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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 (upper Permian) sedimentary succession of the Falkland/Malvinas Islands is used to constrain depositional age, provenance and palaeogeography, and test the Natal Embayment model for the Falkland/Malvinas Islands microplate. The upper Permian was a period of extensive magmatism and sediment recycling along the accretionary margin of West Gondwana. Deposition into retroarc 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 upper 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, Theron Mountains of East Antarctica and sandstone 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, Lu-Hf isotope compositions are clearly distinct indicating that there was no direct link between the upper Permian successions of the Falkland/Malvinas Islands (εHf -3 to +3) to the volcano-sedimentary successions of southern South America (εHf <-5).

The geological and tectonic history of the Falkland/Malvinas Islands has been the source of considerable debate for over 100 years (Stone 2016), with multiple investigations (e.g. Halle 1912; Du Toit 1927; Adie 1952; Borello 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 Palaeozoic geological history aligned with Africa or South America.

The overwhelming consensus is that the Falkland/Malvinas Islands had a Palaeozoic origin in the Natal Embayment adjacent to the Eastern Cape of southeast 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 southeast Africa (Adie 1952). Therefore, other workers (e.g. Ramos et al. 2017; Eagles and Eisermann 2020) favour either a South American affinity for the Falkland/Malvinas Islands, or it being part of an allochthonous Deseado Massif microcontinent (Schilling et al. 2017). These alternate models negate the requirement for crustal block rotation (Richards et al. 1996), which they interpreted as being consistent with the sea floor architecture. However, recent structural and seismic analysis 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 its geological history and position within Gondwana, prior to breakup, all of which have failed 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 has been applied by Ramos et al. (2017) and Malone et al. (2023) to investigate wider links to South Africa, South America, and East Antarctica, but although there was no clear consensus to resolve the palaeo-location of the Falkland/Malvinas Islands, Malone et al. (2023) determined that the 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 sedimentary successions of the Falkland/Malvinas Islands have thus far focussed 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 upper Permian sequences of the Falkland/Malvinas Islands are part of an extensive belt of volcano-sedimentary successions across West Gondwana (Fig. 1), which although disparate, have in part, been correlated (e.g. Nelson and Cottle 2019). This study will examine, for the first time, the detrital zircon population of deltaic sandstone 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 depositional age and provenance constraints from the Bay of Harbours Formation are compared with the middle- to upper Permian successions from across West Gondwana. This will permit a comprehensive analysis of potential correlations across the extensive distribution of Permian sedimentary and volcaniclastic successions of West Gondwana (Fig. 1). Sequences from South Africa, South America, Antarctic Peninsula, Ellsworth Mountains, East Antarctica, and South Georgia are all evaluated; successions that were deposited during a dynamic period of subduction, volcanism, basin inversion and recycling of detrital material. Evaluation of these units with respect to the upper Permian of the Falkland/Malvinas Islands will allow 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 summarised by Stone (2016). The geology of the islands is shown in Fig. 2, with the stratigraphy summarised in Fig. 3. The geology is almost entirely Palaeozoic in age, with the exception being a Mesoproterozoic basement complex at Cape Meredith (Fig. 2), and a suite of Early

Jurassic and middle-Cretaceous mafic dykes that crosscut the entire succession (Stone et al. 2008). The basement complex comprises amphibolite, paragneiss, orthogneiss and granite (Thistlewood et al. 1997). The complex has been dated in 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 succession over 7 km in thickness of fluvial-marine quartz sandstone, quatzo-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 ~4500 m thick Port Stephens Formation (Fig. 3) of fluvial-shallow marine sandstone (Hunter and Lomas 2003) which have 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 in thickness and consists of medium-grained quartz sandstone that form 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 ~200 m thick Bluff Cove Formation (Fig. 3) of fine-grained sandstone and localised shale beds and has been interpreted as a glaciomarine unit (Aldiss and Edwards 1999). This unit is overlain by the distinctive Fitzroy Tillite Formation, a massive sandy diamictite up to 750 m in thickness (Fig. 3). The Fitzroy Tillite Formation is an Upper Carboniferous to lower Permian glaciogenic diamictite that forms part of a succession recognised 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 analysis (e.g. Craddock et al. 2017; Malone et al. 2023). The glaciogenic succession is widely inferred to have had an Antarctic source, supported by fossil-bearing clasts within the diamictite, linked with Palaeozoic successions of 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 ~250 m (Aldiss and Edwards 1999) and crops out in a narrow band of central East Falkland (Fig. 2).

The middle-Permian Brenton Loch Formation crops out either side of Choiseul Sound (Fig. 2) and forms a succession ~3 km in thickness 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) and 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, and 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 delta slope to delta top environment and forms a ~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 a succession up to 1700 m in thickness (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 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 northeast sector, which would represent a broadly southwest vector in a 180° rotated reconstruction.

The entire sedimentary succession of the Falkland/Malvinas Islands is cut by a swarm of Early Jurassic (Hole et al. 2016) and middle-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) were selected for detrital zircon provenance analysis from across the Falkland Islands (Fig. 2). The primary focus of this study is the upper Permian Bay of Harbours Formation 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 is from the Fox Bay Formation as 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 and crops out at New Haven (Fig. 2) at a narrow coastal exposure.

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 sandstone 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. Zircon crystals are 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, FI22.26.3) was carried out at University College London (November 2023) using laser ablation inductively coupled mass spectrometry (LA-ICP-MS) facilities (Agilent 7700 coupled to a New Wave Research 193 nm excimer laser) at the London Geochronology Centre. 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. Background measurement before ablation lasted 15 seconds and laser ablation dwell time was 25 seconds. The external zircon standard was Plešovice, which has a TIMS reference age 337.13 ± 0.37 Ma (Sláma et al. 2008). Standard errors on isotope ratios and ages include the standard deviation of ^{206}Pb/^{238}U ages of the Plešovice standard zircon. Time-resolved signals that record isotopic ratios with depth in each crystal were processed using GLITTER 4.5, data reduction software, developed by the ARC National Key Centre for Geochemical Evolution and Metallogeny of Continents (GEMOC) at Macquarie University and CSIRO Exploration and Mining. Processing enabled filtering to remove spurious signals owing to overgrowth boundaries, weathering, inclusions, or fractures. Ages were calculated using the

^{206}Pb/^{238}U ratios for samples dated as <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 ^{207}Pb/^{206}Pb ages.

Full analyses are 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), 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). Grain sizes for sample FI22.10.1 were all generally in the range 130-160 µm. All grains >150 µm (46 total) in sample FI22.2.1 that were analysed for U-Pb geochronology were 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 U-Pb geochronology. The analyses were determined (April 2024) on a Neptune multi-collector inductively coupled plasma-mass spectrometer (ICP-MS) coupled with a laser ablation system at the British Geological Survey (UK) following the methods of Bauer and Horstwood (2018). Initial ^{176}Hf/^{177}Hf ratios were calculated using the U-Pb crystallisation age of each grain and the results are expressed as initial εHf (εHf$_i$). εHf values were calculated using a ^{176}Lu decay constant of 1.867 x 10-11y^{-1} (Söderlund et al. 2004), the present-day chondritic ^{176}Lu/^{177}Hf value of 0.0336 and ^{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 Fig. 2 along with 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 Fig. 4 as kernel density estimator plots (KDE). The five samples from the Bay of Harbours Formation all share very similar age distribution profiles (Fig. 4) with a prominent upper Permian unimodal age peak and a broad, but minor distribution of recycled zircon grains through the Palaeozoic and Neo-Mesoproterozoic. The two samples from the Egg Harbour Member have upper 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 upper Permian Bay of Harbours Formation that were also analysed for U-Pb geochronology. The data are plotted in Fig. 5a alongside data from the middle-Permian Brenton Loch Formation of Malone et al. (2023). The Egg Harbour Member (FI22.10.1) yields εHf_i values in the range -4 to +3 broadly defining a middle to upper Permian age εHf_i 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 εHf_i to the Egg Harbour Member, with the majority of values lying in the range, -2 to +3 for the upper Permian age grains.

Provenance analysis

To aid our interpretation of the potential correlations to Permian successions across Gondwana here we compare the units from the Falkland/Malvinas Islands with middle to upper Permian sequences from South America, South Africa, Antarctic Peninsula, Ellsworth Mountains, East Antarctica and the Scotia Sea (Supplementary Table S4). We will use available U-Pb and Lu-Hf datasets from across

West Gondwana, combined with palaeocurrent evidence to test reconstruction models for the upper Permian.

South Africa

The upper Permian units from the upper Ecca Group and Beaufort Group of the Karoo Basin succession of South Africa (Fig. 6) are used for comparison to the Permian successions from the Falkland/Malvinas Islands, including palaeocurrrent evidence from Trewin et al. (2002). Dean (2014) and Viglietti et al. (2018) have determined U-Pb detrital zircon analysis on a suite of successions from the Karoo Basin. Dean (2014) investigated samples (13ZA93, 13ZA91, 13ZA26,09-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. (2918) investigated samples (PV-NbDo1, PV-Springfontein, PV-KT-In1, PV-Venterstad, PV-H1, PV-Java, PV-Cr1, PV-LC, PV-BM-In2, 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 are examined for comparison to 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 in thickness 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 northeast (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, SLV-VE-23; Fig. 6).

In southern Patagonia, the Madre de Dios terrane is host to fragments of Permian accretionary complexes which 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. 2023a). Four samples (AL1, MD3, MD32, DSOL-16; Fig. 6) are compared with the Falkland/Malvinas Islands data (Herve 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 LeMay Group, which have been investigated by Castillo et al. (2016), Barbeau et al. (2010) and Riley et al. (2023b) 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 – lower Permian View Point Formation (Bradshaw et al. 2012), the Hope Bay Formation (upper Permian – Early Triassic; Birkenmajer et al. 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 which are associated with mélange belts of ocean floor material (Riley et al. 2023b). Two main groups (1 and 2) are identified from the LeMay Group (Fig. 6) which have an upper Permian maximum likely depositional age and an accretion event in the middle-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 (Salomon Glacier Formation; BAS unpublished data) and dredged metasedimentary samples from Bruce Bank (Riley et al. 2022) are examined here for comparison to the Falkland/Malvinas Islands Permian units.

Also included for comparison are middle- to upper Permian feldspar-rich sandstone units from the southern Antarctic Peninsula at Erewhon Nunatak-Mount Peterson (Fig. 6). Elliot et (2016) and Riley et al. (2023a) determined an upper Permian age for the units at Erewhon Nunatak-Mount Peterson based on their detrital zircon age profiles (R.8006.1, R.8008.2, R.8009.3, R.8009.4, 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-Mount Peterson of the Antarctic Peninsula (Elliot et al. 2016). Three samples (MW54.3, MW210.5, PRR299; Fig. 6) are included in this analysis, with data from Nelson and Cottle (2019) and Elliot et al. (2016).

Upper Permian sandstone beds from the Theron Mountains in East Antarctica were examined by Flowerdew et al. (2012) who recognised their source was a mixture from the upper 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.

An upper 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).

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 to estimate the depositional age of siliciclastic rocks. Detrital zircon U–Pb geochronology has become a popular technique to obtain maximum likely depositional ages, but there is little consistency in the estimation algorithms used. We follow the revised approach of Vermeesch (2021) to calculate the maximum likely age of deposition (MLA) 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, 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.

This study analysed five samples from the Bay of Harbours Formation. Samples from the Praltos Member having dominant zircon ages in the range c. 271 – 265 Ma, with a broad spectrum of Palaeozoic and Proterozoic ages. The calculated (Vermeesch 2021) MLAs are c. 263 Ma (FI22.2.1), c. 265 Ma (FI22.17.1) and c. 271 Ma (FI22.23.1). In contrast, two samples from the Egg Harbour Member have primary age peaks at c. 258 Ma, with MDAs of c. 259 Ma (FI222.10.1) and c. 257 Ma (FI22.26.3), and also display a broad spectrum of Palaeozoic and Proterozoic ages.

Multi-dimensional scaling analysis

Multi-dimensional scaling (MDS) plots of U-Pb detrital zircon data are used here 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 middle – Early Palaeozoic that have been 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 share a close association with the Ellsworth Mountains and East Antarctica, as well as units from South Africa and South America, and consequently provide limited palaeogeographical insight given the highly recycled nature of the detrital zircon population (Anderson et al. 2016). The five upper Permian samples from the Bay of Harbours Formation cluster in Fig. 8a, with a close similarity to units from the Karoo Basin (Katberg and Balfour formations), units from the Antarctic Peninsula (Trinity Peninsula Group) and South America (Duque de York Complex), as well as sandstone beds from the Ellsworth Mountains (Polarstar Formation) and the

Theron Mountains. In Fig 8b, the Permian units with the most proximal relationship to the Bay of Harbours Formation in Fig. 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 on the MDS plot (Fig. 8a) have the closest similarity to the Bay of Harbours Formation are subdivided into individual samples to allow a better assessment of those samples which 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, 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 to samples from Erewhon Nunatak-Mount 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 to the middle- to upper Permian Beaufort Group of the Karoo Basin (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 upper 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 (Upper Beaufort Group). This finding contrasts with previous studies (e.g. Trewin et al. 2002; Aldiss and Edwards 1999; Malone et al. 2023), who all favoured a lithostratigraphic correlation with the Lower Beaufort Group of the Karoo Basin.

The middle-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 is closer in age to the middle-Permian Brenton Loch Formation (c. 270 Ma). The MDS plot (Fig. 8b) illustrates that the Tunas Formation is distinct from 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 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. In 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 characterised by a ~65% upper Permian age population and is similar in profile to the Polarstar Formation of the Ellsworth Mountains (Fig. 9). In contrast, the younger Egg Harbour Member is characterised by a less pronounced upper Permian age population at c. 55% of 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 upper Permian age population of <30% and is distinct in age distribution to 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 upper Permian accretionary complex (Riley et al. 2023b) of Alexander Island (Antarctic Peninsula), has the most pronounced upper Permian unimodal age population comprising ~80% of the total age distribution which is consistent with its location adjacent to the convergent margin (Fig. 9).

The Tunas Formation, Ventania System of eastern Argentina, has a middle-Permian population (~40%; Fig. 9) and is distinct to other Permian units examined here.

Lu-Hf isotopes

Lu-Hf isotope data aid with the interpretation of zircon U-Pb data to better define 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 et al. 2023) are plotted in Fig. 5a and form a tight grouping for the upper Permian population (εHf_i = -2 to +3).

There is broad overlap in age and εHf values between the upper Permian units from the Falkland/Malvinas Islands with upper Permian sedimentary successions from the Ellsworth Mountains, Erewhon Nunatak-Mount 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 central Transantarctic Mountains. Samples of the LeMay Group accretionary complex from Alexander Island (western Antarctic Peninsula) have maximum likely depositional ages in the range 260 -250 Ma (Riley et al. 2023b) 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 Fig. 5d where a more complex picture is evident. The upper Permian – Early Triassic metasedimentary successions from the Trinity Peninsula Group (Antarctic Peninsula), 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 Lu-Hf isotopic data illustrate 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 εHf values and exhibit a clear trend to more radiogenic values in the upper Permian – Early Triassic population from Patagonia (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 with the upper Permian units from the Falkland/Malvinas Islands, especially so for the youngest units (Egg Harbour Member). Falco et al. (2022) attributed changes in εHf values of the North Patagonian Massif through the middle – upper Permian to steepening of the subducted slab at c. 253 Ma. Their analysis demonstrates that for upper Permian volcanism in South America to have been a primary sediment source zircons contained within the sediment succession would 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 the from the Bay of Harbours Formation sedimentary units, which must 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 (εHf_i), and although overlapping with the εHf range of the Bay of Harbours Formations, is considerably older at c. 280 Ma.

Unfortunately, there is no Lu-Hf data 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 upper Permian. They attributed the shift to upper Permian extension related to the development of a back-arc rift, with upper 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 Palaeozoic, 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 upper Permian magmatic province and accretionary complexes of Patagonia with the upper 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 upper Permian radiogenic εHf 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 overlap in εHf values between the magmatic and accretionary complexes of Patagonia with the Lafonia Group during the lower – middle-Permian, the overlap diminishes during the upper Permian (Fig. 5d). This relationship demonstrates that the sedimentary units of the Falkland/Malvinas Islands had a different source in the upper Permian. This may reflect a change in εHf values along the Permian continental margin, which could be the consequence of subducting slab angle, crustal thickness and whether contiguous parts of the margin are undergoing extension or compression (Nelson and Cottle 2019).

Detrital zircons from the LeMay Group accretionary complex of Alexander Island partially overlap in age and εHf composition with the accretionary complexes of Patagonia and the northern Antarctic Peninsula (Fig. 5c), but more extensively overlaps with the Bay of Harbours Formation during the upper Permian. A counterclockwise rotated Antarctic Peninsula during the upper Permian (McKay et al. 2016; Elliot 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, Ellsworth Mountains and Erewhon Nunatak-Mount 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 dataset do not support a model where the Falkland/Malvinas Islands are adjacent to South America or form part of the Deseado terrane (e.g. Schilling et al. 2017) during the upper Permian, given the considerable dissimilarity in Lu-Hf isotopes between the accretionary and magmatic complexes of southern Patagonia (Fig. 5d) with the upper Permian sedimentary successions of the Falkland/Malvinas Islands.

Natal Embayment model

Our detrital zircon analysis demonstrates 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, and as such is compatible with a Natal Embayment origin for the Falkland/Malvinas Islands crustal block in the Late Palaeozoic. Both the Egg Harbour and Praltos members have very similar age profiles to units from the uper Balfour and Katberg formations of the upper Beaufort Group from the Karoo Basin, whilst the Brenton Loch Formation is also akin to successions of the upper Beaufort Group from the western Karoo Basin. Adjacent to the Natal Embayment in Permian reconstructions of Gondwana are sectors of East Antarctica and the crustal block of the Ellsworth-Whitmore Mountains (EWM; Fig. 6), which is geologically related to the feldspar-rich sandstone beds from the southern Antarctic Peninsula at Erewhon Nunatak-Mount Peterson (Fig. 6). Elliot et al. (2016) considered that Erewhon Nunatak-Mount Peterson may form a distinct allochthonous block that was originally adjacent to the

Ellsworth-Whitmore Mountains during the Permian. Age correlations between the upper Permian units of the Falkland/Malvinas Islands and units from East Antarctica-Ellsworth Mountains-Erewhon Nunatak-Mount 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-Mount Peterson sector also strongly support a strong association with the Falkland/Malvinas Islands crustal block, with a similar range in εHf values to the Bay of Harbours Formation from the Falkland/Malvinas Islands, particularly in the age range 260-275 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-Mount 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 upper Permian succession of the Falkland/Malvinas Islands with 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 Mount 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 upper Permian sedimentary succession (Bay of Harbours Formation) of the Falkland/Malvinas Islands with the upper 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-Mount Peterson (Antarctic Peninsula), with a potential correlation also to components of the LeMay Group accretionary complex of the western Antarctic Peninsula.
- There is no evidence, based on Lu-Hf isotope geochemistry, for any direct or secondary association between the accretionary complexes of Patagonia and the northern Antarctic Peninsula to 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, but our data support a palaeo-position in the Natal Embayment adjacent to the Karoo Basin and East Antarctica/Ellsworth Mountains.
- The locus of the upper 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 upper Permian in comparison to the Choiyoi Province further north.

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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

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List of figures

Figure 1: Late Permian paleogeographic reconstruction of West Gondwana showing the location of volcano-sedimentary successions along the proto-Pacific margin and hinterland basins. Adapted from Nelson and Cottle (2019). 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.

Figure 2: Geological map of the Falkland/Malvinas Islands. Modified from Aldiss and Edwards (1999). Sample sites are from Ramos et al. (2017) (IM-), Malone et al. (2023) (F) and this study (FI22., FI.). 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).

Figure 3: Stratigraphy of the geological history of the Falkland/Malvinas Islands adapted from Malone et al. (2023). Sample sites from Ramos et al. (2017), Malone et al. (2023) and this study. Estimated maximum likely depositional ages are from supplementary figure S1.

Figure 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. Binwidths for all plotted samples are 50 Ma.

Figure 5: U–Pb zircon ages (^{238}U/ ^{206}Pb) versus initial εHf 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, Mount Peterson and Erewhon Nunatak (Elliot et al., 2015, 2016; Nelson and Cottle 2019; Riley et al. 2023a). (c) LeMay Group accretionary complex (Riley et al. 2023b). (d) Trinity Peninsula Group, Duque de York Complex, Thunas Formation and South Georgia accretionary complex (Barbeau et al., 2010; Bradshaw et al., 2012; Castillo et al., 2015, 2016; Fanning et al., 2011; Ramos et al. 2014; BAS unpublished data). Shaded/dashed data fields are from magmatic rocks.

Figure 6: Sample sites from Late Permian volcano-sedimentary successions from across West Gondwana. Data sources: [1]this study; [2]Malone et al. (2023); [3]Dean 2014; [4]Viglietti et al. (2018); [5]Ramos et al. (2014); [6]Herve et al. (2003); [7]Castillo et al. (2016); [8]BAS unpublished data; [9]Castillo et al. (2016); [10]Barbeau et al. (2010); [11]Riley et al. (2023b); [12]Riley et al. (2023a); [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). FI:/Mv Falkland/Malvinas Islands; EWM: Ellsworth-Whitmore Mountains; EN: Erewhon Nunatak-Mount Peterson; AP: Antarctic Peninsula; LMG: LeMay Group; BB: Bruce Bank; SG: South Georgia; TdF: Tierra del Fuego ; NPM : North Patagonian Massif.

Figure 7: West Gondwana Late Palaeozoic stratigraphic correlations and depositional environments. 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. (2023b).

Figure 8: Multidimensional scaling maps (MDS; Vermeesch, 2013, 2018) comparing the age spectra in dissimilar samples calculated using the Kolmogorov-Smirnov statistic. A 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 Fig. 8a. These data are plotted relative to each other, hence the adjustment in relative positions compared to Fig. 8a. Data sources are provided in Fig. 6 and Supplementary Table 2.

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

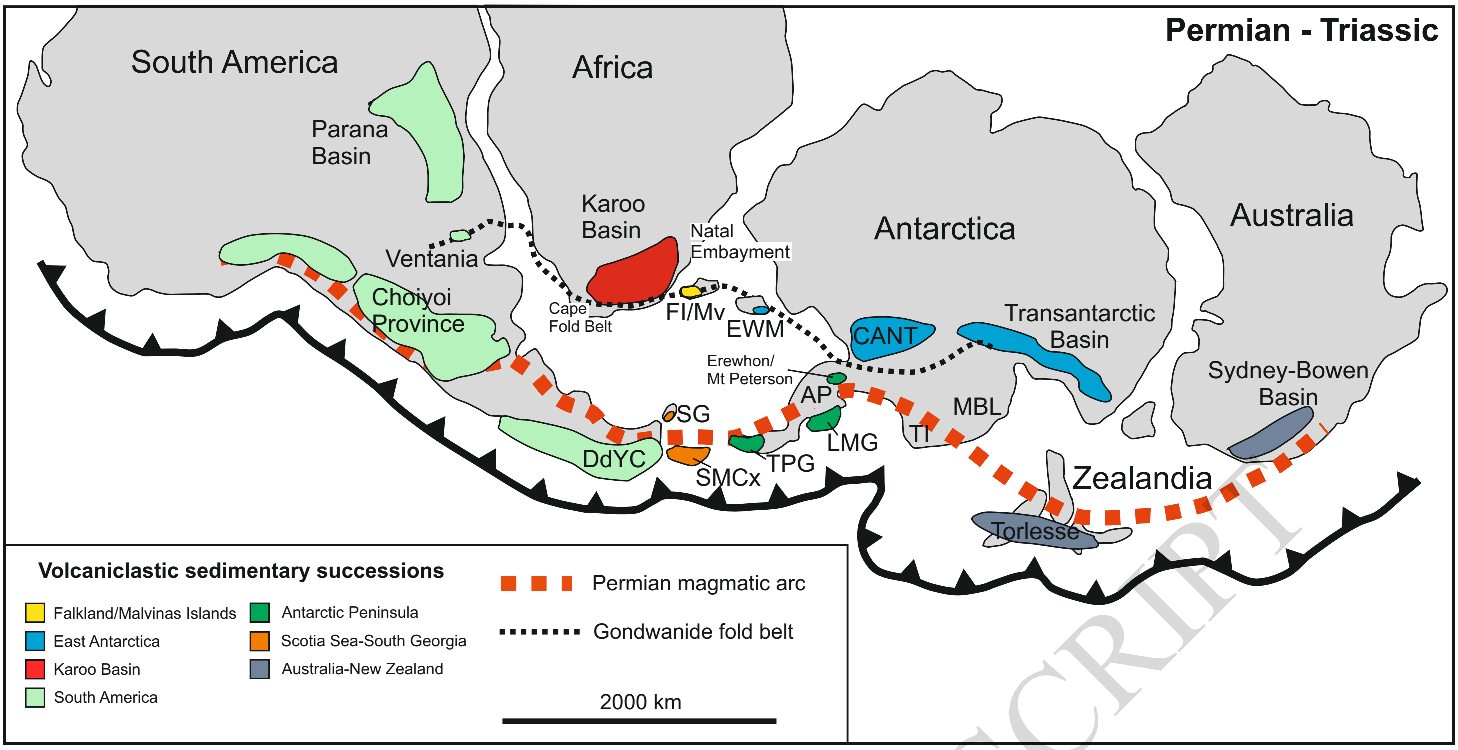
Permian - Triassic
South America
Africa
Parana Basin
Karoo Basin
Natal Embayment
Antarctica
Australia
Ventania
Choiyoi Province
Cape Fold Belt
FI/Mv
EWM
CANT
Transantarctic Basin
Erewhon/ Mt Peterson
AP
MBL
Sydney-Bowen Basin
SG
DdYC
SMCx
TPG
LMG
TI
Zealandia
Torlesse
Volcaniclastic sedimentary successions
🟨 Falkland/Malvinas Islands
🟦 East Antarctica
🟥 Karoo Basin
🟩 South America
🟩 Antarctic Peninsula
🟧 Scotia Sea-South Georgia
⬛ Australia-New Zealand
Permian magmatic arc
Gondwanide fold belt
2000 km

Figure 1

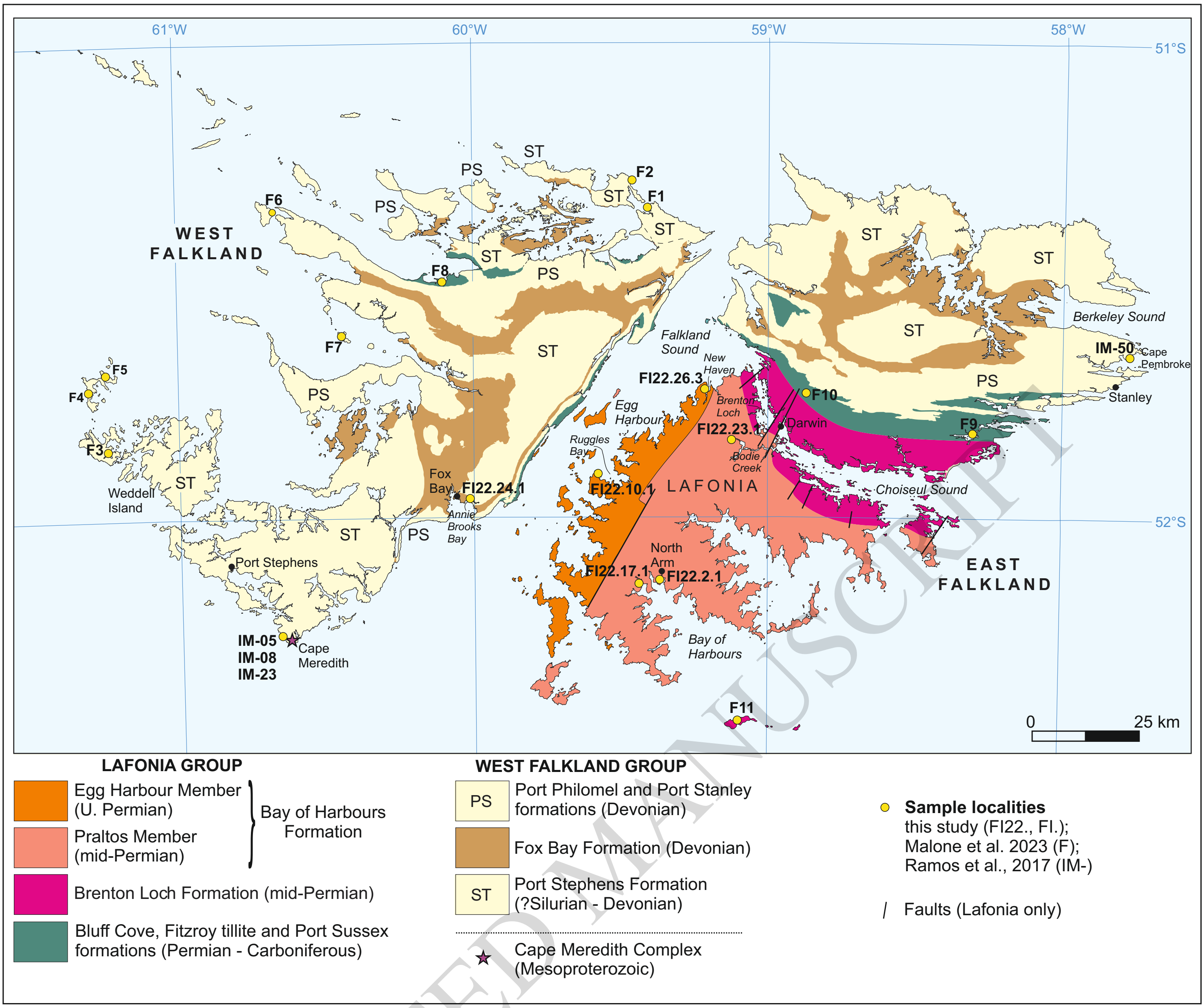
61°W
60°W
59°W
58°W
51°S
52°S
WEST FALKLAND
EAST FALKLAND
LAFONIA
PS
ST
F1
F2
F3
F4
F5
F6
F7
F8
F9
F10
F11
FI22.26.3
FI22.23.1
FI22.24.1
FI22.10.1
FI22.17.1
FI22.2.1
IM-05
IM-08
IM-23
IM-50
Falkland Sound
New Haven
Egg Harbour
Brenton Loch
Darwin
Ruggles Bay
Bodie Creek
Fox Bay
Annie Brooks Bay
Weddell Island
Port Stephens
Cape Meredith
North Arm
Bay of Harbours
Choiseul Sound
Berkeley Sound
Cape Pembroke
Stanley
0
25 km
LAFONIA GROUP
Egg Harbour Member (U. Permian)
Praltos Member (mid-Permian)
Bay of Harbours Formation
Brenton Loch Formation (mid-Permian)
Bluff Cove, Fitzroy tillite and Port Sussex formations (Permian - Carboniferous)
WEST FALKLAND GROUP
PS Port Philomel and Port Stanley formations (Devonian)
Fox Bay Formation (Devonian)
ST Port Stephens Formation (?Silurian - Devonian)
Cape Meredith Complex (Mesoproterozoic)
Sample localities
this study (FI22., FI.);
Malone et al. 2023 (F);
Ramos et al., 2017 (IM-)
Faults (Lafonia only)

Figure 2

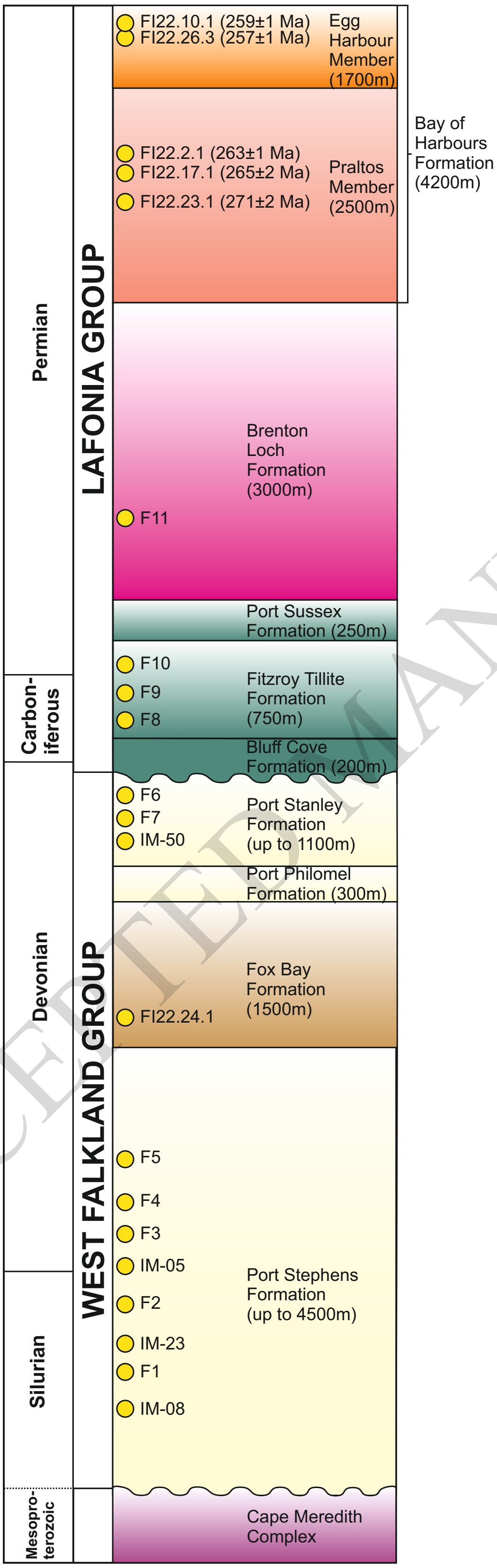
Permian
Carbon-
iferous
Devonian
Silurian
Mesopro-
terozoic
LAFONIA GROUP
WEST FALKLAND GROUP
FI22.10.1 (259±1 Ma)
FI22.26.3 (257±1 Ma)
Egg Harbour Member (1700m)
FI22.2.1 (263±1 Ma)
FI22.17.1 (265±2 Ma)
FI22.23.1 (271±2 Ma)
Praltos Member (2500m)
Bay of Harbours Formation (4200m)
Brenton Loch Formation (3000m)
F11
Port Sussex Formation (250m)
F10
F9
F8
Fitzroy Tillite Formation (750m)
Bluff Cove Formation (200m)
F6
F7
IM-50
Port Stanley Formation (up to 1100m)
Port Philomel Formation (300m)
Fox Bay Formation (1500m)
FI22.24.1
F5
F4
F3
IM-05
F2
IM-23
F1
IM-08
Port Stephens Formation (up to 4500m)
Cape Meredith Complex

Figure 3

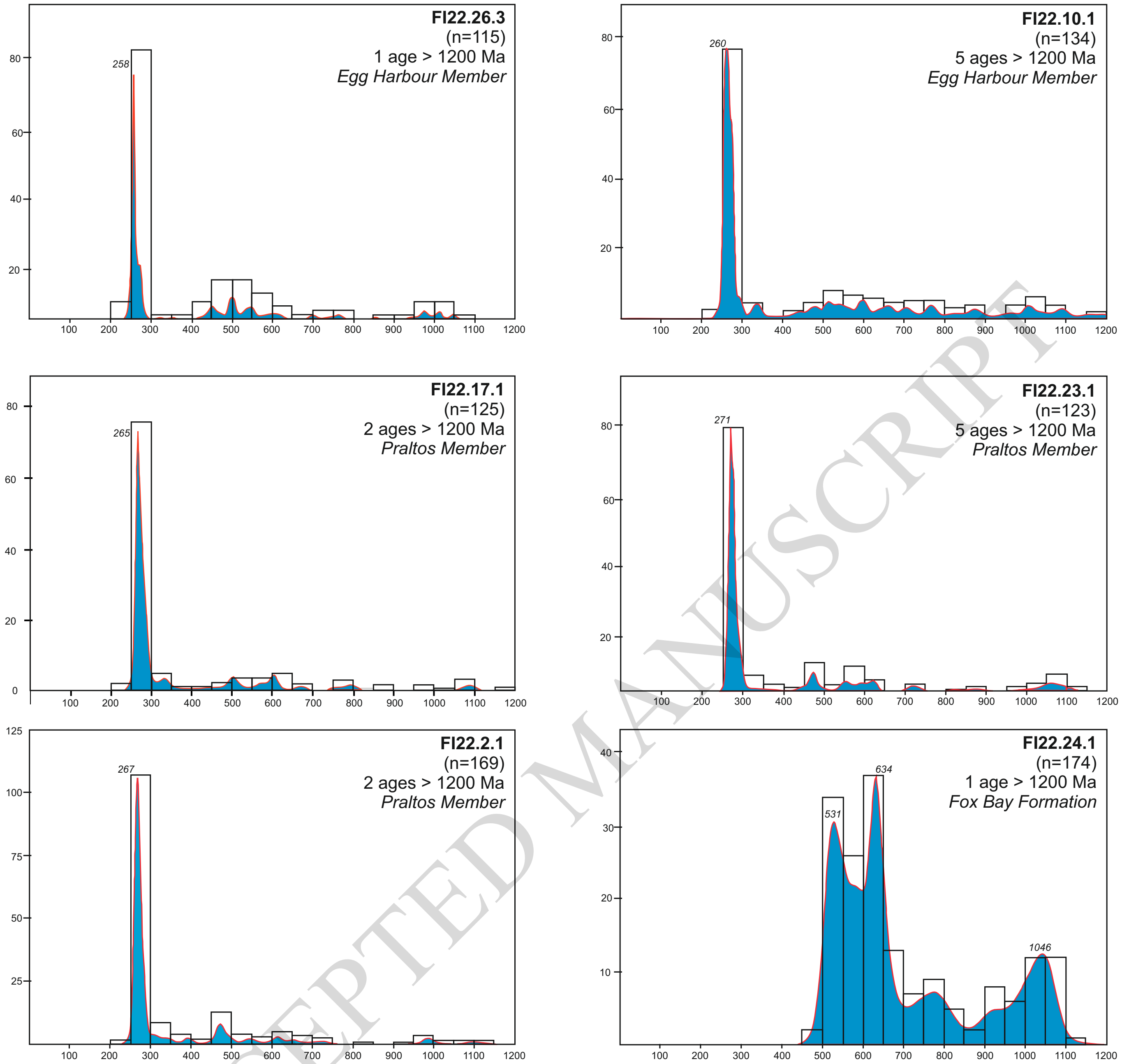
FI22.26.3
(n=115)
1 age > 1200 Ma
Egg Harbour Member
258
FI22.10.1
(n=134)
5 ages > 1200 Ma
Egg Harbour Member
260
FI22.17.1
(n=125)
2 ages > 1200 Ma
Praltos Member
265
FI22.23.1
(n=123)
5 ages > 1200 Ma
Praltos Member
271
FI22.2.1
(n=169)
2 ages > 1200 Ma
Praltos Member
267
FI22.24.1
(n=174)
1 age > 1200 Ma
Fox Bay Formation
531
634
1046
0
20
40
60
80
25
50
75
100
125
10
30
100
200
300
400
500
600
700
800
900
1000
1100
1200

Figure 4

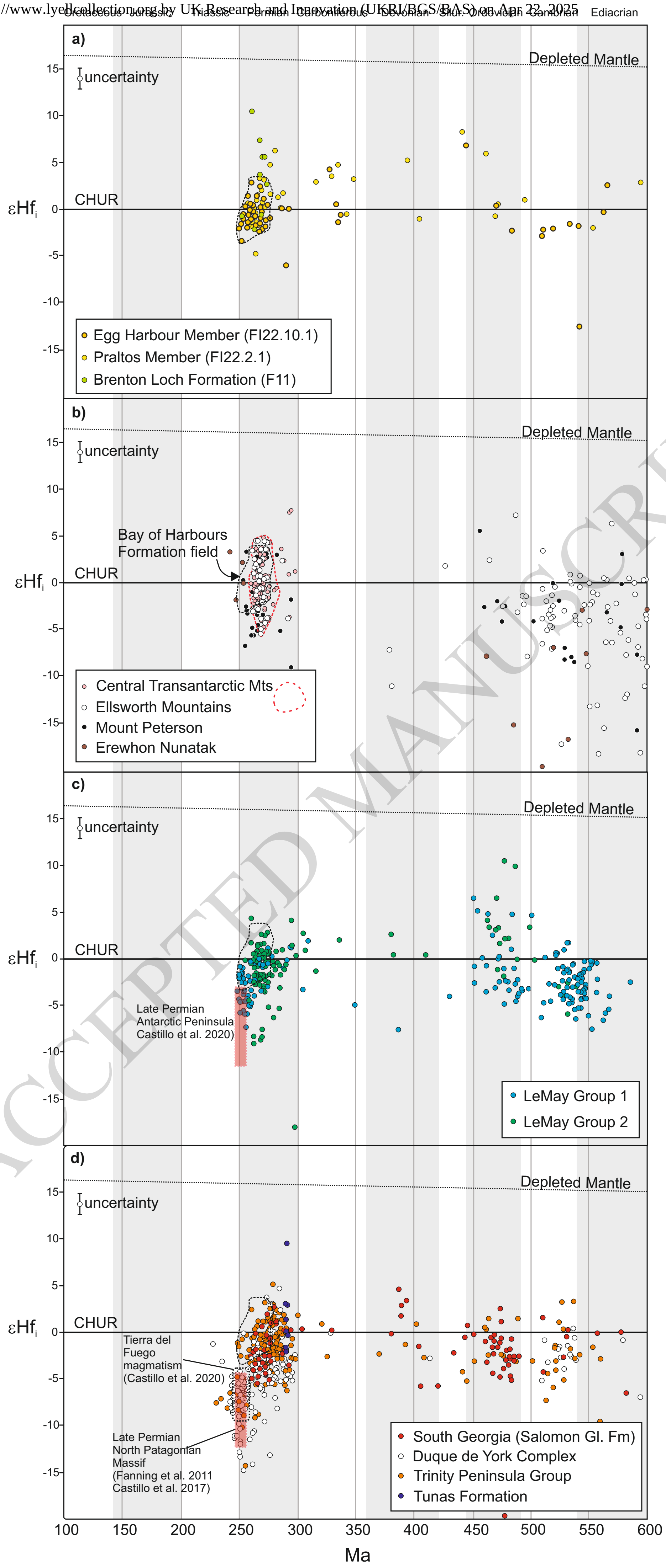
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Devonian
Silur.
Ordovician
Cambrian
Ediacrian
a)
b)
c)
d)
Depleted Mantle
uncertainty
CHUR
εHf$_i$
15
10
5
0
-5
-10
-15
Egg Harbour Member (FI22.10.1)
Praltos Member (FI22.2.1)
Brenton Loch Formation (F11)
Bay of Harbours Formation field
Central Transantarctic Mts
Ellsworth Mountains
Mount Peterson
Erewhon Nunatak
Late Permian Antarctic Peninsula Castillo et al. 2020)
LeMay Group 1
LeMay Group 2
Tierra del Fuego magmatism (Castillo et al. 2020)
Late Permian North Patagonian Massif (Fanning et al. 2011 Castillo et al. 2017)
South Georgia (Salomon Gl. Fm)
Duque de York Complex
Trinity Peninsula Group
Tunas Formation
100
150
200
250
300
350
400
450
500
550
600
Ma

Figure 5

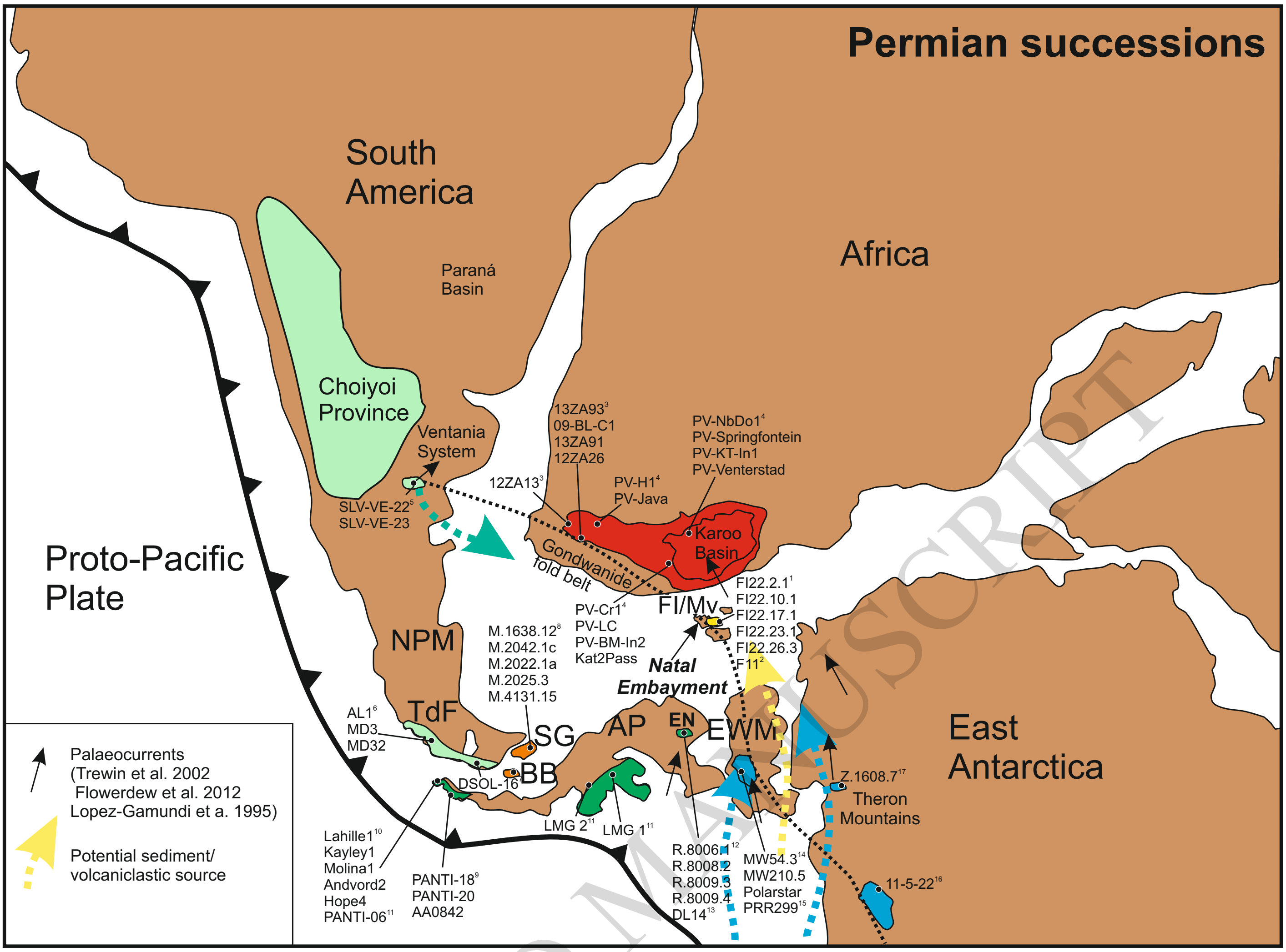
Permian successions
South America
Paraná Basin
Africa
Choiyoi Province
Ventania System
SLV-VE-22[5]
SLV-VE-23
13ZA93[3]
09-BL-C1
13ZA91
12ZA26
12ZA13[3]
PV-H1[4]
PV-Java
PV-NbDo1[4]
PV-Springfontein
PV-KT-In1
PV-Venterstad
Karoo Basin
Gondwanide fold belt
PV-Cr1[4]
PV-LC
PV-BM-In2
Kat2Pass
FI/Mv
FI22.2.1[1]
FI22.10.1
FI22.17.1
FI22.23.1
FI22.26.3
F11[2]
Natal Embayment
Proto-Pacific Plate
NPM
M.1638.12[8]
M.2042.1c
M.2022.1a
M.2025.3
M.4131.15
AL1[6]
MD3
MD32
TdF
SG
BB
DSOL-16[7]
AP
EN
EWM
East Antarctica
Z.1608.7[17]
Theron Mountains
Lahille1[10]
Kayley1
Molina1
Andvord2
Hope4
PANTI-06[11]
PANTI-18[9]
PANTI-20
AA0842
LMG 2[11]
LMG 1[11]
R.8006.1[12]
R.8008.2
R.8009.3
R.8009.4
DL14[13]
MW54.3[14]
MW210.5
Polarstar
PRR299[15]
11-5-22[16]
Palaeocurrents (Trewin et al. 2002 Flowerdew et al. 2012 Lopez-Gamundi et a. 1995)
Potential sediment/ volcaniclastic source

Figure 6

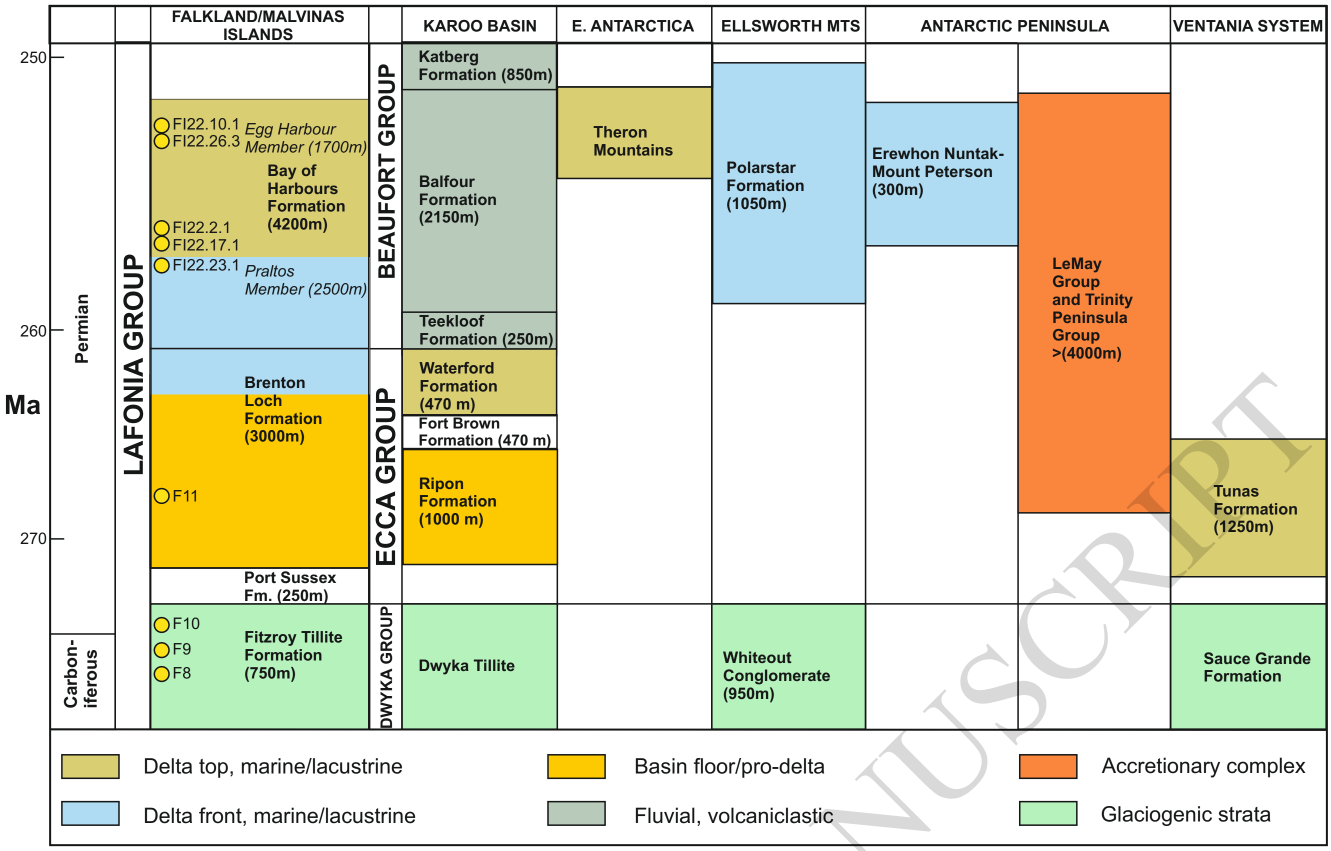
FALKLAND/MALVINAS ISLANDS
KAROO BASIN
E. ANTARCTICA
ELLSWORTH MTS
ANTARCTIC PENINSULA
VENTANIA SYSTEM
250
260
270
Ma
Permian
Carbon-iferous
LAFONIA GROUP
FI22.10.1
FI22.26.3
Egg Harbour Member (1700m)
Bay of Harbours Formation (4200m)
FI22.2.1
FI22.17.1
FI22.23.1
Praltos Member (2500m)
Brenton Loch Formation (3000m)
F11
Port Sussex Fm. (250m)
F10
F9
F8
Fitzroy Tillite Formation (750m)
BEAUFORT GROUP
ECCA GROUP
DWYKA GROUP
Katberg Formation (850m)
Balfour Formation (2150m)
Teekloof Formation (250m)
Waterford Formation (470 m)
Fort Brown Formation (470 m)
Ripon Formation (1000 m)
Dwyka Tillite
Theron Mountains
Polarstar Formation (1050m)
Whiteout Conglomerate (950m)
Erewhon Nuntak-Mount Peterson (300m)
LeMay Group and Trinity Peninsula Group >(4000m)
Tunas Forrmation (1250m)
Sauce Grande Formation
Delta top, marine/lacustrine
Delta front, marine/lacustrine
Basin floor/pro-delta
Fluvial, volcaniclastic
Accretionary complex
Glaciogenic strata

Figure 7

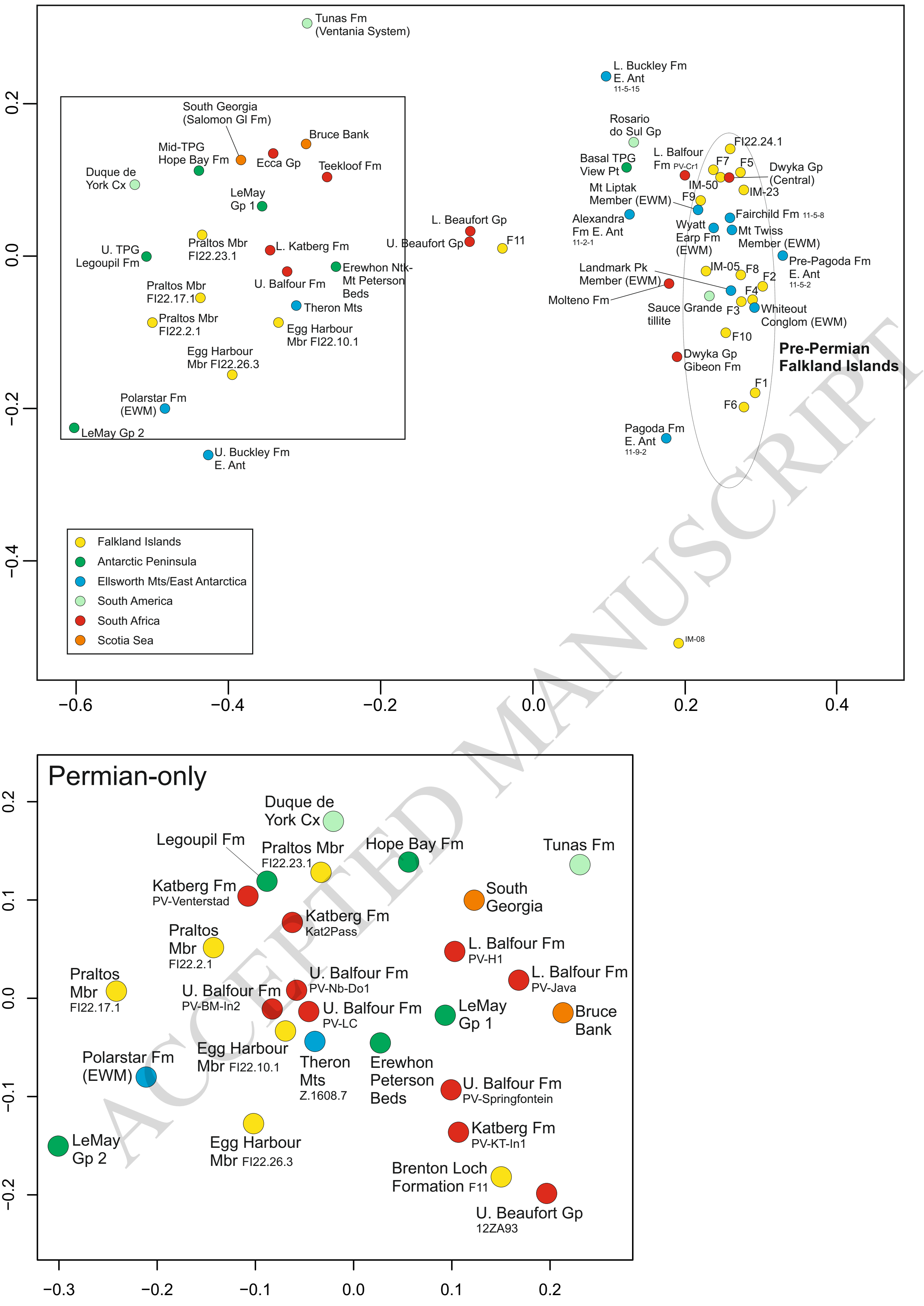
Tunas Fm
(Ventania System)
L. Buckley Fm
E. Ant
11-5-15
Rosario
do Sul Gp
FI22.24.1
Basal TPG
View Pt
L. Balfour
Fm PV-Cr1
F7
F5
Dwyka Gp
(Central)
IM-50
IM-23
Mt Liptak
Member (EWM)
F9
Alexandra
Fm E. Ant
11-2-1
Fairchild Fm 11-5-8
Wyatt
Earp Fm
(EWM)
Mt Twiss
Member (EWM)
L. Beaufort Gp
U. Beaufort Gp
F11
Pre-Pagoda Fm
E. Ant
11-5-2
Landmark Pk
Member (EWM)
IM-05
F8
F2
F4
Molteno Fm
Sauce Grande
tillite
F3
Whiteout
Conglom (EWM)
F10
Pre-Permian
Falkland Islands
Dwyka Gp
Gibeon Fm
F1
F6
Pagoda Fm
E. Ant
11-9-2
IM-08
South Georgia
(Salomon Gl Fm)
Bruce Bank
Mid-TPG
Hope Bay Fm
Ecca Gp
Teekloof Fm
Duque de
York Cx
LeMay
Gp 1
U. TPG
Legoupil Fm
Praltos Mbr
FI22.23.1
L. Katberg Fm
Erewhon Ntk-
Mt Peterson
Beds
U. Balfour Fm
Praltos Mbr
FI22.17.1
Theron Mts
Praltos Mbr
FI22.2.1
Egg Harbour
Mbr FI22.10.1
Egg Harbour
Mbr FI22.26.3
Polarstar Fm
(EWM)
LeMay Gp 2
U. Buckley Fm
E. Ant
Falkland Islands
Antarctic Peninsula
Ellsworth Mts/East Antarctica
South America
South Africa
Scotia Sea
0.2
0.0
−0.2
−0.4
−0.6
−0.4
−0.2
0.0
0.2
0.4
Permian-only
Duque de
York Cx
Legoupil Fm
Praltos Mbr
FI22.23.1
Hope Bay Fm
Tunas Fm
Katberg Fm
PV-Venterstad
South
Georgia
Katberg Fm
Kat2Pass
Praltos
Mbr
FI22.2.1
L. Balfour Fm
PV-H1
Praltos
Mbr
FI22.17.1
U. Balfour Fm
PV-Nb-Do1
L. Balfour Fm
PV-Java
U. Balfour Fm
PV-BM-In2
U. Balfour Fm
PV-LC
LeMay
Gp 1
Bruce
Bank
Polarstar Fm
(EWM)
Egg Harbour
Mbr FI22.10.1
Theron
Mts
Z.1608.7
Erewhon
Peterson
Beds
U. Balfour Fm
PV-Springfontein
LeMay
Gp 2
Egg Harbour
Mbr FI22.26.3
Katberg Fm
PV-KT-In1
Brenton Loch
Formation F11
U. Beaufort Gp
12ZA93
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.2
−0.1
0.0
0.1
0.2

Figure 8

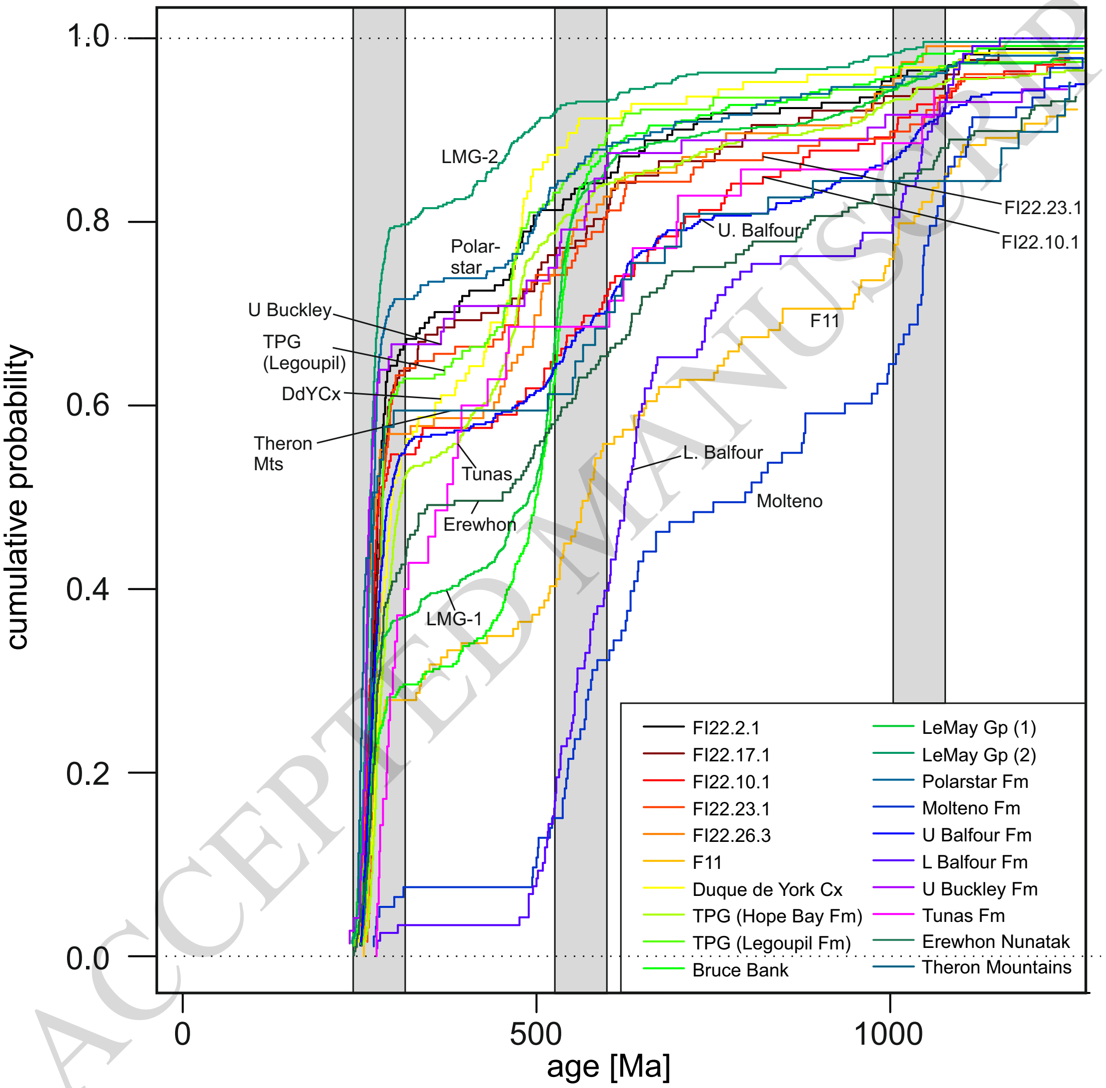
1.0
0.8
0.6
0.4
0.2
0.0
cumulative probability
0
500
1000
age [Ma]
LMG-2
Polar-
star
U Buckley
TPG
(Legoupil)
DdYCx
Theron
Mts
Tunas
Erewhon
LMG-1
U. Balfour
F11
L. Balfour
Molteno
FI22.23.1
FI22.10.1
FI22.2.1
FI22.17.1
FI22.10.1
FI22.23.1
FI22.26.3
F11
Duque de York Cx
TPG (Hope Bay Fm)
TPG (Legoupil Fm)
Bruce Bank
LeMay Gp (1)
LeMay Gp (2)
Polarstar Fm
Molteno Fm
U Balfour Fm
L Balfour Fm
U Buckley Fm
Tunas Fm
Erewhon Nunatak
Theron Mountains

Figure 9