following the same spot locations as for the U–Pb geochronology.

The analyses were determined (April 2024) on a Neptune multi-collector inductively coupled plasma mass spectrometer coupled with a laser ablation system at the British Geological Survey (Keyworth, Nottingham, UK) following the methods of Bauer and Horstwood (2018). The initial $^{176}Hf/^{177}Hf$ ratios were calculated using the U–Pb crystallization age of each grain and the results are expressed as initial ε_{Hf} (ε_{Hfi}). The ε_{Hf} values were calculated using a ^{176}Lu decay constant of 1.867×10^{-11} a^{-1} (Söderlund *et al.* 2004), the present-day chondritic $^{176}Lu/^{177}Hf$ value of 0.0336 and an $^{176}Hf/^{177}Hf$ ratio of 0.282785 (Bouvier *et al.* 2008). Full analytical details are provided in the Supplementary Files and the data are presented in Supplementary Table S3.

Results

U–Pb detrital zircon geochronology

The sample locations are shown in Figure 2 along with the detrital zircon sample sites from Ramos *et al.* (2017) and Malone *et al.* (2023). The age distribution of all six samples analysed are plotted in Figure 4 as kernel density estimator plots. The five samples from the Bay of Harbours Formation all share similar age distribution profiles (Fig. 4), with a prominent late Permian unimodal age peak and a broad, but minor, distribution of recycled zircon grains through the Paleozoic and Neo-Mesoproterozoic. The two samples from the Egg Harbour Member have late Permian age peaks at *c.* 258 Ma and the three samples from the underlying Praltos Member have strongly unimodal age peaks in the range 271–265 Ma. The single sample from the West Falkland Group records broad age profiles dominated by Pan African (*c.* 540 Ma), Neoproterozoic (*c.* 630 Ma) and Grenvillian (*c.* 1100 Ma) ages.

Lu–Hf isotopes

Lu–Hf isotopic analysis was conducted on two samples from the late Permian Bay of Harbours Formation that were also analysed for U–Pb geochronology. The data are plotted in Figure 5a alongside data from the mid-Permian Brenton Loch Formation of Malone *et al.* (2023). The Egg Harbour Member (FI22.10.1) yielded ε_{Hfi} values in the range −4 to +3, broadly defining a mid to late Permian age ε_{Hfi} field, within which many grains cluster at values from −2 to +1 (Fig. 5a). The Praltos Member (FI22.2.1) exhibits a similar range in ε_{Hfi} values to the Egg Harbour Member, with the majority of values lying in the range −2 to +3 for the late Permian age grains.

Provenance analysis

To aid our interpretation of the potential correlations to Permian successions across Gondwana, we compared the units from the Falkland/Malvinas Islands with mid- to late Permian sequences from South America, South Africa, the Antarctic Peninsula, the Ellsworth Mountains, East Antarctica and the Scotia Sea (Supplementary Table S4). We used the available U–Pb and Lu–Hf datasets from across West Gondwana, combined with palaeo-current evidence, to test reconstruction models for the late Permian.

South Africa

The late Permian units from the upper Ecca and Beaufort groups of the Karoo Basin succession of South Africa (Fig. 6) were compared with the Permian successions from the Falkland/Malvinas Islands, including palaeocurrrent evidence from Trewin *et al.* (2002). Dean (2014) and Viglietti *et al.* (2018) determined U–Pb detrital zircon analysis on a suite of successions from the Karoo Basin. Dean (2014) investigated samples (13ZA93, 13ZA91, 13ZA26 and 09-BL-C1; Fig. 6) from the western sector of the Karoo Basin from the upper part of the Ecca Group and the Beaufort Group (Fig. 7). Viglietti *et al.* (2018) investigated samples (PV-NbDo1, PV-Springfontein, PV-KT-In1, PV-Venterstad, PV-H1, PV-Java, PV-Cr1, PV-LC, PV-BM-In2 and Kat2Pass; Fig. 6) from the upper part of the Beaufort Group, including the Teekloof, Balfour and Katberg formations at the Permo-Triassic boundary (Fig. 7).

South America

Zircon data from sedimentary successions across several areas of South America were compared with data from the Falkland/Malvinas Islands. The Permian Tunas Formation of the Ventania System of eastern Argentina (Fig. 6) lies to the east of the extensive Permian magmatic complex of the Choiyoi Province (Bastías-Mercado *et al.* 2020). The succession is at least 1200 m thick and is dominated by yellow–grey fine- to medium-grained sandstone deposited in a deltaic setting with *Glossopteris* and rare tuff beds yielding an age of 280.8 ± 1.9 Ma (López Gamundi *et al.* 2013). The succession has a dominant palaeocurrent vector towards the NE (López Gamundi *et al.* 1995). Ramos *et al.* (2014) determined U–Pb ages on detrital zircon from a broad section of units from the Ventania System, including the Permian Tunas Formation (SLV-VE-22 and SLV-VE-23; Fig. 6).

In southern Patagonia, the Madre de Dios terrane is host to fragments of Permian accretionary complexes that developed along the West Gondwana margin, including the Duque de York Complex, which records Permian magmatism in the detrital zircon record at 280, 265 and 250 Ma (Riley *et al.* 2023*a*). Four samples (AL1, MD3, MD32 and DSOL-16; Fig. 6) were compared with the Falkland/Malvinas Islands data (Hervé *et al.* 2003; Castillo *et al.* 2016).

Antarctic Peninsula and Scotia Sea

The accretionary complexes of Patagonia continue into the Antarctic Peninsula and crustal blocks of the proto-Scotia Sea. Permian volcaniclastic successions in the Antarctic Peninsula include the Trinity Peninsula Group and the LeMay Group, which have been investigated by Castillo *et al.* (2016), Barbeau *et al.* (2010) and Riley *et al.* (2023*b*), who reported U–Pb and Lu–Hf data from the detrital zircon population of the metasedimentary rocks. The Trinity Peninsula Group has been subdivided into three major units (Fig. 6): the Carboniferous–early Permian View Point Formation (Bradshaw *et al.* 2012); the Hope Bay Formation (late Permian–Early Triassic; Birkenmajer 1992); and the Permian–Triassic Legoupil Formation (Thomson 1975).

The LeMay Group is a *c.* 4 km thick accretionary complex of variably deformed trench-fill turbidites and trench-slope sediments associated with mélange belts of ocean floor material (Riley *et al.* 2023*b*). Two main groups (1 and 2) identified from the LeMay

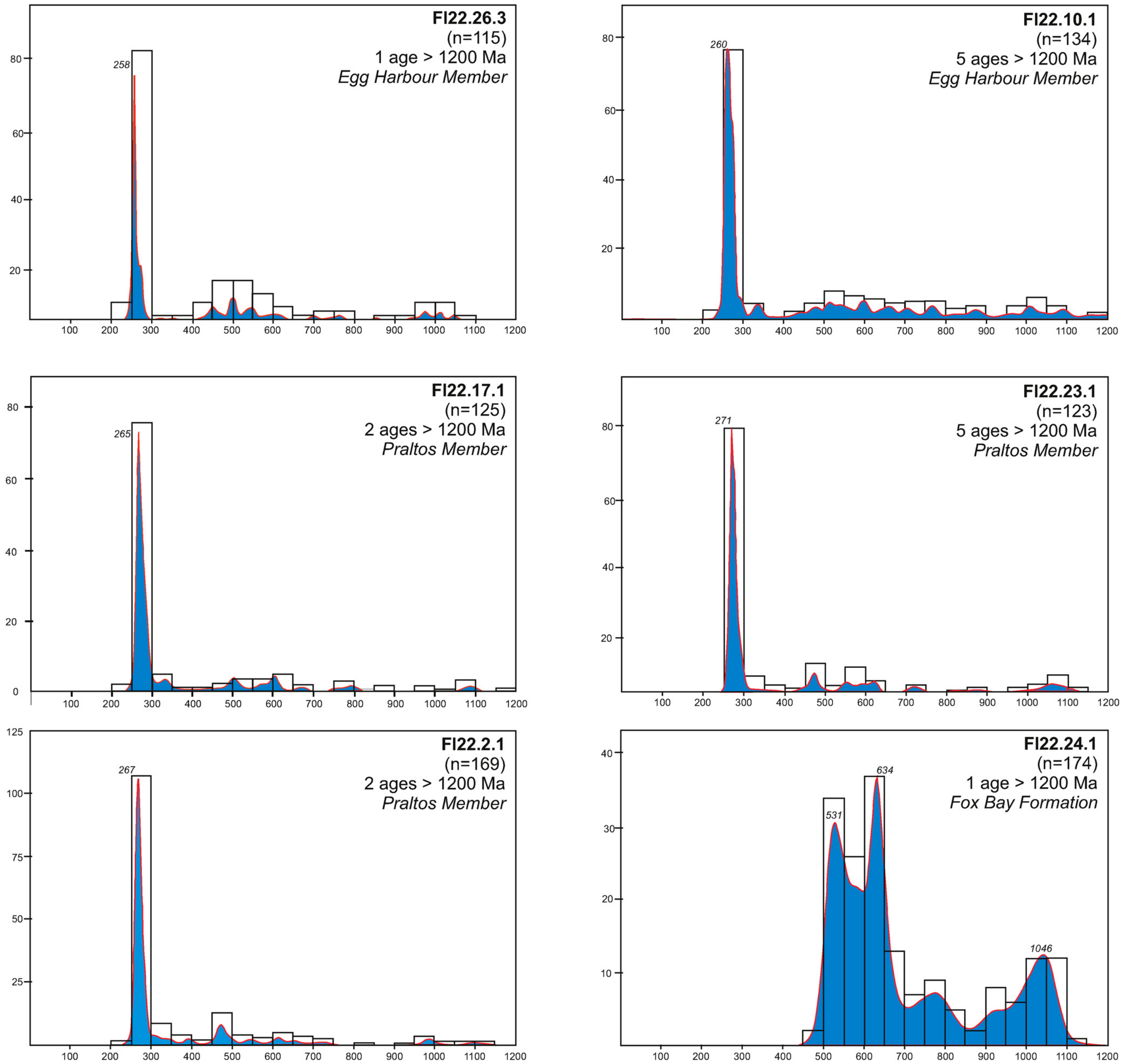

Fig. 4. Kernel density estimator plots (Vermeesch 2013) of U–Pb detrital zircon ages for a range of sandstone lithologies from the West Falkland and Lafonia groups of the Falkland/Malvinas Islands. Full datasets are available in Supplementary Table 2. Bin widths for all plotted samples are 50 Ma.

Group (Fig. 6) have a late Permian MLA of deposition and suggest an accretion event in the Mid-Triassic during an episode of flat-slab subduction.

Prior to the opening of the Scotia Sea in the Eocene, the crustal blocks of the present-day North and South Scotia ridges would have been located adjacent to Patagonia and the northern Antarctic Peninsula (Fig. 6). Permian successions from South Georgia (the Salomon Glacier Formation; unpublished data, British Antarctic Survey) and dredged metasedimentary samples from Bruce Bank (Riley *et al.* 2022) were compared with the Falkland/Malvinas Islands Permian units.

Also included for comparison are mid to late Permian feldspar-rich sandstone units from the southern Antarctic Peninsula at Erewhon Nunatak–Mt Peterson (Fig. 6). Elliot *et al.* (2016) and Riley *et al.* (2023*a*) determined a late Permian age for the units at Erewhon Nunatak–Mt Peterson based on their detrital zircon age profiles (R.8006.1, R.8008.2, R.8009.3, R.8009.4 and DL14; Fig. 6) and *Glossopeteris* flora.

Ellsworth Mountains and East Antarctica

The Polarstar Formation is the youngest stratigraphic unit of the Ellsworth Mountains of West Antarctica and has been correlated with the sandstone beds of Erewhon Nunatak–Mt Peterson units of the Antarctic Peninsula (Elliot *et al.* 2016). Three samples (MW54.3, MW210.5 and PRR299; Fig. 6) are included in this analysis, together with data from Nelson and Cottle (2019) and Elliot *et al.* (2016).

Late Permian sandstone beds from the Theron Mountains in East Antarctica were examined by Flowerdew *et al.* (2012), who recognized that their source was a mixture from the late Permian arc, alongside recycled sources. A medium-grained, feldspar-rich sandstone unit from Faraway Nunatak in the Theron Mountains (Z.1608.7; Fig. 6) is included here for comparison. A late Permian volcanic sandstone from the Buckley Formation (11-5-22; Fig. 6) of the central Transantarctic Mountains is also included for comparison (Elliot *et al.* 2015, 2017).

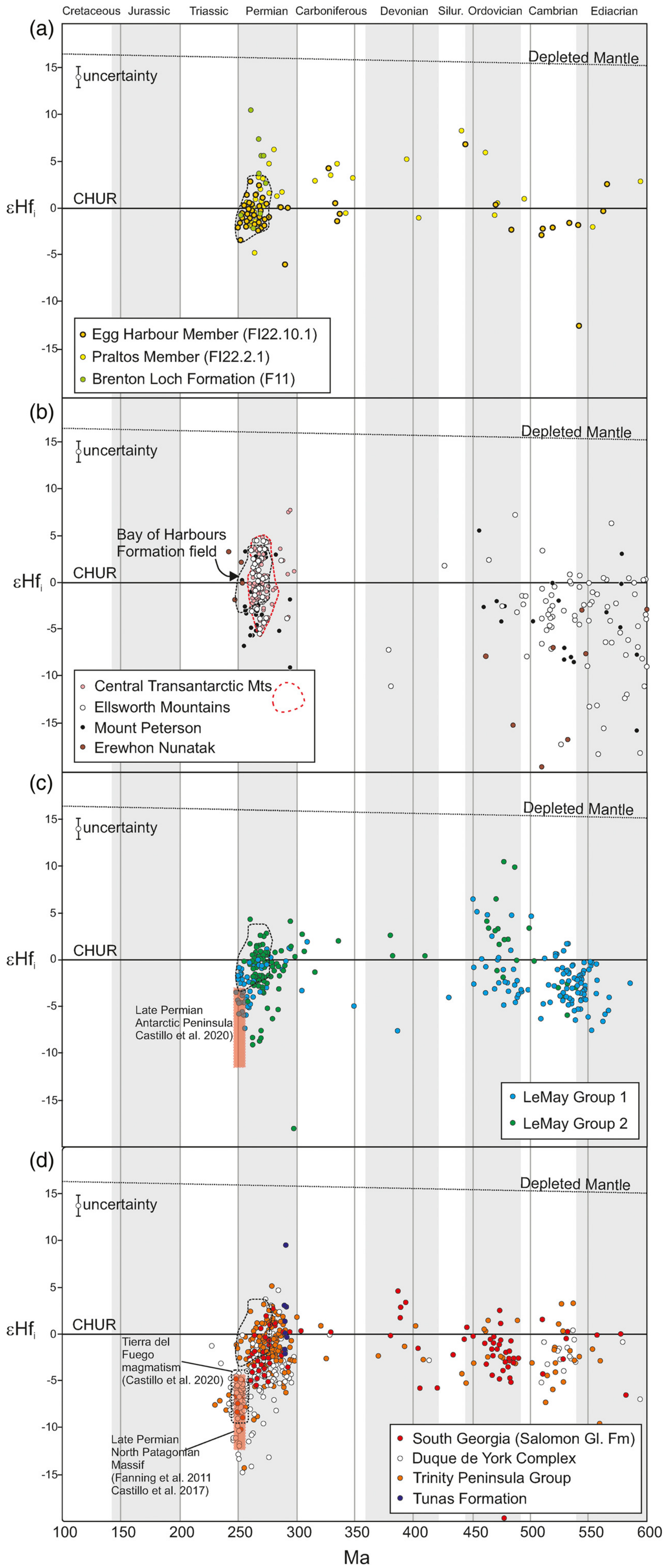

Fig. 5. U–Pb zircon ages ($^{238}U/^{206}Pb$) v. initial ε_{Hf} values for zircon grains from sedimentary units examined as part of this study. Vertical bars represent geological periods. (**a**) Bay of Harbours Formation (this study; Supplementary Table S3) and Brenton Loch Formation (Malone *et al.* 2023). (**b**) Ellsworth Mountains, Mt Peterson and Erewhon Nunatak (Elliot *et al.* 2015, 2016; Nelson and Cottle 2019; Riley *et al.* 2023*a*). (**c**) LeMay Group accretionary complex (Riley *et al.* 2023*b*). (**d**) Trinity Peninsula Group, Duque de York Complex, Tunas Formation and South Georgia accretionary complex (Barbeau *et al.* 2010; Fanning *et al.* 2011; Bradshaw *et al.* 2012; Ramos *et al.* 2014; Castillo *et al.* 2015, 2016; British Antarctic Survey, unpublished data). Shaded/dashed data fields are from magmatic rocks.

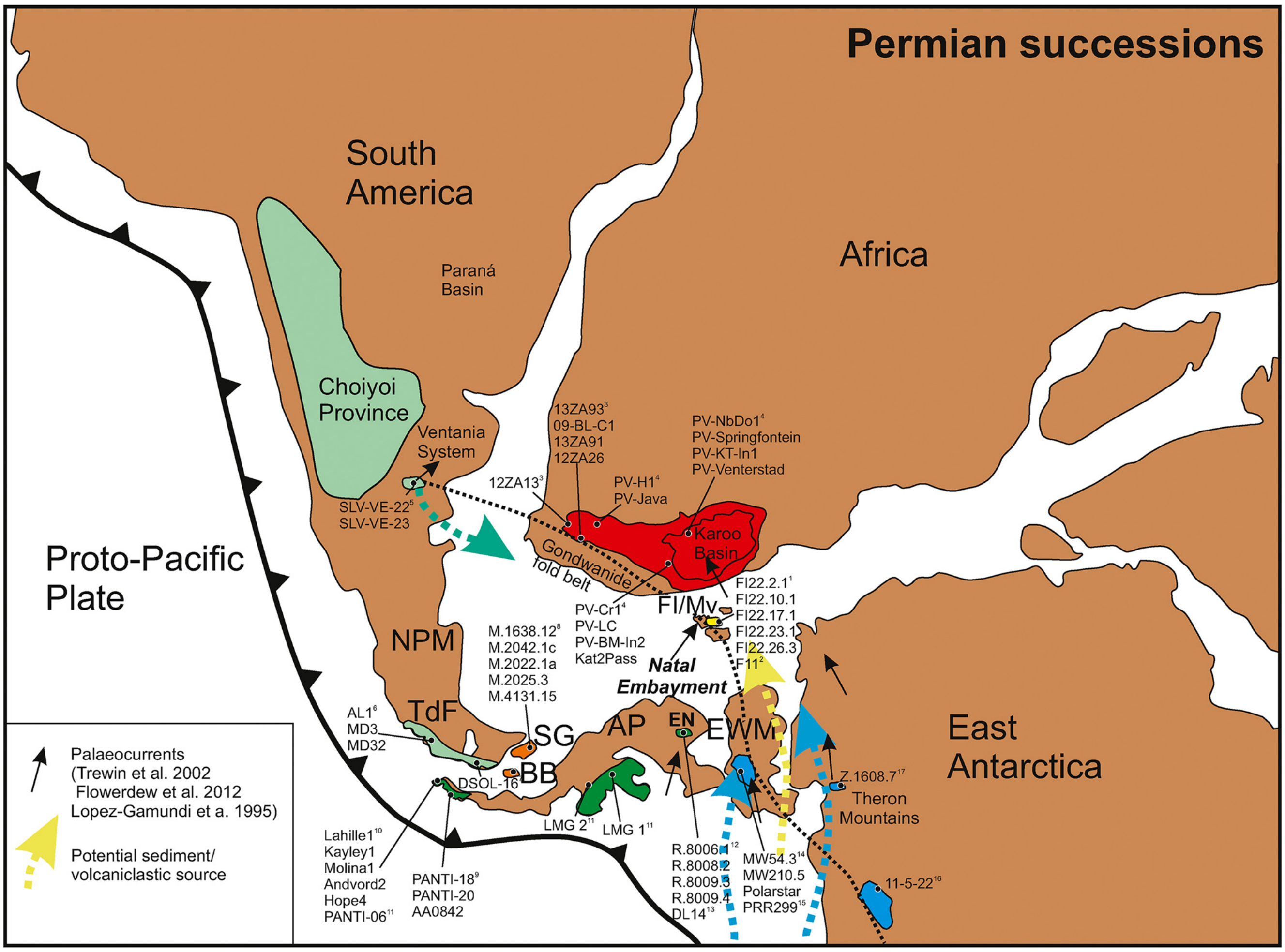

Fig. 6. Sample sites from late Permian volcano-sedimentary successions from across West Gondwana. FI/Mv, Falkland/Malvinas Islands; EWM, Ellsworth–Whitmore Mountains; EN, Erewhon Nunatak–Mt Peterson; AP, Antarctic Peninsula; LMG, LeMay Group; BB, Bruce Bank; SG, South Georgia; TdF, Tierra del Fuego; NPM, North Patagonian Massif. Data sources: [1]this study; [2]Malone *et al.* (2023); [3]Dean 2014; [4]Viglietti *et al.* (2018); [5]Ramos *et al.* (2014); [6]Hervé *et al.* (2003); [7]Castillo *et al.* (2016); [8]British Antarctic Survey, unpublished data; [9]Castillo *et al.* (2016); [10]Barbeau *et al.* (2010); [11]Riley *et al.* (2023*b*); [12]Riley *et al.* (2023*a*); [13]Elliot *et al.* (2016); [14]Elliot *et al.* (2016); [15]Nelson and Cottle (2019); [16]Elliot *et al.* (2015); [17]Flowerdew *et al.* (2012).

Detrital zircon data analysis

Maximum likely depositional age

In the absence of directly dateable volcanic layers or a diagnostic fossil assemblage, detrital mineral geochronology is often the only method available to estimate the depositional age of siliciclastic rocks. Detrital zircon U–Pb geochronology has become a popular technique to obtain MLAs of deposition, but there is little consistency in the estimation algorithms used. We follow the revised approach of Vermeesch (2021) to calculate the MLA of

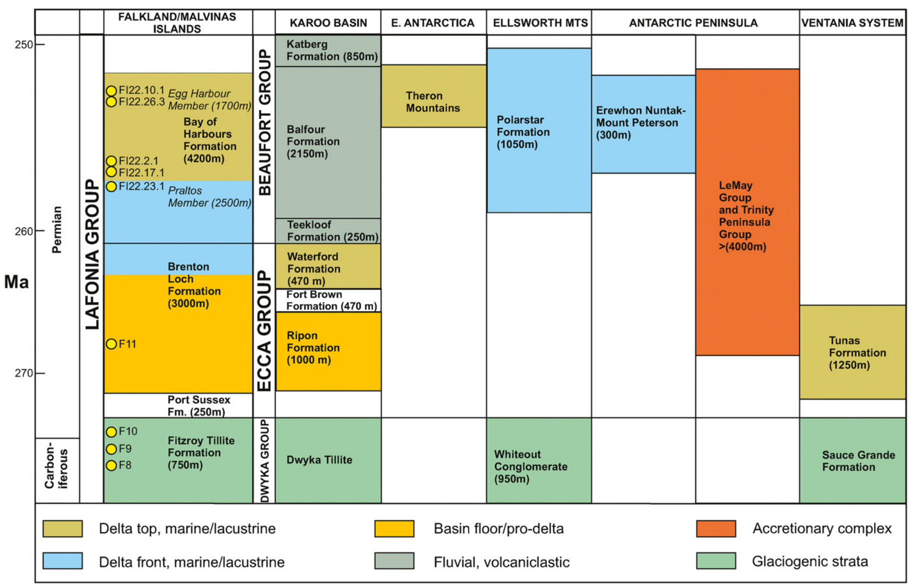

Fig. 7. West Gondwana Late Paleozoic stratigraphic correlations and depositional environments. Source: derived from López Gamundi *et al.* (1995); Trewin *et al.* (2002); Simões *et al.* (2012); Elliot *et al.* (2016); Malone *et al.* (2023); Riley *et al.* (2023*b*).

deposition for the Bay of Harbours Formation samples analysed in this study. The results are presented in Supplementary Figure S2 using radial plots to derive the MLA of deposition, but prior knowledge of the geological setting and field relationships are essential to fully interpret the derived MLA. For detrital zircon geochronology from comparative units, we also use the methods of Vermeesch (2021) to determine the MLA of deposition.

Five samples from the Bay of Harbours Formation were analysed. The samples from the Praltos Member had dominant zircon ages in the range *c*. 271–265 Ma, with a broad spectrum of Paleozoic and Proterozoic ages. The calculated (Vermeesch 2021) MLAs were *c*. 263 Ma (FI22.2.1), *c*. 265 Ma (FI22.17.1) and *c*. 271 Ma (FI22.23.1). By contrast, two samples from the Egg Harbour Member had primary age peaks at *c*. 258 Ma, with MDAs of *c*. 259 Ma (FI222.10.1) and *c*. 257 Ma (FI22.26.3); they also displayed a broad spectrum of Paleozoic and Proterozoic ages.

Multi-dimensional scaling analysis

Multi-dimensional scaling (MDS) plots of U–Pb detrital zircon data were used to help evaluate which correlative units from West Gondwana shared a common source. The samples from the Falkland/Malvinas Islands are plotted in Figure 8a alongside a broad suite of samples from across South Africa, Antarctica and South America. The MDS plot includes the Permian units that are the focus of this study, but also units from the mid- to Early Paleozoic discussed by Malone *et al.* (2023) and Ramos *et al.* (2017), alongside new data from this study. The pre-Permian field for the Falkland/Malvinas Islands shares a close association with the Ellsworth Mountains and East Antarctica, as well as units from South Africa and South America. As a consequence, it provides limited palaeogeographical insight given the highly recycled nature of the detrital zircon population (Anderson *et al.* 2016).

The five late Permian samples from the Bay of Harbours Formation cluster in Figure 8a, with a close similarity to units from the Karoo Basin (the Katberg and Balfour formations), units from the Antarctic Peninsula (the Trinity Peninsula Group) and South America (the Duque de York Complex), as well as sandstone beds from the Ellsworth Mountains (the Polarstar Formation) and the Theron Mountains. In Figure 8b, the Permian units with the most proximal relationship to the Bay of Harbours Formation in Figure 8a are replotted relative to each other, hence the adjustment in relative positions in an MDS configuration.

The samples from the Balfour and Katberg formations, which have the closest similarity to the Bay of Harbours Formation on the MDS plot (Fig. 8a), are subdivided into individual samples to allow a better assessment of those samples that may share a common source. There is a strong similarity between sample FI22.10.1 from the upper Bay of Harbours Formation to three samples (PV-BM-In2, PV-Nb-Do1 and PV-LC; Fig. 8b) from the upper Balfour Formation (Viglietti *et al.* 2018) and the sandstone unit from the Theron Mountains (Z.1608.7; Fig. 8b). There is also a close relationship with samples from Erewhon Nunatak–Mt Peterson from the southern Antarctic Peninsula and, to some extent, the Polarstar Formation of the Ellsworth Mountains. Samples FI22.2.1, FI22.17.1 and FI22.23.1 from the lower Bay of Harbours Formation (Praltos Member) share a close relationship with the middle to upper Permian Beaufort Group of the Karoo Basin (the Balfour and Katberg formations) and also the accretionary complexes from the northern Antarctic Peninsula and Patagonia. The Balfour Formation is upper Permian in age and has recalculated MLAs of *c*. 260 Ma (Viglietti *et al.* 2018), akin to the Egg Harbour Member (*c*. 258 Ma; Fig. S2) and the sandstone bed from the Theron Mountains, with a recalculated MLA of *c*. 263 Ma.

Our new data demonstrate that the closest age relationship between the late Permian sequences of the Falkland/Malvinas Islands and those of the Karoo Basin is between the Bay of Harbours Formation and the Balfour and Katberg formations (the upper Beaufort Group). This finding contrasts with previous studies (e.g. Aldiss and Edwards 1999; Trewin *et al.* 2002; Malone *et al.* 2023), which all favoured a lithostratigraphic correlation with the lower Beaufort Group of the Karoo Basin.

The mid-Permian succession from the Ventania System (Tunas Formation) of South America is examined here. The Tunas Formation of the Ventania System is the most proximal to the Karoo Basin and Natal Embayment (Fig. 6), but has a depositional age of *c*. 281 Ma (López Gamundi *et al.* 1995) and is therefore significantly older than the Bay of Harbours Formation (<260 Ma) and closer in age to the mid-Permian Brenton Loch Formation (*c*. 270 Ma). The MDS plot (Fig. 8b) illustrates that the Tunas Formation is distinct from the Permian units of the Falkland/Malvinas Islands, but has a nearest neighbour relationship with the accretionary complex on South Georgia and the Balfour Formation of the Karoo Basin. However, the Tunas Formation plots remotely to the similarly aged Brenton Loch Formation of the Falkland/Malvinas Islands (F11; Fig. 8b).

Cumulative age distribution

The cumulative age distribution plot (Fig. 9) is shown for a selection of Permian samples that share the closest similarity in the MDS plot (Fig. 8b). Cawood *et al.* (2012) outlined that detrital zircon age population characteristics in sedimentary and volcaniclastic successions are strongly controlled by the tectonic setting, with zircon-rich intermediate–silicic magmatism typically related to subduction at convergent margins, which leads to characteristic unimodal detrital zircon age profiles dominated by the youngest grains. By contrast, divergent and passive margin settings have detrital zircon profiles that are characteristically polymodal and reflect varied sources reflecting extensive recycling. The Bay of Harbours Formation has a broadly unimodal Permian population (Fig. 4), but records differences between the Praltos Member and the Egg Harbour Member. The Praltos Member is characterized by a *c*. 65% late Permian age population and is similar in profile to the Polarstar Formation of the Ellsworth Mountains (Fig. 9). By contrast, the younger Egg Harbour Member is characterized by a less pronounced late Permian age population at *c*. 55% of the total ages recorded and is almost identical in profile to the upper Balfour Formation of the Karoo Basin and the Theron Mountains sandstone beds. The sample from the Brenton Loch Formation (F11; Malone *et al.* 2023) has a far less pronounced late Permian age population of <30% and is distinct in age distribution from other Permian successions (Fig. 9).

Barham *et al.* (2022) noted that sedimentary units with a strongly unimodal population of the youngest detrital zircon grains are likely to originate from a depositional setting closer to the convergent margin and the primary magmatic source. The LeMay Group (Group 2), which forms the late Permian accretionary complex (Riley *et al.* 2023*b*) of Alexander Island (Antarctic Peninsula), has the most pronounced late Permian unimodal age population comprising *c*. 80% of the total age distribution, which is consistent with its location adjacent to the convergent margin (Fig. 9).

The Tunas Formation, part of the Ventania System of eastern Argentina, has a mid-Permian population (*c*. 40%; Fig. 9) and is distinct from the other Permian units examined here.

Lu–Hf isotopes

Lu–Hf isotope data aid with the interpretation of zircon U–Pb data to better define the provenance and correlate similar sediment source regions. Two samples from the Bay of Harbours Formation (this study) and one from the Brenton Loch Formation (Malone

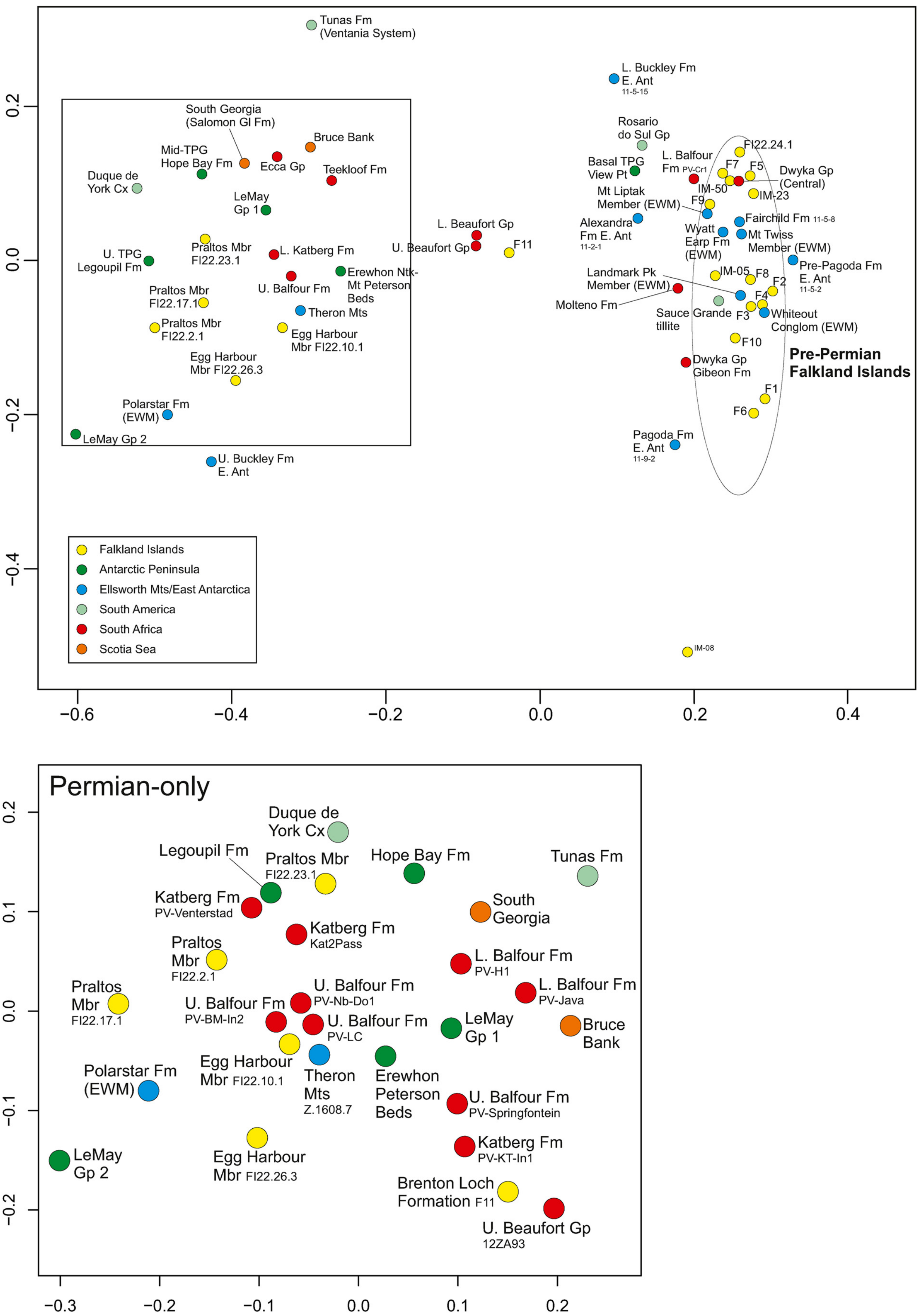

Fig. 8. Multi-dimensional scaling (MDS) maps (Vermeesch 2013, 2018) comparing the age spectra in dissimilar samples calculated using the Kolmogorov–Smirnov statistic. An MDS plot maps the degree of similarity between each sample, with any two points plotting closer if they are more similar. The axis scales are dimensionless and have no physical meaning. (**a**) MDS plot for samples from the Falkland/Malvinas Islands and adjacent sectors in West Gondwana. Permian data sources are provided in Figure 6. Pre-Permian data sources are detailed in Supplementary Table 2. (**b**) MDS plot for Permian-only samples that plot in close proximity to the Bay of Harbours Formation in Figure 8a. These data are plotted relative to each other, hence the adjustment in relative positions compared with Figure 8a. Data sources: provided in Figure 6 and Supplementary Table 2.

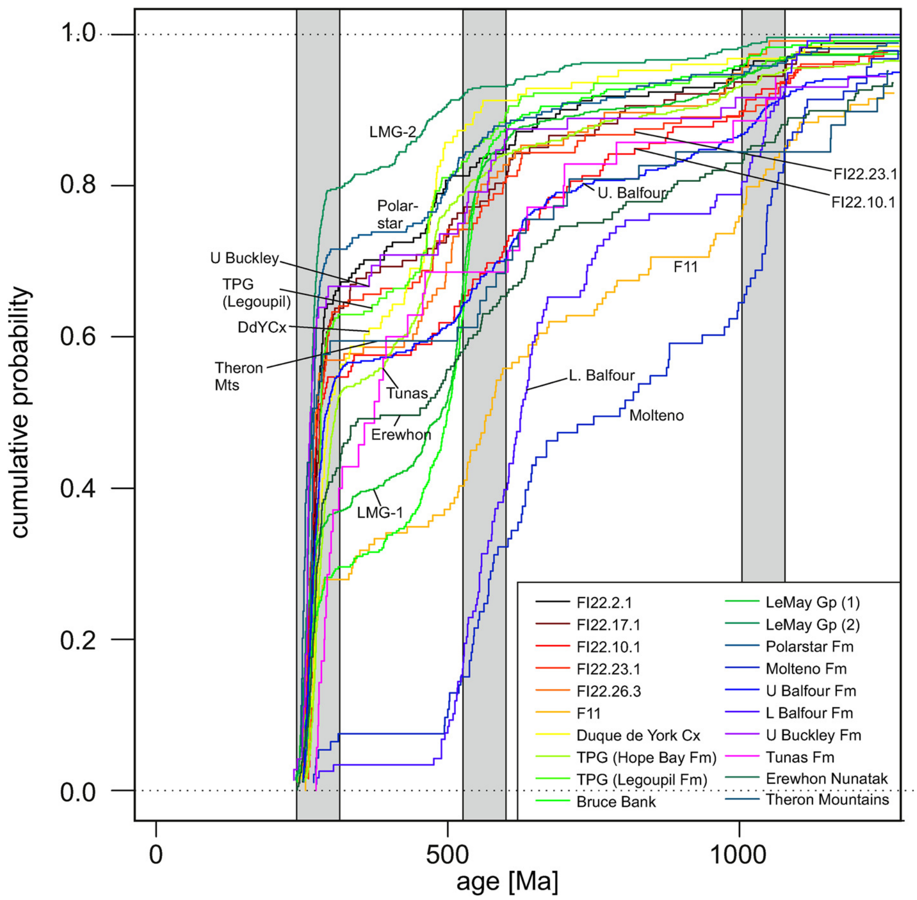

Fig. 9. Cumulative age distribution plot for late Permian samples from Figure 8b. Grey bars represent significant zircon peaks. TPG, Trinity Peninsula Group; LMG, LeMay Group; DdYCx, Duque de York Complex.

et al. 2023) are plotted in Figure 5a and form a tight grouping for the late Permian population (ε_{Hfi} = −2 to +3).

There is broad overlap in age and ε_{Hf} values between the late Permian units from the Falkland/Malvinas Islands with late Permian sedimentary successions from the Ellsworth Mountains, Erewhon Nunatak–Mt Peterson and the central Transantarctic Mountains (Fig. 5b). The greatest overlap is with the Praltos Member, given there is a low abundance of ages <265 Ma from the Ellsworth Mountains and the central Transantarctic Mountains. Samples of the LeMay Group accretionary complex from Alexander Island (western Antarctic Peninsula) have MLAs of deposition in the range 260–250 Ma (Riley *et al.* 2023*b*), with both Group 1 and Group 2 overlapping to some degree with the Bay of Harbours Formation, although the LeMay Group trends to more radiogenic values and has a broader distribution of recycled zircon grains (Fig. 5c).

Correlations with the accretionary complexes of the northern Antarctic Peninsula and southern Patagonia (including South Georgia) are examined in Figure 5d, where a more complex picture is evident. The late Permian–Early Triassic metasedimentary successions from the Trinity Peninsula Group (Antarctic Peninsula), the Duque de York Complex (Patagonia) and South Georgia/Bruce Bank (Scotia Sea) yield zircons with very similar U–Pb age ranges to those obtained from the Bay of Harbours Formation, but the Lu–Hf isotopic data show that there is limited overlap in composition and the accretionary complexes share a separate source to the Bay of Harbours Formation. The accretionary units have a broad range of ε_{Hf} values and show a clear trend to more radiogenic values in the late Permian–Early Triassic population from Patagonia (the Duque de York Complex), where there is significant overlap with magmatic units from the North Patagonian Massif (Falco *et al.* 2022) and the igneous complexes of Tierra del Fuego (Castillo *et al.* 2020). However, there is almost no overlap between these South American sources and the late Permian units from the Falkland/Malvinas Islands, especially so for the youngest units (the Egg Harbour Member). Falco *et al.* (2022) attributed changes in the ε_{Hf} values of the North Patagonian Massif through the mid to late Permian to steepening of the subducted slab at *c.* 253 Ma. Their analysis demonstrates that for late Permian volcanism in South America to have been a primary source of sediment, the zircons contained within the sedimentary succession would need to be strongly radiogenic (typically −5 to −12), incorporating the isotopic ‘pull-down’ at *c.* 255 Ma. This pattern is not reflected in the zircons analysed from the Bay of Harbours Formation sedimentary units, which must therefore have had an alternative source.

The few Lu–Hf isotope data available from the Tunas Formation of the Ventania System (Fig. 5d; Ramos *et al.* 2014) fall in a narrow range of −2 to +2 (ε_{Hfi}), and, although overlapping with the ε_{Hf} range of the Bay of Harbours Formations, is considerably older at *c.* 280 Ma.

Unfortunately, no Lu–Hf data is available from the sedimentary successions of the Karoo Basin and Theron Mountains to compare with the Lafonia Group units of the Falkland/Malvinas Islands. However, McKay *et al.* (2016) investigated the trace element composition of zircon from volcanic tuffs of the Karoo Basin and determined that magmatism was subduction-driven prior to 270 Ma, but with a shift to intraplate, shallow-sourced magmatism in the late Permian. They attributed the shift to late Permian extension related to the development of a back-arc rift, with late Permian volcanism related to a source proximal to East Antarctica.

Discussion

Deseado terrane/South America model

Proponents of a proximal relationship between the Falkland/Malvinas Islands and South America infer that the crustal blocks of the Falkland/Malvinas Islands and southern Patagonia were contiguous during the Paleozoic, potentially forming part of a

Deseado terrane (Ramos *et al.* 2017; Schilling *et al.* 2017). Such a tectonic configuration would imply proximity, continuity and source-to-sink relationships between the volcano-sedimentary units of the late Permian magmatic province and the accretionary complexes of Patagonia with the late Permian successions of the Falkland/Malvinas Islands. The upper Permian units from Patagonia and the Falkland/Malvinas Islands share strong similarities (Fig. 8); however, the broader detrital zircon U–Pb age distribution and Lu–Hf isotopes are dissimilar.

Age and Lu–Hf data from the extensive North Patagonian Massif Province (Fig. 6) illustrate that it has a distinctive late Permian radiogenic ε_{Hf} signature (−12 to −5; Fig. 5d). Although it is likely to be the primary source for the accretionary complexes of Patagonia and the northern Antarctic Peninsula, it is not a suitable source candidate for the Lafonia Group of the Falkland/Malvinas Islands, an interpretation supported by palaeocurrent data from Trewin *et al.* (2002), which indicates transport with a present-day southern vector. Although there is an overlap in ε_{Hf} values between the magmatic and accretionary complexes of Patagonia and the Lafonia Group during the early to mid-Permian, the overlap diminishes during the late Permian (Fig. 5d). This relationship demonstrates that the sedimentary units of the Falkland/Malvinas Islands had a different source in the late Permian. This may reflect a change in ε_{Hf} values along the Permian continental margin, which could be the consequence of the subducting slab angle, the crustal thickness and whether contiguous parts of the margin were undergoing extension or compression (Nelson and Cottle 2019).

Detrital zircons from the LeMay Group accretionary complex of Alexander Island partially overlap in age and ε_{Hf} composition with the accretionary complexes of Patagonia and the northern Antarctic Peninsula (Fig. 5c), but more extensively overlap with the Bay of Harbours Formation during the late Permian. A counterclockwise rotated Antarctic Peninsula during the late Permian (Elliot *et al.* 2016; McKay *et al.* 2016) could place the LeMay Group accretionary complex in a palaeo-location adjacent to the Natal Embayment and the crustal blocks of the Falkland/Malvinas Islands, the Ellsworth Mountains and Erewhon Nunatak–Mt Peterson, particularly in a pre-Mesozoic setting (Fig. 6). This configuration is, in part, consistent with the Eagles and Eisermann (2020) Skytrain plate model that places the Falkland/Malvinas Islands adjacent to the southern Antarctic Peninsula (albeit during the Early Jurassic), but their reconstruction is not compatible with our data in other areas (e.g. South Georgia in a distal position to South America and the northern Antarctic Peninsula).

In summary, our combined U–Pb and Lu–Hf isotopic datasets do not support a model where the Falkland/Malvinas Islands were adjacent to South America or formed part of the Deseado terrane (e.g. Schilling *et al.* 2017) during the late Permian given the considerable dissimilarity in Lu–Hf isotopes between the accretionary and magmatic complexes of southern Patagonia (Fig. 5d) and the late Permian sedimentary successions of the Falkland/Malvinas Islands.

Natal Embayment model

Our detrital zircon analysis shows that the strongest correlations are evident between the upper Lafonia Group (Falkland/Malvinas Islands) and sedimentary units from the Karoo Basin of South Africa and the Theron Mountains of East Antarctica, compatible with a Natal Embayment origin for the Falkland/Malvinas Islands crustal block in the Late Paleozoic. Both the Egg Harbour and Praltos members have very similar age profiles to units from the upper Balfour and Katberg formations of the upper Beaufort Group from the Karoo Basin, while the Brenton Loch Formation is also akin to successions of the upper Beaufort Group from the western Karoo Basin. Sectors of East Antarctica and the crustal block of the Ellsworth–Whitmore Mountains (Fig. 6), which is geologically related to the feldspar-rich sandstone beds from the southern Antarctic Peninsula at Erewhon Nunatak–Mt Peterson (Fig. 6), are adjacent to the Natal Embayment in Permian reconstructions of Gondwana. Elliot *et al.* (2016) considered that Erewhon Nunatak–Mt Peterson may form a distinct allochthonous block that was originally adjacent to the Ellsworth–Whitmore Mountains during the Permian. Age correlations between the late Permian units of the Falkland/Malvinas Islands and units from East Antarctica–Ellsworth Mountains–Erewhon Nunatak–Mt Peterson are also evident in the statistical analysis presented here (Fig. 8), particularly the sandstone beds from the Theron Mountains. Lu–Hf isotopic data from the East Antarctic–Ellsworth Mountains–Erewhon Nunatak–Mt Peterson sector also strongly support a strong association with the Falkland/Malvinas Islands crustal block, with a similar range in ε_{Hf} values to the Bay of Harbours Formation from the Falkland/Malvinas Islands, particularly in the age range 275–260 Ma.

A primary magmatic source, at least in part, for the volcano-sedimentary successions from the Falkland/Malvinas Islands, Theron Mountains, Ellsworth Mountains, Erewhon Nunatak–Mt Peterson, and potentially components of the LeMay Group, would likely have its locus further along the palaeo-Pacific margin (Fig. 6), although the primary evidence is lacking in the geological record and is likely to have been eroded.

Overall, the data are consistent with a close relationship between the late Permian succession of the Falkland/Malvinas Islands and the upper Permian sedimentary units from the Karoo Basin (Balfour Formation), the Theron Mountains (East Antarctica) and sectors of the Ellsworth Mountains (Polarstar Formation), and the sequences from Erewhon Nunatak and Mt Peterson (Antarctic Peninsula). This relationship is strongly supported by the detrital zircon U–Pb and Lu–Hf analysis, but also by palaeocurrent evidence from across the Natal Embayment.

Conclusions

- Detrital zircon (U–Pb and Lu–Hf) data strongly suggest a direct association between the late Permian sedimentary succession (Bay of Harbours Formation) of the Falkland/Malvinas Islands and the late Permian Balfour Formation (Upper Beaufort Group) of the Karoo Basin.
- Correlations are also evident between the Bay of Harbours Formation and sequences in East Antarctica (Theron Mountains), the Ellsworth Mountains (Polarstar Formation) and the feldspar-rich sandstone of Erewhon Nunatak–Mt Peterson (Antarctic Peninsula), with a potential correlation to components of the LeMay Group accretionary complex of the western Antarctic Peninsula.
- There is no evidence, based on the Lu–Hf isotope geochemistry, for any direct or secondary association between the accretionary complexes of Patagonia and the northern Antarctic Peninsula and the deltaic sandstone of the Falkland/Malvinas Islands.
- We do not favour a scenario that places the Falkland/Malvinas Islands adjacent to South America, or as part of a Deseado terrane, although our data do support a palaeo-position in the Natal Embayment adjacent to the Karoo Basin and East Antarctica/Ellsworth Mountains.
- The locus of the late Permian primary magmatic source for the volcano-sedimentary successions of the Natal Embayment is uncertain, but is likely to be adjacent to the southern Antarctic Peninsula/Ellsworth Mountains and reflects a change in tectonic regime along the margin during the late Permian compared with the Choiyoi Province further north.

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Author contributions **TRR**: conceptualization (lead), methodology (lead), writing – original draft (lead), writing – review and editing (lead); **AC**: conceptualization (equal), formal analysis (lead), writing – original draft (equal), writing – review and editing (equal); **MAH**: conceptualization (supporting), formal analysis (supporting), writing – review and editing (supporting); **ILM**: formal analysis (lead), writing – review and editing (supporting); **MJF**: writing – original draft (supporting), writing – review and editing (supporting); **MLC**: investigation (equal), writing – review and editing (supporting); **DAH**: funding acquisition (lead), investigation (equal), writing – review and editing (supporting).

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Data availability The data that support this research are all available as Supplementary files linked to this article. Full datasets are also hosted at the British Antarctic Survey's Polar Data Centre, https://doi.org/10.5285/612ab314-0398-42a2-8f33-65308a4157dc

References

Adie, R.J. 1952. The position of the Falkland Islands in a reconstruction of Gondwanaland. *Geological Magazine*, **89**, 401–410, https://doi.org/10.1017/S0016756800068102

Aldiss, D.T. and Edwards, E.J. 1999. *The Geology of the Falkland Islands*. British Geological Survey Technical Report **WC/99/10**, https://nora.nerc.ac.uk/507542/

Anderson, J.B., Wallace, D.J., Simms, A.R., Rodriguez, A.B., Weight, R.W.R. and Taha, Z.P. 2016. Recycling sediments between source and sink during a eustatic cycle: systems of late Quaternary northwestern Gulf of Mexico. *Earth-Science Reviews*, **153**, 111–138, https://doi.org/10.1016/j.earscirev.2015.10.014

Barbeau, D.L., Davis, J.T., Murray, K.E., Valencia, V., Gehrels, G.E., Zahid, K.M. and Gombosi, D.J. 2010. Detrital-zircon geochronology of the metasedimentary rocks of north-western Graham Land. *Antarctic Science*, **22**, 65–78, https://doi.org/10.1017/S095410200999054X

Barham, M., Kirkland, C.L. and Handoko, A.D. 2022. Understanding ancient tectonic settings through detrital zircon analysis. *Earth and Planetary Science Letters*, **583**, 117425, https://doi.org/10.1016/j.epsl.2022.117425

Bastías-Mercado, F., González, J. and Oliveros, V. 2020. Volumetric and compositional estimation of the Choiyoi magmatic province and its comparison with other silicic large igneous provinces. *Journal of South American Earth Sciences*, **103**, 102749, https://doi.org/10.1016/j.jsames.2020.102749

Bauer, A.M. and Horstwood, M.S.A. 2018. Small-volume Lu–Hf and U–Pb isotope determination of complex zircons by solution and laser ablation MC-ICP-MS. *Chemical Geology*, **476**, 85–99, https://doi.org/10.1016/j.chemgeo.2017.11.007

Birkenmajer, K. 1992. Trinity Peninsula Group (Permo-Triassic?) at Hope Bay, Antarctic Peninsula. *Polish Polar Research*, **13**, 215–240, https://doi.org/10.1016/j.jsames.2020.102749.2013

Borrello, A.V. 1963. *Sobre la geologia de las Islas Malvinas*. Ministerio de Educación y Justica, Buenos Aires.

Bouvier, A., Vervoort, J.D. and Patchett, P.J. 2008. The Lu–Hf and Sm–Nd isotopic composition of CHUR: constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. *Earth and Planetary Science Letters*, **273**, 8–57, https://doi.org/10.1016/j.epsl.2008.06.010

Bradshaw, J.D., Vaughan, A.P.M., Millar, I.L., Flowerdew, M.J., Trouw, R.A.J., Fanning, C.M. and Whitehouse, M.J. 2012. Permo-Carboniferous conglomerates in the Trinity Peninsula Group at View Point, Antarctic Peninsula: sedimentology, geochronology and isotope evidence for provenance and tectonic setting in Gondwana. *Geological Magazine*, **149**, 626–644, https://doi.org/10.1017/S001675681100080X

Castillo, P., Lacassie, J., Augustsson, C. and Hervé, F. 2015. Petrography and geochemistry of the Carboniferous–Triassic Trinity Peninsula Group, West Antarctica: implications for provenance and tectonic setting. *Geological Magazine*, **152**, 575–588, https://doi.org/10.1017/S0016756814000454

Castillo, P., Fanning, C.M., Hervé, F. and Lacassie, J.P. 2016. Characterization and tracing of Permian magmatism in the south-western segment of the Gondwanan margin; U–Pb age, Lu–Hf and O isotopic compositions of detrital zircons from metasedimentary complexes of northern Antarctic Peninsula and western Patagonia. *Gondwana Research*, **36**, 1–13, https://doi.org/10.1016/j.gr.2015.07.014

Castillo, P., Fanning, C.M. and Riley, T.R. 2020. Zircon O and Hf isotopic constraints on the genesis of Permian–Triassic magmatic and metamorphic rocks in the Antarctic Peninsula and correlations with Patagonia. *Journal of South American Earth Sciences*, **104**, 102848, https://doi.org/10.1016/j.jsames.2020.102848

Cawood, P.A., Hawkesworth, C.J. and Dhuime, B. 2012. Detrital zircon record and tectonic setting. *Geology*, **40**, 875–878, https://doi.org/10.1130/G32945.1

Chemale, F., Ramos, V.A., Naipauer, M., Girelli, T.J. and Vargas, M. 2018. Age of basement rocks from the Maurice Ewing Bank and the Falkland/Malvinas Plateau. *Precambrian Research*, **314**, 28–40, https://doi.org/10.1016/j.precamres.2018.05.026

Craddock, J.P., Fitzgerald, P., Konstantinou, A., Nereson, A. and Thomas, R.J. 2017. Detrital zircon provenance of upper Cambrian–Permian strata and tectonic evolution of the Ellsworth Mountains, West Antarctica. *Gondwana Research*, **45**, 191–207, https://doi.org/10.1016/j.gr.2016.11.011

Craddock, J.P., Ojakangas, R.W. *et al.* 2019. Detrital zircon provenance of Permo-Carboniferous glacial diamictites across Gondwana. *Earth-Science Reviews*, **192**, 285–316, https://doi.org/10.1016/j.earscirev.2019.01.014

Curtis, M.L. and Hyam, D.M. 1998. Late Palaeozoic to Mesozoic structural evolution of the Falkland Islands: a displaced segment of the Cape Fold Belt. *Journal of the Geological Society, London*, **155**, 115–129, https://doi.org/10.1144/gsjgs.155.1.0115

Dean, J.R. 2014. *U–Pb Detrital Zircon Geochronology within the Cape Fold Belt Karoo Basin System*. Thesis, University of West Virginia, https://researchrepository.wvu.edu/etd/5456

Dickinson W.R., Beard L.S. *et al.* 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. *GSA Bulletin*, **94**, 222–235, https://doi.org/10.1130/0016-7606(1983)94<222:PONAPS>2.0.CO;2

Du Toit, A.L. 1927. *A Geological Comparison of South America with South Africa*. Carnegie Institution, Washington.

Eagles, G. and Eisermann, H. 2020. The Skytrain plate and tectonic evolution of southwest Gondwana since Jurassic times. *Scientific Reports*, **10**, 1–17, https://doi.org/10.1038/s41598-020-77070-6

Elliot, D.H., Fanning, C.M. and Hullet, S.R.W. 2015. Age provinces in the Antarctic craton: evidence from detrital zircons in Permian strata from the Beardmore Glacier region, Antarctica. *Gondwana Research*, **28**, 152–164, https://doi.org/10.1016/j.gr.2014.03.013

Elliot, D.H., Fanning, C.M. and Laudon, T.S. 2016. The Gondwana plate margin in the Weddell Sea sector: zircon geochronology of Upper Paleozoic (mainly Permian) strata from the Ellsworth Mountains and eastern Ellsworth Land, Antarctica. *Gondwana Research*, **29**, 234–247, https://doi.org/10.1016/j.gr.2014.12.001

Elliot, D.H., Fanning, C.M., Isbell, J.L. and Hulett, S.R.W. 2107. The Permo-Triassic Gondwana sequence, central Transantarctic Mountains, Antarctica: zircon geochronology, provenance, and basin evolution. *Geosphere*, **13**, 155–178, https://doi.org/10.1130/GES01345.1

Falco, J.I., Hauser, N., Scivetti, N., Reimold, W.U. and Folguera, A. 2022. The origin of Patagonia: insights from Permian to Middle Triassic magmatism of the North Patagonian Massif. *Geological Magazine*, **159**, 1490–1512, https://doi.org/10.1017/S0016756822000450

Fanning, C.M., Hervé, F., Pankhurst, R.J., Rapela, C.W., Kleiman, L.E., Yaxley, G.M. and Castillo, P. 2011. Lu–Hf isotope evidence for the provenance of Permian detritus in accretionary complexes of western Patagonia and the northern Antarctic Peninsula region. *Journal of South American Earth Sciences*, **32**, 485–496, https://doi.org/10.1016/j.jsames.2011.03.007

Flowerdew, M.J., Tyrell, S., Riley, T.R., Whitehouse, M.J., Mulvaney, R.W., Leat, P.T. and Marschall, H.R. 2012. Distinguishing East and West Antarctic sediment sources using the Pb isotope composition of detrital K feldspar. *Chemical Geology*, **292–293**, 88–102, https://doi.org/10.1016/j.chemgeo.2011.11.006

Halle, T.G. 1912. On the geological structure and history of the Falkland Islands. *Bulletin of the Geological Institution of the University of Uppsala*, **11**, 115–229.

Hervé, F., Fanning, C.M. and Pankhurst, R.J. 2003. Detrital zircon age patterns and provenance of the metamorphic complexes of southern Chile. *Journal of South American Earth Sciences*, **16**, 107–123, https://doi.org/10.1016/S0895-9811(03)00022-1

Hole, M.J., Ellam, R.M., MacDonald, D.I.M. and Kelley, S.P. 2016. Gondwana break-up related magmatism in the Falkland Islands. *Journal of the Geological Society, London*, **173**, 108–126, https://doi.org/10.1144/jgs2015-027

Hunter, M.A. and Lomas, S.A. 2003. Reconstructing the Siluro-Devonian coastline of Gondwana: insights from the sedimentology of the Port Stephens Formation, Falkland Islands. *Journal of the Geological Society, London*, **160**, 459–476, https://doi.org/10.1144/0016-764902-038

Jacobs, J., Thomas, R.J., Armstrong, R.A. and Henjes-Kunst, F. 1999. Age and thermal evolution of the Mesoproterozoic Cape Meredith Complex, West Falkland. *Journal of the Geological Society, London*, **156**, 917–928, https://doi.org/10.1144/gsjgs.156.5.0917

López Gamundi, O.R., Conaghan, P.J., Rossello, E.A. and Cobbold, P.R. 1995. The Tunas Formation (Permian) in the Sierras Australes Fold belt, east central Argentina: evidence for syntectonic sedimentation in a foreland basin. *Journal of South American Earth Sciences*, **8**, 129–142, https://doi.org/10.1016/0895-9811(95)00001-V
López Gamundi, O.R., Fildani, A., Weislogel, A. and Rossello, E. 2013. The age of the Tunas Formation in the Sauce Grande basin–Ventana fold belt (Argentina): implications for the Permian evolution of the southwestern margin of Gondwana. *Journal of South American Earth Sciences*, **45**, 250–258, https://doi.org/10.1016/j.jsames.2013.03.011
Malone, J.R., Dalziel, I.W.D., Stone, P. and Horton, B.K. 2023. Provenance analysis of Palaeozoic strata in the Falkland/Malvinas Islands: implications for paleogeography and Gondwanan reconstructions. *Gondwana Research*, **121**, 33–55, https://doi.org/10.1016/j.gr.2023.04.004
Marshall, J.E.A. 1994. The Falkland Islands: a key element in Gondwana paleogeography. *Tectonics*, **13**, 499–514, https://doi.org/10.1029/93TC03468
McKay, M.P., Coble, M.A., Hessler, A.M., Weislogel, A.L. and Fildani, A. 2016. Petrogenesis and provenance of distal volcanic tuffs from the Permian–Triassic Karoo Basin, South Africa: a window into a dissected magmatic province. *Geosphere*, **12**, 1–14, https://doi.org/10.1130/GES01215.1
Mitchell, C., Taylor, G.K., Cox, K.G. and Shaw, J. 1986. Are the Falkland Islands a rotated microplate? *Nature*, **319**, 131–134, https://doi.org/10.1038/319131a0
Mussett, A.E. and Taylor, G.K. 1994. ^{40}Ar–^{39}Ar ages for dykes from the Falkland Islands with implications for the break-up of southern Gondwanaland. *Journal of the Geological Society, London*, **151**, 79–81, https://doi.org/10.1144/gsjgs.151.1.0079
Nelson, D.A. and Cottle, J.M. 2019. Tracking voluminous Permian volcanism of the Choiyoi Province into central Antarctica. *Lithosphere*, **11**, 386–398, https://doi.org/10.1130/L1015.1
Ramos, V.A., Chemale, F., Naipauer, M. and Pazos, P.J. 2014. A provenance study of the Paleozoic Ventania System (Argentina): transient complex sources from Western and Eastern Gondwana. *Gondwana Research*, **26**, 719–740, https://doi.org/10.1016/j.gr.2013.07.008
Ramos, V.A., Cingolani, C., Chemale, F., Naipauer, M. and Rapalini, A. 2017. The Malvinas (Falkland) Islands revisited: the tectonic evolution of southern Gondwana based on U–Pb and Lu–Hf detrital zircon isotopes in the Paleozoic cover. *Journal of South American Earth Sciences*, **76**, 320–345, https://doi.org/10.1016/j.jsames.2016.12.013
Richards, P.C., Gatliff, R.W., Quinn, M.F., Williamson, J.P. and Fannin, N.G.T. 1996. The geological evolution of the Falkland Islands continental shelf. *Geological Society, London, Special Publications*, **108**, 105–128 https://doi.org/10.1144/GSL.SP.1996.108.01.08
Riley, T.R., Flowerdew, M.J., Pankhurst, R.J., Millar, I.L., Leat, P.T., Fanning, C.M. and Whitehouse, M.J. 2017. A revised geochronology of Thurston Island, West Antarctica and correlations along the proto-Pacific margin of Gondwana. *Antarctic Science*, **29**, 47–60, https://doi.org/10.1017/S0954102016000341
Riley, T.R., Flowerdew, M.J., Pankhurst, R.J., Millar, I.L. and Whitehouse, M.J. 2020. U–Pb zircon geochronology from Haag Nunataks, Coats Land and Shackleton Range (Antarctica): constraining the extent of juvenile Late Mesoproterozoic arc terranes. *Precambrian Research*, **340**, 105646, https://doi.org/10.1016/j.precamres.2020.105646
Riley, T.R., Carter, A., Burton-Johnson, A., Leat, P.T., Hogan, K.A. and Bown, P.R. 2022. Crustal block origins of the South Scotia Ridge. *Terra Nova*, **34**, 495–502, https://doi.org/10.1111/ter.12613
Riley, T.R., Burton-Johnson, A. *et al.* 2023*a*. Palaeozoic–Early Mesozoic geological history of the Antarctic Peninsula and correlations with Patagonia: kinematic reconstructions of the proto-Pacific margin of Gondwana. *Earth-Science Reviews*, **236**, 104265, https://doi.org/10.1016/j.earscirev.2022.104265
Riley, T.R., Millar, I.L. *et al.* 2023*b*. Evolution of an accretionary complex (LeMay Group) and terrane translation in the Antarctic Peninsula. *Tectonics*, **42**, e2022TC007578, https://doi.org/10.1029/2022TC007578
Schilling, M.E., Carlson, R.W. *et al.* 2017. The origin of Patagonia revealed by Re–Os systematics of mantle xenoliths. *Precambrian Research*, **294**, 15–32, https://doi.org/10.1016/j.precamres.2017.03.008
Simões, M.G., Quaglio, F. *et al.* 2012. Permian non-marine bivalves of the Falkland Islands and their palaeoenvironmental significance. *Alcheringa*, **36**, 543–554, https://doi.org/10.1080/03115518.2012.688682
Sláma, J., Košler, J. *et al.* 2008. Plešovice zircon – a new natural reference material for U–Pb and Hf isotopic microanalysis. *Chemical Geology*, **249**, 1–35, https://doi.org/10.1016/j.chemgeo.2007.11.005
Söderlund, U., Patchett, P.J., Vervoort, J.D. and Isachsen, C.E. 2004. The ^{176}Lu decay constant determined by Lu–Hf and U–Pb isotope systematics of Precambrian mafic intrusions. *Earth and Planetary Science Letters*, **219**, 311–324, https://doi.org/10.1016/S0012-821X(04)00012-3
Stanca, R.M., Paton, D.A., Hodgson, D.M., McCarthy, D.J. and Mortimer, E.J. 2019. A revised position for the rotated Falkland Islands microplate. *Journal of the Geological Society, London*, **176**, 417–429, https://doi.org/10.1144/jgs2018-163
Stanca, R.M., McCarthy, D.J., Paton, D.A., Hodgson, D.M. and Mortimer, E.J. 2022. The tectono-stratigraphic architecture of the Falkland Plateau basin; implications for the evolution of the Falkland Islands microplate. *Gondwana Research*, **105**, 320–342, https://doi.org/10.1016/j.gr.2021.09.014
Stone, P. 2016. Geology reviewed for the Falkland Islands and their offshore sedimentary basins. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, **106**, 115–143, https://doi.org/10.1017/S1755691016000049
Stone, P., Richards, P.C., Kimbell, G.S., Esser, R.P. and Reeves, D. 2008. Cretaceous dykes discovered in the Falkland Islands: implications for regional tectonics. *Journal of the Geological Society, London*, **165**, 1–4, https://doi.org/10.1144/0016-76492007-072
Stone, P., Kimbell, G.S. and Richards, P.C. 2009. Rotation of the Falklands microplate reassessed after recognition of discrete Jurassic and Cretaceous dyke swarms. *Petroleum Geoscience*, **15**, 279–287, https://doi.org/10.1144/1354-079309-847
Stone, P., Thomson, M.R.A. and Rushton, A.W.A. 2012. An Early Cambrian archaeocyath–trilobite fauna in limestone erratics from the Upper Carboniferous Fitzroy Tillite Formation, Falkland Islands. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, **102**, 201–225, https://doi.org/10.1017/S175569101101005X
Storey, B.C., Curtis, M.L., Ferris, J.K., Hunter, M.A. and Livermore, R.A. 1999. Reconstruction and break-out model for the Falkland Islands within Gondwana. *Journal of African Earth Sciences*, **29**, 153–163, https://doi.org/10.1016/S0899-5362(99)00086-X
Svensen, H., Corfu, F., Polteau, S., Hammer, O. and Planke, S. 2012. Rapid magma emplacement in the Karoo large igneous province. *Earth and Planetary Science Letters*, **325–326**, 1–9, https://doi.org/10.1016/j.epsl.2012.01.015
Thistlewood, L., Leat, P.T., Millar, I.L., Storey, B.C. and Vaughan, A.P.M. 1997. Basement geology and Palaeozoic–Mesozoic mafic dykes from the Cape Meredith Complex, Falkland Islands: a record of repeated intracontinental extension. *Geological Magazine*, **134**, 355–367, https://doi.org/10.1017/S0016756897007085
Thomson, M.R.A. 1975. New palaeontological and lithological observations on the Legoupil Formation, northwest Antarctic Peninsula. *British Antarctic Survey Bulletin*, **41/42**, 169–185.
Trewin, N.H., Macdonald, D.I.M. and Thomas, C.G.C. 2002. Stratigraphy and sedimentology of the Permian of the Falkland Islands: lithostratigraphic and palaeoenvironmental links with South Africa. *Journal of the Geological Society, London*, **159**, 5–19, https://doi.org/10.1144/0016-764900-089
Vermeesch, P. 2013. Multi-sample comparison of detrital age distributions. *Chemical Geology*, **341**, 140–146, https://doi.org/10.1016/j.chemgeo.2013.01.010
Vermeesch, P. 2018. IsoplotR: a free and open toolbox for geochronology. *Geoscience Frontiers*, **9**, 1479–1493, https://doi.org/10.1016/j.gsf.2018.04.001
Vermeesch, P. 2021. Maximum depositional age estimation revisited. *Geoscience Frontiers*, **12**, 843–850, https://doi.org/10.1016/j.gsf.2020.08.008
Viglietti, P.A., Frei, D., Rubidge, B.S. and Smith, R.M.H. 2018. U–Pb detrital zircon dates and provenance data from the Beaufort Group (Karoo Supergroup) reflect sedimentary recycling and air-fall tuff deposition in the Permo-Triassic Karoo foreland basin. *Journal of African Earth Sciences*, **143**, 59–66, https://doi.org/10.1016/j.jafrearsci.2017.11.006
Visser, J.N.J., van Niekerk, B.N. and van der Merwe, S.W. 1997. Sediment transport of the late Palaeozoic glacial Dwyka Group in the southwestern Karoo Basin. *South African Journal of Geology*, **100**, 223–236.
Vorster, C., Kramers, J.D., Beukes, N.J. and Penn-Clarke, C.R. 2021. Long-lived stable shelf deposition along Gondwana's southern margin during the Ordovician–Silurian: inferences from U–Pb detrital zircon ages of the Table Mountain Group (South Africa) and correlatives in Argentina and the Falklands/Malvinas Islands. *Chemical Geology*, **576**, 1–28, https://doi.org/10.1016/j.chemgeo.2021.120274