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West Antarctic mantle deduced from mafic magmatism

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Abstract: Distinct mantle compositions recorded in primitive West Antarctic magmatic rocks vary by tectonic setting and time. Deep asthenospheric mantle-plume sources or shallow metasomatized mantle sources may operate either coincidently or independently to supply melts for magmatism. For example, contemporaneous subduction and plume dynamics produced the Ferrar–Karoo Large Igneous Province; subduction-related melting followed by slab-rollback or melting of slab-hosted pyroxenite explains Antarctic Peninsula volcanism through time; Marie Byrd Land magmatism results from plume materials variably mixed with subduction-modified mantle; while magmatism in Victoria Land and western Ross Sea is best explained by plate dynamics and melting of asthenospheric and metasomatized lithospheric sources, and not by an upwelling plume. Element and isotopic ratios show a fundamental change between Marie Byrd Land and Victoria Land mantle domains. Specifically, Pb isotopes indicate that Victoria Land magmatism sources have a stronger focal zone (FOZO) mantle component, while Marie Byrd Land magmatism possesses more of the high μ = high $^{238}U/^{204}Pb$ (HIMU) mantle component that leads to high $^{206}Pb/^{204}Pb$ over time. The chemical and isotopic heterogeneity of relatively unfractionated igneous rocks in West Antarctica reflects fundamental differences in mantle domains and melting conditions. This mantle variability coincides with changes in crustal structure and composition, and has a geophysical signature that is manifest in seismic data and tomographic models.

Petrological studies of mafic igneous rocks from Antarctica yield crucial information about upper-mantle compositions and insights into the geodynamic evolution of the Antarctic Plate. Mantle-derived mafic magmas were intruded and erupted within several distinct tectonic settings over the past 200 million years (Smellie *et al.* 2020; Panter 2021), including continental break-up and the formation of the Ferrar and Karoo Large Igneous Provinces (LIPs), subduction to form the Antarctic Peninsula volcanic arc that has transitioned to post-subduction slab-rollback and slab-window magmatism, and broad extension resulting in widespread intraplate magmatism associated with the West Antarctic Rift System (WARS) – one of Earth's major continental rifts (Fig. 1). The diverse and dynamic tectonic history of Antarctica is revealed by the geochemical and isotopic diversity of igneous rock types, whose origins can ultimately be traced back to differences in mantle source (i.e. mineral mode, and geochemical and isotopic composition) and the conditions that promoted melting. The identification of different sources for magmatism (e.g. plume, upwelling asthenosphere and lithosphere) can provide important constraints on heat flux to the crust. Furthermore, information on the mineral mode for melting (e.g. anhydrous peridotite, pyroxenite and volatile-phase-bearing varieties) can contribute to our understanding of mantle rheology, which, in turn, can aid interpretations of seismic velocity and models for glacial isostatic adjustment.

The occurrence of igneous rocks representing primary melts in equilibrium with mantle peridotite are exceedingly rare and thus petrologists often rely on samples that are the least fractionated chemically (e.g. low SiO_2 and high MgO, Cr, Ni concentrations, and high olivine forsterite contents) to best tackle questions related to mantle source types and melting conditions. These mafic compositions that are used to reconcile magma origins in Antarctica include olivine tholeiite, basaltic andesite, alkaline and subalkaline basalts, basanite, hawaiite, trachybasalt, tephrite, and olivine nephelinite (Fig. 2a). The wide-ranging geochemical characteristics of Antarctic mafic magmatism permit discrimination by tectonic setting (Fig. 2b–d). Compositions plotted on tectonic discrimination diagrams fall consistently within fields that delimit two basic types: intraplate and convergent margin settings. Notably, compositions associated with the WARS and post-subduction compositions from the Antarctic Peninsula are tightly constrained to within-plate alkaline types. Conversely, compositions of the Ferrar–Karoo LIP and back-arc magmatism from the Antarctic Peninsula fall within both the arc (i.e. volcanic arc basalt (VAB) and island arc basalt (IAB)) and within-plate tholeiitic fields that encompass mid-ocean ridge basalt (MORB)-type compositions (Fig. 2b–d).

Major and trace element concentrations are also used to estimate mantle source enrichment or depletion (i.e. concentration of highly incompatible trace elements relative to undifferentiated or primitive mantle) and fertility (i.e. source mineralogy that dictates the degree of partial melting) to generate magma. Radiogenic isotopes, most commonly the Rb–Sr, Sm–Nd and U–Th–Pb systems, are used to characterize the long (hundreds of millions to billions of years) time-integrated history of different mantle end-member reservoirs (e.g. depleted mantle (DMM), enriched mantle (EM), high $\mu = {}^{238}U/^{204}Pb$ (HIMU), etc.) that have been defined by MORB and ocean island basalt (OIB) sample suites worldwide (Fig. 3). Results from radiogenic isotopes, coupled with oxygen isotopes and trace elements, are used to identify mantle source heterogeneities but are also important in identifying magmas that have been contaminated by crust during their ascent towards the surface.

Over the past 30 years, there has been significant progress in our understanding of the primary origins of magmas in Antarctica, facilitated by more comprehensive petrological data coverage along with better constraints on age (Smellie *et al.* 2021 and references therein). Other contributions include higher-resolution imaging of the architecture of the upper mantle and lithosphere, as well as finer-tuned plate reconstructions, all an outcome of extensive geological and geophysical campaigns (e.g. Pappa *et al.* 2019; Jordan *et al.* 2020; Lloyd *et al.* 2020; Martin and van der Wal 2022). Despite these advances, considerable debate remains. Petrological studies on intraplate alkaline magmatism associated with the WARS differ on whether magmas were produced within the asthenosphere or within metasomatized lithospheric mantle, and whether melting was facilitated by extension-enhanced edge-driven mantle flow or by mantle plumes (e.g. LeMasurier and Rex 1989; Kyle *et al.* 1992; Hole and LeMasurier 1994; Hart *et al.* 1995, 1997; Rocchi *et al.* 2002; Gaffney and Siddoway 2007; Nardini *et al.* 2009; Martin *et al.* 2013; LeMasurier *et al.* 2016; Phillips *et al.* 2018; Panter *et al.* 2018). Debate also

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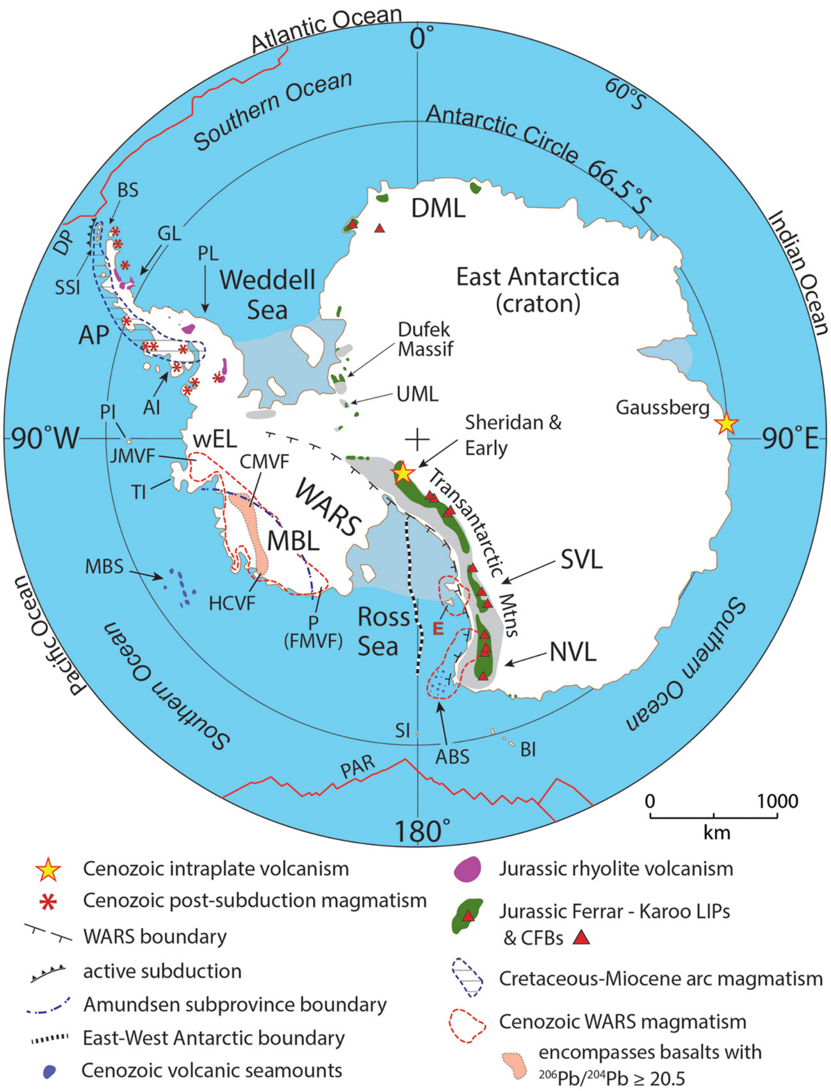

Fig. 1. Map of Antarctica showing the distribution of Mesozoic (Jurassic and Cretaceous) and Cenozoic tectonomagmatic provinces and volcanism (after Panter 2021). The distribution of Ferrar and Karoo LIPs and associated continental flood basalts (CFBs) are after Luttinen (2018) and Elliot and Fleming (2021). The locations of Jurassic rhyolite volcanism are from Riley and Leat (2021). The boundary of the Amundsen (seaward) and Ross (inland) geotectonic provinces of the West Antarctica Rift System (WARS) is after Jordan *et al.* (2020), and the geotectonic boundary between East and West Antarctica (cratonic margin province) is after Tinto *et al.* (2019) and Jordan *et al.* (2020). Cenozoic intraplate basalts with ^{206}Pb/^{204}Pb isotopic ratios ≥20.5 occur in four volcanic fields in Marie Byrd Land (MBL) and the region that encompasses them is outlined (from Panter *et al.* 2021*b* and references therein). Abbreviations: ABS, Adare Basin seamounts; AI, Alexander Island; AP, Antarctic Peninsula; BI, Balleny Islands; BS, Bransfield Strait; CMVF, Crary Mountains Volcanic Field; DML, Dronning Maud Land; DP, Drake Passage; E, Mount Erebus volcano on Ross Island; GL, Graham Land; HCVF, Hobbs Coast Volcanic Field; JMVF, Jones Mountains Volcanic Field; MBS, Marie Byrd seamounts; NVL, northern Victoria Land; P, Mount Perkins, which is part of the Fosdick Mountains Volcanic Field (FMVF); PAR, Pacific–Antarctic Ridge; PI, Peter I Island; PL, Palmer Land; SI, Scott Island; SSI, South Shetland Islands; SVL, southern Victoria Land; TI, Thurston Island; UML, ultramafic lamprophyres of the Ferrar LIP; wEL, western Ellsworth Land.

exists among petrologists who study intraplate magmatism closely associated with continental margin tectonics (i.e. Antarctic Peninsula, and the Jurassic Ferrar and Karoo LIPs). Magmatism in these areas has been explained by upwelling asthenosphere and plumes and/or upper mantle modified by subduction activity (e.g. Heinonen *et al.* 2014; Luttinen 2018; Choi *et al.* 2019; Elliot and Fleming 2021 and references therein).

In this chapter we provide a synthesis of mantle-source compositions that have been proposed for magmatism across West Antarctica, with reference to East Antarctica and sub-Antarctic island and seamount locations where relevant. It should be noted that this overview chapter is not a summary of the occurrence of mafic igneous rocks in Antarctica. Furthermore, all geochemical and isotopic data gathered from mafic igneous rocks in Antarctica that are discussed within this synthesis were procured from published studies, including compilations of Cenozoic samples from the WARS by Martin *et al.* (2021*b*), Panter *et al.* (2021*a*) and Rocchi and Smellie (2021). A detailed overview of mantle information recorded in igneous rocks from East Antarctica is provided by Foley *et al.* (2021) and is not repeated here. Because igneous activity has occurred intermittently from the Jurassic Period to the present and within a variety of tectonic settings, secular changes in mantle sources have been identified and offer a unique view of the evolution of the Antarctic Plate and the physical and chemical influences of plate dynamics on mantle domains that lie beneath.

Melt sources: deep origins

Sublithospheric mantle sources for magmatism include the melting of convecting upper mantle and emerging mantle plumes. Plumes are broadly defined as thermally buoyant mantle (i.e. having high Rayleigh numbers above that of ambient mantle) that rise as diapirs from deep thermochemical boundary layers (e.g. 410 km, 660 km or from ultralow-velocity zones in the lower mantle) and flatten at the base of the lithosphere where they decompressively melt. Geologically, mantle plumes can cause regional domal uplift, produce magmatism to form LIPs and long-lived linear volcanic ranges (e.g. Hawaiian–Emperor chain), and cause lithospheric thinning that can initiate rifting and continental break-ups. Geophysically, mantle plumes are defined by seismic tomography models that image low-velocity anomalies extending from the surface into the deep mantle (e.g. Montelli *et al.* 2004; Zhao 2007; French and Romanowicz 2015; Marignier *et al.* 2020). Geochemically, mantle plumes are characterized by OIBs with a range of compositions, erupted from oceanic island 'hotspot' volcanoes (e.g. Hofmann 1997; Stracke *et al.* 2005; Hawkesworth and Scherstén 2007; White 2010; Castillo 2015; Zhang *et al.* 2020) whose isotopic end members (HIMU, focus zone (FOZO), and enriched mantle types I (EMI) and II (EMII): Fig. 3) are considered to be the products of long-term recycling of subducted oceanic lithosphere and subduction-modified oceanic crust with or without a sedimentary cargo. However, in continental settings, especially

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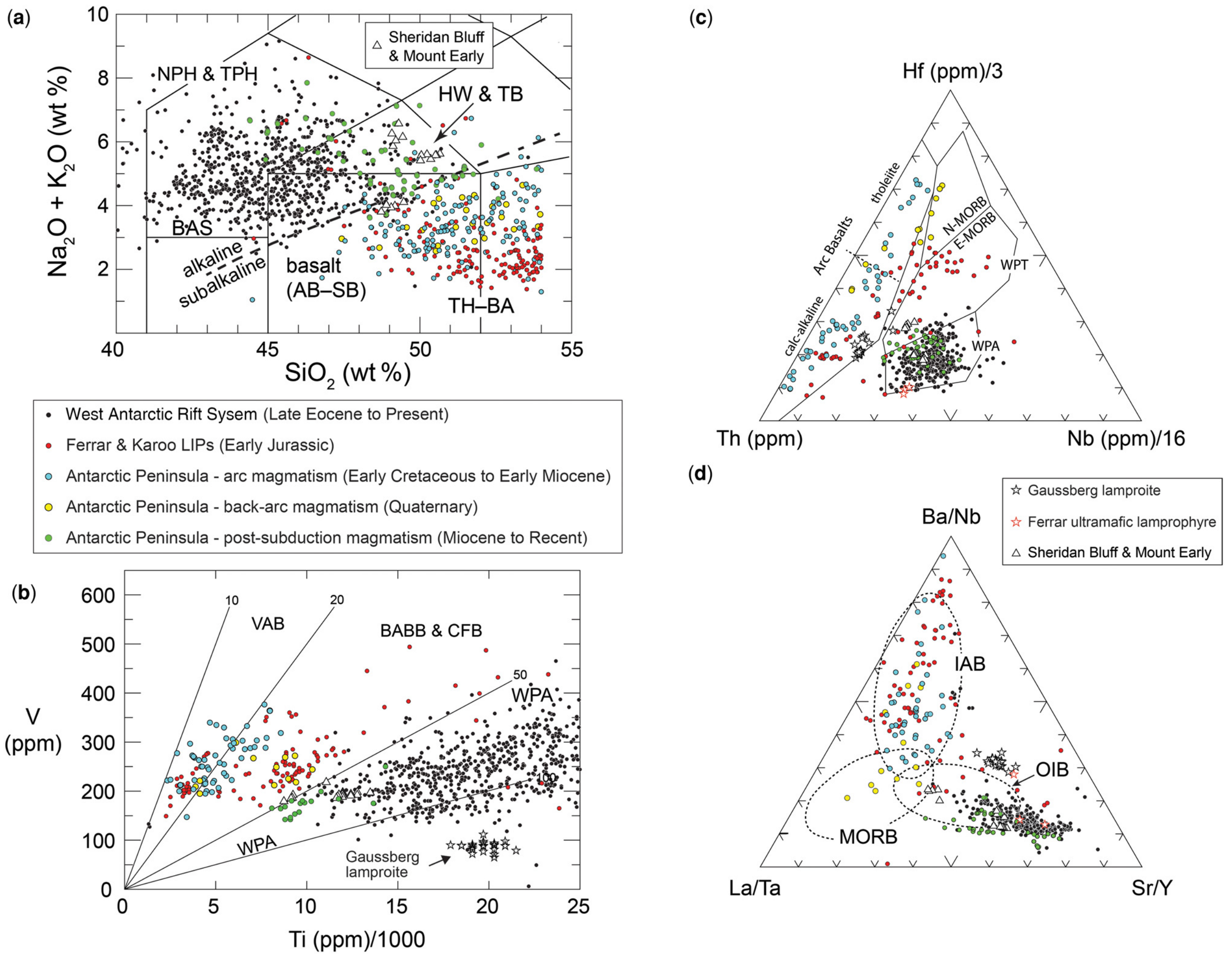

Fig. 2. Plots of mafic igneous rock compositions from Antarctica and their tectonomagmatic associations. Mafic samples are restricted in SiO_2 between 40 and 54 wt%, and MgO between 5 and 15 wt%. All analyses are normalized to a 100% volatile-free basis. (**a**) Total alkalis v. silica classification plot following the criteria of LeMaitre (2002). The thick dashed line delimits the subalkaline from the alkaline compositions (after Irvine and Baragar 1971). Field abbreviations are for nephelinite (NPH), tephrite (TPH), basanite (BAS), hawaiite (HW), trachybasalt (TB), tholeiite (TH), basaltic andesite (BA), alkaline basalt (AB) and subalkaline basalt (SB). Olivine-bearing dolerites of the Ferrar LIP plot with tholeiite and basaltic andesite compositions, and lamproite dykes from the Karoo LIP in Dronning Maud Land (Fig. 1) fall within the basanite classification field. Not plotted are the ultramafic lamprophyre dykes of the Ferrar LIP (Riley *et al.* 2003) with SiO_2 contents of *c.* 35 wt% and $Na_2O + K_2O$ <4 wt% (MgO >16 wt%) and lamproite pillow lavas from the Gaussberg volcano with SiO_2 contents of *c.* 50 wt% and $Na_2O + K_2O$ >12 wt% (MgO *c.* 8 wt%). (**b**) Mafic compositions plotted on a ppm Ti v. V diagram, with tectonomagmatic associations from Shervais (1982). Field labels between lines of equal proportions are volcanic arc basalt (VAB), back-arc basin basalt (BABB), continental flood basalt (CFB) and within-plate alkaline (WPA) basalt. (**c**) Mafic compositions plotted on the Th–Hf–Nb discrimination diagram of Wood (1980). Abbreviations: WPA, within-plate alkaline; WPT, within-plate tholeiite; N-MORB, normal mid-ocean ridge basalt; E-MORB, enriched mid-ocean ridge basalt. (**d**) A La/Ta–Ba/Nb–Sr/Y basalt discrimination diagram from Zhang *et al.* (2020). Zhang *et al.* (2020) employed GEOROC and PetDB global databases and big data statistical methods to define confidence ellipses (dashed) that discriminate island arc basalts (IAB) from mid-ocean ridge basalts (MORB) and ocean island basalts (OIB). Data sources for Antarctic mafic samples for the West Antarctic rift system are from Martin *et al.* (2021*b*), Panter *et al.* (2021*b*) and Rocchi and Smellie (2021), which are compilations of previously published and unpublished datasets for the Ross Sea and Marie Byrd Land regions of the rift. Please refer to these publications for the original data sources. Samples for the Ferrar and Karoo LIPs and arc magmatism from the Antarctic Peninsula are from the GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/), samples for back-arc magmatism from the Bransfield Strait, Antarctic Peninsula are from Keller *et al.* (2002), and the compositions for post-subduction magmatism on the Antarctic Peninsula are from Hole (2021) and the GEOROC database. The compositions of ultramafic lamprophyre dykes from the Ferrar LIP are from Riley *et al.* (2003) and lamproite pillow lava compositions from Gaussberg in East Antarctica provided by Murphy *et al.* (2002). Basaltic compositions from Sheridan Bluff and Mount Early are from Panter *et al.* (2021*a*).

beneath thick cratons or inboard of active subduction zones, assigning a geochemical signature to a mantle plume is a complex undertaking that requires the unravelling of other potential lithospheric and sublithospheric influences on magma composition (e.g. Yellowstone hotspot: Hanan *et al.* 2008; Leeman *et al.* 2009; Stefano *et al.* 2019).

Mantle-plume sources have been proposed for Antarctic magmatism based on geological, geophysical and geochemical evidence. Magmatism that produced the Ferrar and Karoo LIPs and fostered Gondwana break-up, which separated Africa from Antarctica by the Late Jurassic, is one such case (Storey and Kyle 1997). Outcrops of the Middle Jurassic Ferrar and Karoo LIPs are intermittently exposed from northern Victoria Land along the Transantarctic Mountains to Dronning Maud Land (Fig. 1). The magmatism occurred over a very short time interval of less than 0.4 myr at *c.* 183 Ma (Svensen *et al.* 2012; Elliot and Fleming 2021) with an estimated volume of greater than 1×10^6 km^3 (Eldholm and Coffin 2000; Burgess *et al.* 2015). There has been extensive study and debate on the origin of Ferrar–Karoo magmatism stemming from its unique distribution and geochemistry relative to other LIPs (e.g. Marsh 2004; Elliot and Fleming

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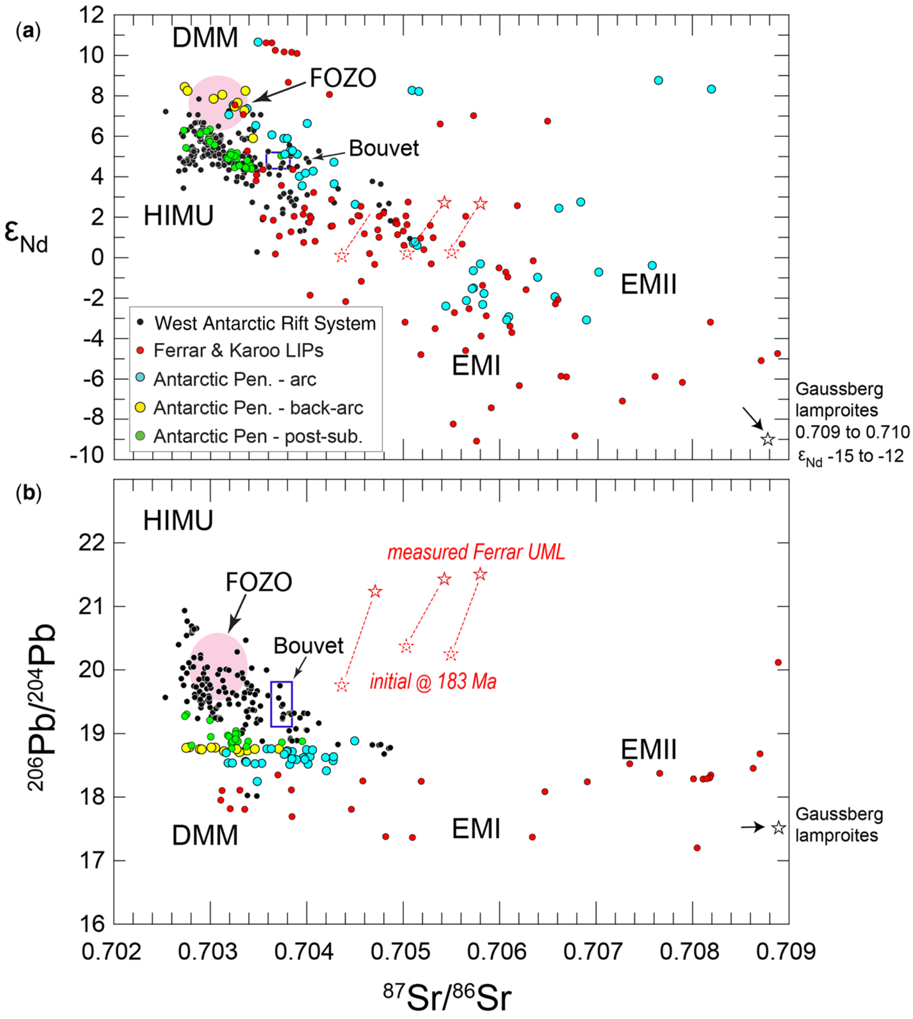

Fig. 3. Variations in $^{87}Sr/^{86}Sr$ v. (**a**) ε_{Nd} and (**b**) $^{206}Pb/^{204}Pb$ in Antarctic mafic igneous rocks. Data sources are the same as in Figure 2. Compositional restrictions in major element concentrations are also the same as in Figure 2 except for Ferrar–Karoo, which include some samples with higher SiO_2 contents (up to 62 wt%), and several samples with higher (up to 20 wt%) and lower (≥4 wt%) MgO contents. Mantle end-member compositions HIMU, DMM, EMI and EMII are plotted after Hofmann (2007), and FOZO (Hart *et al.* 1992) are after Stracke *et al.* (2005). The isotopic composition of the Bouvet OIB is from Riley *et al.* (2003 and references therein). The initial isotopic ratios for the Ferrar ultramafic lamprophyres (UML) are corrected to 183 Ma (Riley *et al.* 2003). All other isotopic data are plotted as measured values. Note that in (b) the Pb isotopic values are not available for samples of Antarctic Peninsula arc magmatism that have $^{87}Sr/^{86}Sr$ values >0.7046.

2021). In Antarctica, the long and narrow distribution of outcrops is explained by two different scenarios: (1) magmas are sourced from a single region of mantle melting followed by long-distance lateral migration within the crust; and (2) magmas were supplied from multiple, roughly aligned mantle-melt regions (i.e. ‘linear source’) and emplaced within the crust with restricted lateral migration (Elliot and Fleming 2021). Geochemically, mafic rocks of the Karoo and the Ferrar LIPs have mantle-like oxygen and osmium isotopic signatures; however, they also have enriched Sr, Nd and Pb isotopic values (Fig. 3), which, along with trace element patterns on normalized multi-element plots (not shown), suggest addition from continental crust (Luttinen 2018; Elliot and Fleming 2021). To explain both the geographical distribution (Fig. 1) and geochemistry, some researchers call upon a single mantle-plume source, now represented by compositions from the current Bouvet hotspot (Fig. 3) located in the South Atlantic Ocean, and long-distance transport of magma at various depths within the crust (e.g. Storey and Kyle 1997; Elliot *et al.* 1999; Riley *et al.* 2003; Vaughan and Storey 2007). Other researchers call for a linear zone of melting of subduction-modified mantle along the length of the palaeo-Pacific Gondwana margin (e.g. Hergt *et al.* 1991; Molzahn *et al.* 1996; Ivanov *et al.* 2017). In a recent study by Choi *et al.* (2019), an arc-like mantle source is favoured over a plume source based on platinum group elements abundances and Os isotope systematics. The authors suggest that rapid decompression of hydrated mantle materials parallel to the Gondwana margin subduction zone facilitated the large-volume and short-lived duration of Ferrar magmatism. Alternatively, a mixture of subduction-modified MORB-type mantle (pyroxenite source) and depleted ambient upper-mantle or plume(?) recycled MORB-type mantle (peridotite source) is used by Heinonen *et al.* (2014) to explain the Sr, Nd, Pb and Os isotopic and trace element compositions of mafic Karoo dykes in Dronning Maud Land. Luttinen (2018) proposed that melting occurred under the influence of both active subduction and an active mantle plume head. Here, subduction-modified mantle sources explain the Nb-depleted Karoo compositions found in Dronning Maud Land (Fig. 1) and, along with the distribution of similarly Nb-depleted compositions of the Ferrar LIP, the plume-influenced and subduction-influenced mantle regions of the palaeo-Pacific margin of Gondwana (Fig. 4). In summary, it is likely that both mantle-plume and subduction-modified mantle sources supplied Ferrar and Karoo LIP magmas based on the geological and geochemical evidence. This mixture of primary mantle-source types is reinforced by the distribution of Karoo–Ferrar mafic magma compositions across fields that define both arc basalts and within-plate tholeiitic flood basalts in Figure 2b–d.

Further disintegration of Gondwana in the Late Cretaceous separated the continental fragments that became Zealandia. The rapid transition (*c.* 110–80 Ma) from subduction to extension to seafloor spreading occurred without voluminous magmatism (i.e. no LIP formed) and did not produce any known volcanism in Antarctica (Smellie *et al.* 2020). Yet, there was relatively extensive intraplate volcanism in Zealandia occurring prior to and just after break-up between 99 and 79 Ma (Hoernle *et al.* 2020 and references therein). A large Late Cretaceous plume may have aided in this continental break-up event and may have provided a mantle reservoir – a ‘fossil

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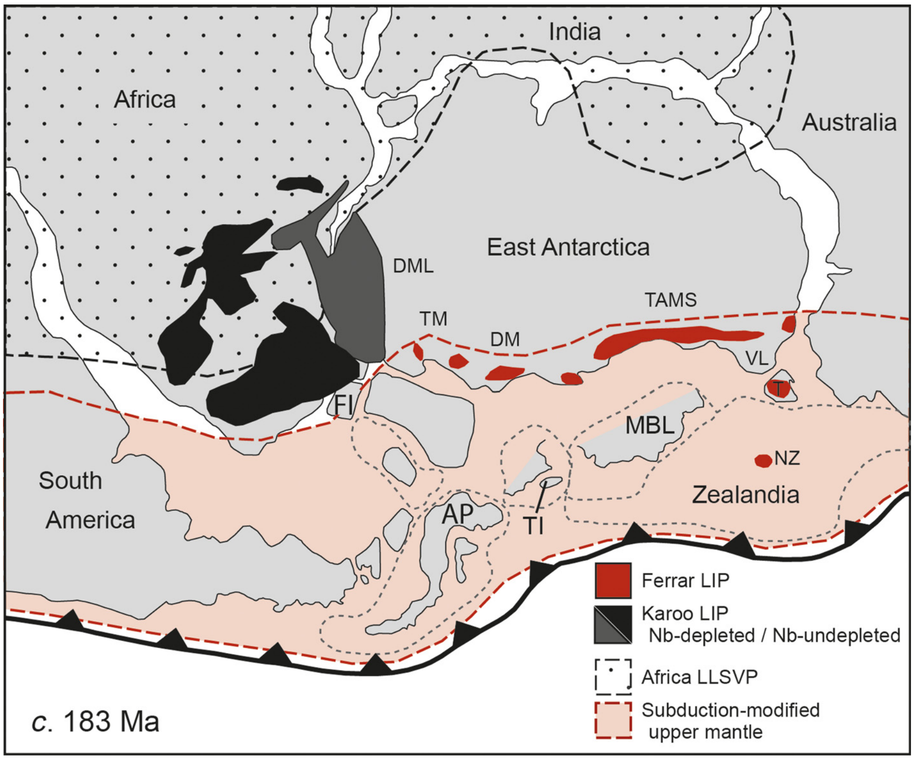

Fig. 4. Plate reconstruction at *c.* 183 Ma after Storey and Kyle (1997) showing for comparison the position of the Ferrar LIP after Smellie (2021) and the Karoo LIP after Luttinen (2018). The Karro LIP is divided into Nb-depleted (grey) and Nb-undepleted (black) regions, and together mark the location of a Jurassic plume head. Shown for comparison is the region were the shallow mantle is inferred to have been modified by subduction (Luttinen 2018) (in red) and the sub-African large low-shear velocity province (LLSVP) projected onto the surface from a depth of 2800 km (Luttinen 2018: stippled pattern). AP, Antarctic Peninsula; DM, Dufek Massif; DML, Dronning Maud Land; FI, Falkland Islands; MBL, Marie Byrd Land; NZ, New Zealand; T, Tasmania; TAMS, Transantarctic Mountains; TI, Thurston Island; TM, Theron Mountains; VL, Victoria Land.

plume source' for intraplate alkaline magmatism in West Antarctica throughout the Cenozoic (Lanyon *et al.* 1993; Weaver *et al.* 1994; Rocholl *et al.* 1995; Hart *et al.* 1997; Storey *et al.* 1999; Panter *et al.* 2000; Kipf *et al.* 2014; Park *et al.* 2019).

Apart from the magmatism along the Antarctic Peninsula and a few isolated volcanic centres in the southern Transantarctic Mountains (Mount Early and Sheridan Bluff) and in East Antarctica (Gaussberg), all other known Cenozoic igneous activity exposed on the continent is associated with the WARS (Fig. 1). The WARS initiated during the Late Cretaceous breakoff of Zealandia, and continued to develop with motion occurring between the East Antarctic craton and the geotectonic provinces of West Antarctica (Granot *et al.* 2013; Jordan *et al.* 2020; Storey and Granot 2021). The extension has produced a very broad region of thinned continental lithosphere (Behrendt *et al.* 1991; Behrendt 1999) that is 3000 km in length and 750–1000 km wide. Rift magmatism began approximately 50 myr ago (Tonarini *et al.* 1997; Rocchi *et al.* 2002) but only became abundant and widespread since the Middle Miocene (Martin *et al.* 2010). The WARS-related volcanism produced over 30 major polygenetic shield-like composite volcanoes (each ≥30–1800 km^3 of exposed volume above ice sheet or sea level) and numerous monogenetic volcanic fields, including seamounts in the southern Ross Sea (Aviado *et al.* 2015; Martin *et al.* 2021*b*) and in the oceanic Adare Basin (Fig. 1) (Panter *et al.* 2018). Mafic compositions from the WARS are almost exclusively alkaline (Fig. 2a) and consistently classify on tectonic discriminate diagrams as within-plate alkali basalt (Fig. 2b, c) that are OIB-like (Fig. 2d). Isotopically, WARS compositions indicate a mantle source with strong HIMU- and FOZO-like affinities ($^{206}Pb/^{204}Pb \cong 19–21$, $^{87}Sr/^{86}Sr \cong 0.7027–0.7040$, $\varepsilon_{Nd} \cong 3–7$: Fig. 3). The affinity of WARS magmatism with the geochemical and isotopic characteristics of ocean-island hotspot volcanoes has been the cornerstone of mantle-plume models. Plume activity beneath West Antarctica has also been based on the geographical distribution and age migration patterns of volcanism, as well as more recently by seismic tomography (e.g. Bredow and Steinberger 2021).

An active mantle plume beneath Marie Byrd Land (Fig. 1) has been used to explain the geochemistry of Cenozoic magmatism, along with regional doming and volcanic migration patterns (LeMasurier and Rex 1989; Hole and LeMasurier 1994; Hole *et al.* 1994; Hansen *et al.* 2014; Wiens *et al.* 2021). The volcanoes in Marie Byrd Land province are mostly located on a *c.* 1000 × 500 km structural dome (LeMasurier 2006) that lies on the north flank of the WARS and has been interpreted as a topographical expression of a mantle plume (LeMasurier and Landis 1996). The mean crustal thicknesses beneath the Marie Byrd Land dome are calculated from seismic data to be 28–33 km, which is 5–10 km thicker than in the rest of the WARS (Chaput *et al.* 2014; Ramirez *et al.* 2017; Shen *et al.* 2018; Wiens *et al.* 2021). However, the dome is not attributed to isostatic compensation of thicker crust but to a thermal anomaly beneath this volcanic province (Winberry and Anandakrishnan 2004). Marie Byrd Land primitive magma compositions have been explained by mixing between subduction-modified lithosphere (discussed below) and HIMU-like and/or FOZO-like mantle-plume materials (e.g. Hart *et al.* 1995, 1997; Panter *et al.* 2000, 2006; Finn *et al.* 2005; Gaffney and Siddoway 2007; LeMasurier *et al.* 2016). There has been a documented west–east gradient in isotopic and trace element composition in primitive volcanic rocks through Marie Byrd Land (LeMasurier *et al.* 2016) that continues into western Ellsworth Land with an interpreted distinct change in Pb isotopic and trace element composition (Hart *et al.* 1995; LeMasurier *et al.* 2016). In a recent compilation and review of basalt compositions from Marie Byrd Land and western Ellsworth Land (Fig. 1), Panter *et al.* (2021*b*), using an extended dataset of major and trace element concentrations and isotopic values (Sr, Nd and Pb), support this regional gradient and show a more extensive and gradual transition from central Marie Byrd Land (e.g. Hobbs Coast Volcanic Field (HCVF) and Crary Mountains Volcanic Field (CMVF): Fig. 1) east into Ellsworth Land (e.g. Jones Mountains Volcanic Field (JMVF)) and west to the Fosdick Mountains (e.g. Fosdick Mountains Volcanic Field (FMVF), Fig. 1). An additional observation is that the current known distribution of the most radiogenic Pb

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signatures ($^{206}Pb/^{204}Pb$ >20) found in Marie Byrd Land reveals a broadly linear feature orientated oblique to the main axis of the WARS (Fig. 1; also refer to figs 44 and 45 in Panter *et al.* 2021*b*) that overlaps with a broad eastward decrease in $^{143}Nd/^{144}Nd$ ratios, which LeMasurier *et al.* (2016) concluded, along with evidence from Sr isotopes and trace elements, to be the result of an increasing influence by subduction-modified mantle that was formed during convergence at the proto-Pacific margin of Gondwana. At *c.* 90 Ma the area encompassed by the radiogenic Pb signatures was roughly parallel with several other colinear features and may reflect continental strike-slip zones formed in response to oblique subduction prior to Gondwana break-up (refer to figs 4 and 5 in Eagles *et al.* 2004). Translithospheric faulting may have helped to localize upwelling HIMU plume materials for melting beneath the region (LeMasurier and Rex 1989; Panter *et al.* 1997). Geophysical studies indicate high heat flow (Seroussi *et al.* 2017; Shen *et al.* 2020; Pappa and Ebbing 2021) and slow seismic velocities (Hansen *et al.* 2014; Heeszel *et al.* 2016; Lloyd *et al.* 2020; Lucas *et al.* 2020; Wiens *et al.* 2021) that extend at least to the mantle transition zone (i.e. 400–600 km) beneath central Marie Byrd Land, thus supporting a mantle-plume influence on volcanism and tectonism.

The ‘Erebus plume’ was proposed by Kyle *et al.* (1992) and Esser *et al.* (2004) to explain the geochemistry, along with volcanic patterns and the generation of large volumes of phonolitic magmas from basanitic melts beneath the active Mount Erebus volcano (Fig. 1). The authors suggested that uplift and crustal extension was enhanced by plume buoyancy, and may explain the radial pattern of volcanism on Ross Island and a similar pattern centred on the Mount Discovery volcano *c.* 100 km to the south. More recent detailed geochemical and isotopic (Sr, Nd, Hf and Pb) studies of Mount Erebus and the rest of Ross Island by Sims *et al.* (2008) and Phillips *et al.* (2018) support a mantle-plume source. Phillips *et al.* (2018) modelled mixing between DMM and HIMU sources to explain Ross Island samples, and concluded that the HIMU isotopic signature originated from high time-integrated (Archean–Early Proterozoic) U/Pb and Th/Pb ratios from crustal materials that were recycled from the deep mantle. They and Emry *et al.* (2020) employed seismic tomography models, which suggested that a low-velocity zone exists to a depth of *c.* 1200 km and the mantle transition zone is thinner beneath Ross Island, supporting the deep plume hypothesis. Alternatively, Day *et al.* (2019) in analysing mantle xenoliths and lava flow rocks from Hut Point Peninsula on Ross Island defined $^{3}He/^{4}He$ ratios of 6.8 ± 0.3 R_A (2σ: where R_A is atmospheric $^{3}He/^{4}He$) beneath Ross Island that are distinct from high-$^{3}He/^{4}He$ plume mantle (e.g. ≥9 R_A: Class and Goldstein 2005). Nardini *et al.* (2009) came to a similar conclusion that northern Victoria Land volcanism with low mantle $^{3}He/^{4}He$ ratios (5.73–7.22 R_A) was a strong argument against involvement of a Cenozoic plume. This would be consistent with mantle images that do not show a deep (>150 km) root beneath Ross Island (e.g. Faccenna *et al.* 2008), and the observation that Ross Island and surrounding areas are a site of rifting rather than doming (Cooper *et al.* 2007; Martin *et al.* 2013).

Melt sources: shallow origins

Shallow melt sources have been proposed for magmatism in Antarctica, and include depleted upper-mantle sources (i.e. MORB-types), metasomatized lithospheric mantle, subducting slab and subduction-modified mantle wedge (i.e. asthenospheric mantle that lies above a subducting slab and below the overriding plate). The contributions from subduction-related processes to mantle sources are most clearly expressed in mafic compositions intimately associated with the progressive development of the Antarctic Peninsula volcanic arc. Yet, subduction dominated the tectonic regime episodically from the Neoproterozoic to the Late Cretaceous (*c.* 450 myr) along the pre-dispersal length of the Pan-Pacific margin of the Gondwana supercontinent (Cawood 2005), including the southern Gondwanan subduction zone and magmatic arc (Fig. 4) that was synchronous with the initial phase of Jurassic break-up magmatism (Rapela *et al.* 2005). As previously discussed, the regional geochemical characteristics of the Karoo and Ferrar LIPs is explained by Luttinen (2018) to be a consequence of magma production under the influence of active zones of subduction and plume upwelling. Subduction-influenced upper mantle may still reside beneath regions of Antarctica (Fig. 4) and could be a source tapped by Late Cenozoic volcanism (Fig. 1).

Continental arc volcanism along the west coast of the Antarctic Peninsula, which began in the Early Cretaceous and was active up until the Early Miocene (*c.* 23 Ma), continues to this day at a slow rate beneath the South Shetland Islands (Fig. 1). The erupted magmas are dominated by calc-alkaline compositions (e.g. basaltic andesite) and tholeiite (Fig. 2a), and show clear geochemical affinities to arc and back-arc settings (Fig. 2b–d). Isotopically, arc magmas were generated by melting of enriched mantle sources, as shown by mafic samples with high $^{87}Sr/^{86}Sr$ ratios and low ε_{Nd} values in Figure 3a. However, other arc magmas, along with back-arc compositions, reveal mantle sources that are much less enriched with much lower $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ ratios (Fig. 3b), and have higher measured ε_{Nd} values. Furthermore, samples with $^{87}Sr/^{86}Sr$ ratios of <0.7040 have Nd and Pb isotopic compositions generated from mantle that is more depleted than the post-subduction magmatism (discussed below). The variable origins of mafic compositions are explained by Leat and Riley (2021) as: (1) melting of variably depleted mantle-wedge material fluxed by hydrous fluids from the subducting slab (e.g. calc-alkaline series: South Shetland Islands); (2) partial melting of slab material and the equilibration of those melts under hydrous conditions within the mantle wedge prior to eruption (e.g. high-Mg andesite group: Alexander Island); (3) partial melting of garnet peridotite within the mantle wedge that incorporated melts of mafic slab material (e.g. adakitic group: South Shetland Islands); and (4) mantle partial melting that was triggered by arc extension or within a back-arc setting (e.g. high-Zr group: southern Graham Land–northern Palmer Land).

Since the Middle–Late Miocene, post-subduction volcanism produced extensive monogenetic volcanic fields, large (≥30 km^3) polygenetic shield volcanoes and small isolated centres scattered along the Antarctic Peninsula (Fig. 1). The geochemistry of mafic compositions is almost exclusively alkaline (Fig. 2a) and classify as being from a within-plate tectonic environment (Fig. 2b, c). Furthermore, they have a strong affinity to OIBs, as well as to intraplate mafic compositions from the WARS (Fig. 2c, d). The compositional resemblance to WARS basalts is also apparent with respect to Sr and Nd isotopes (Fig. 3a), although with Pb values that are much less radiogenic (Fig. 3b). The post-subduction intraplate volcanism in the Bransfield Strait is considered to be the result of extension related to the rollback of the Phoenix Plate, leading to partial melting of shallow mantle, to a high degree, with variable input of materials and fluids from the subducting slab (Haase and Beier 2021). The origin of the remaining post-subduction alkaline volcanism on the Antarctic Peninsula has been ascribed to back-arc extension or slab-window tectonics as a way to promote decompression melting of asthenospheric mantle. As an alternative to the slab-window hypothesis, Hole (2021) proposes that partial melting of slab-hosted pyroxenite can produce the geochemical characteristics

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of the post-subduction alkaline volcanism and may account for the lack of age progression of volcanism, as well as the relatively short time period of activity (i.e. predominantly ≤7 myr).

Submarine volcanism to the north of the South Shetland Islands in the Drake Passage (Fig. 1) records a transition in shallow mantle sources between the Late Miocene and the Pleistocene (Choe *et al.* 2007). Choe *et al.* (2007) found that prior to the shutdown of the Antarctic–Phoenix Ridge at 3.3 Ma (Livermore *et al.* 2000) partial melting of peridotite at shallow depths in the mantle produced tholeiitic basalts (6.4–3.5 Ma) with a normal (N)-MORB source affinity. After spreading ceased, mildly alkaline compositions were erupted (3.1–1.4 Ma) with an enriched (E)-MORB source affinity. Choe *et al.* (2007) suggested that the later phase of partial melting occurred to a smaller degree at greater depths and was facilitated by pyroxenite, possibly localized in veins (i.e. metasomatized mantle).

Metasomatized lithospheric mantle has been proposed as a shallow mantle reservoir for alkaline magmas erupted in continental settings (e.g. Stein *et al.* 1997; Jung *et al.* 2005; Panter *et al.* 2006; Ma *et al.* 2011; Mayer *et al.* 2014; Rooney *et al.* 2014, 2017; Scott *et al.* 2020), as well as oceanic settings (Pilet *et al.* 2008; Pilet 2015), and is prevalent in hypotheses on the origin of Cenozoic magmatism associated with the WARS (Hart *et al.* 1995; Rocchi *et al.* 2002; Panter *et al.* 2003, 2018; Gaffney and Siddoway 2007; Nardini *et al.* 2009; Rilling *et al.* 2009; Perinelli *et al.* 2011; Martin *et al.* 2013, 2015, 2021*b*; Aviado *et al.* 2015; LeMasurier *et al.* 2016; Correale *et al.* 2019; Day *et al.* 2019; Kim *et al.* 2019; Giacomoni *et al.* 2020). The foundations of this idea are to account for the relatively uniform geochemical and isotopic signatures (e.g. Figs 2c & 3) of rocks from three widely dispersed volcanic regions in West Antarctica (Fig. 1) and for the absence of voluminous tholeiitic magma series compositions that would be expected from the melting of a single plume head of the size required to encompass these areas. More specifically, the geochemical arguments for metasomatized sources supplying WARS magmatism are made based on their enriched concentrations of incompatible trace elements and relative depletion in potassium, as illustrated by mafic compositions plotted on mantle-normalized multi-element diagrams (Fig. 5). The negative K anomalies are considered a result of incomplete melting and retention of hydrous potassic minerals (amphibole ± phlogopite) in their sources. Mantle amphiboles are stable at temperatures of <1150°C (Mandler and Grove 2016) and therefore can reside only within the lithosphere. Lithospheric mantle xenoliths that contain amphibole (e.g. disseminated and vein amphibole, as well as their occurrence as reaction replacements of pyroxene) have been reported in both northern Victoria Land (Coltorti *et al.* 2004; Perinelli *et al.* 2006, 2011, 2017; Melchiorre *et al.* 2011; Broadley *et al.* 2016) and southern Victoria Land (Gamble and Kyle 1987; Gamble *et al.* 1988; Martin *et al.* 2014; Day *et al.* 2019). Except for rare occurrences of apatite, hydrous phases are absent in mantle xenoliths collected within the Marie Byrd Land Volcanic Province (Handler *et al.* 2021).

The cause of metasomatism has been attributed to several mechanisms including enrichments from subduction-derived melts and fluids, plume-derived melts and fluids, and extension-related auto-metasomatism. Evidence for metasomatism of West Antarctic lithosphere by subduction-zone processes is well documented in mantle xenoliths. Metasomatism of the lithosphere in northern Victoria Land by marine-derived volatiles is indicated by heavy halogen (Br and I) and noble gas (Ar, Kr and Xe) compositions liberated from fluid inclusions in olivine and pyroxene in peridotite xenoliths (Broadley *et al.* 2016). Broadley *et al.* (2016) suggested that the volatiles were released, perhaps at depths of up to 200 km (Sumino *et al.* 2010; Kendrick *et al.* 2013), during subduction and were incorporated into the overlying mantle wedge and subcontinental lithospheric mantle beneath the Gondwana continental arc during the Paleozoic. In another noble gas study of mantle xenoliths from northern Victoria Land, Correale *et al.* (2019) found homogeneous $^{3}He/^{4}He$ (7.1 ± 0.4 R_A) and low $^{4}He/^{40}Ar^*$ ratios (<0.4) from fluid inclusions in olivine, pyroxene and amphibole that they interpret as a result of subcontinental lithospheric mantle being metasomatized by depleted asthenospheric melts (MORB-type). In southern Victoria Land, Day *et al.* (2019) concluded, based on a petrological, geochemical and isotopic (He and Os) study of glass- and amphibole-rich veins in peridotites, that the mantle lithosphere beneath Ross Island (approximating to Mount Erebus: Fig. 1)

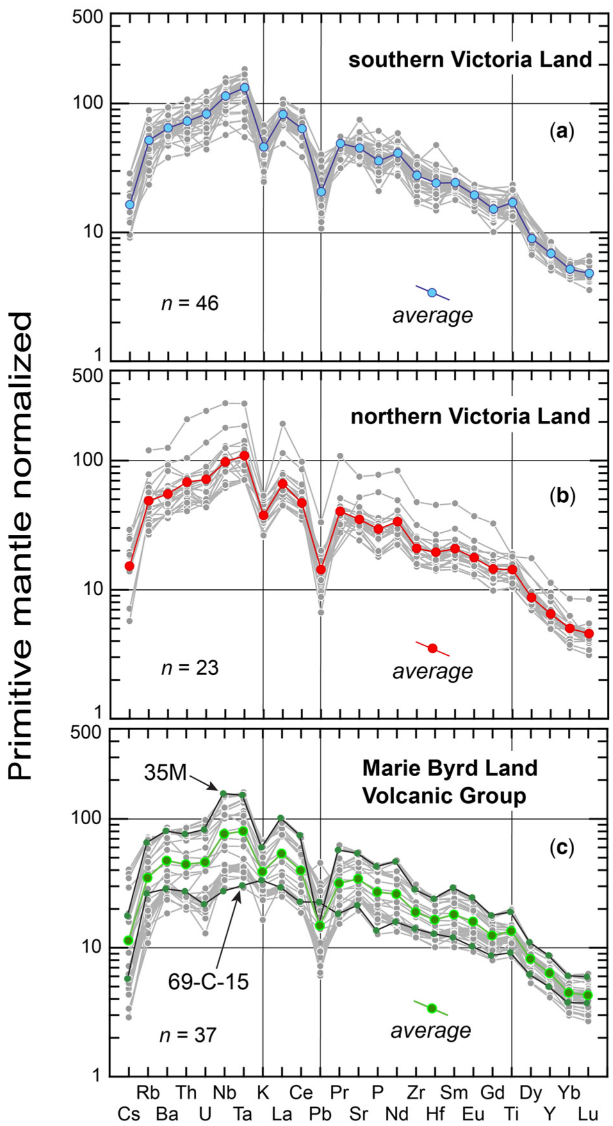

Fig. 5. A trace element comparison of mafic basaltic compositions within the West Antarctic Rift System modified from Panter (2021). Elemental concentrations are normalized to the primitive mantle values provided by McDonough and Sun (1995). Referenced datasets for (**a**) southern Victoria Land (Erebus Volcanic Province) are from Martin *et al.* (2021*b*), (**b**) northern Victoria Land (Hallett Volcanic Province and Melbourne Volcanic Province) from Rocchi and Smellie (2021) and (**c**) Marie Byrd Land and western Ellsworth Land (Marie Byrd Land Volcanic Group after Wilch *et al.* (2021)) are from Panter *et al.* (2021*b*). Labelled in (c) are basanite sample 35M (Hart *et al.* 1997) from the Hobbs Coast Volcanic Field and alkali basalt sample 69-C-15 (Hart *et al.* 1995) from the Jones Mountains Volcanic Field (Fig. 1).

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was metasomatized during the Cretaceous by subduction-related processes prior to Gondwana break-up. Also, within southern Victoria Land, a subduction-enriched component has been inferred from peridotite (EMI) and pyroxenite (EMII) xenoliths 30–100 km distant from Ross Island (Martin *et al.* 2014, 2015, 2021*a*), and in the primitive volcanic rocks of the Erebus Volcanic Province (Martin *et al.* 2013, 2021*b*). Whilst the age of metasomatism is not definitively constrained, existing whole-rock isochron dates on a phlogopite-bearing clinopyroxenite xenolith from the region (and the micas within it) give an age of 439 ± 5 Ma (McGibbon 1991), and an adjacent carbonatite dyke is dated at 531 ± 5 Ma (Hall *et al.* 1995) and may indicate that this was a time of general (carbonatite) metasomatism of the lithospheric mantle in this part of southern Victoria Land. Martin *et al.* (2014) inferred that alkaline metasomatism recorded in plagioclase-bearing spinel lherzolite xenoliths is coincident with alkaline magmatism in the region from *c.* 25 Ma. Handler *et al.* (2021) describe the effects of metasomatic processes on lithospheric mantle xenoliths from Marie Byrd Land, which, based on Os and Nd model ages, occurred between 570 and 130 Ma. These authors conclude that the geochemical and isotopic evidence, along with the ages, are consistent with a lithospheric mantle that was influenced by the long history of Paleozoic subduction that occurred beneath this region.

Geochemical and isotopic studies of mantle xenoliths and their basaltic hosts provide strong support for metasomatism caused by subduction-zone processes and that subduction-modified mantle is a common melt source for alkaline magmatism associated with the WARS (Hart *et al.* 1995; Martin *et al.* 2015; LeMasurier *et al.* 2016; Panter *et al.* 2021*b*; Coltorti *et al.* 2021; Handler *et al.* 2021). However, as has been proposed for the origin of the Karoo and Ferrar LIPs (discussed above), both deep plume sources and shallow metasomatic sources may coexist and supply melts for magmatism. Basalts from the CMVF in central Marie Byrd Land (Fig. 1) have geochemical and isotopic characteristics that led Panter *et al.* (2000) to conclude that mixing had occurred between a HIMU-like ($^{206}Pb/^{204}Pb$ >20.5) plume and a hydrous lower-μ mantle component. They propose a scenario in which a mantle plume was trapped and stored ('fossilized') beneath pre-existing metasomatized lithosphere prior to the Late Cretaceous break-up of Zealandia from West Antarctica. The geographical distribution of the most radiogenic Pb isotopic (HIMU-like) signatures are restricted to the middle portion of the region that comprises the Marie Byrd Land Volcanic Group (MBLVG: Wilch *et al.* 2021), which includes the HCVF (Hart *et al.* 1997) and the CMVF (Fig. 1), while the less radiogenic Pb (lower-μ source) signatures generally lie at the periphery of the MBLVG: that is, the JMVF and the FMVF (Fig. 1) (Hart *et al.* 1995; Gaffney and Siddoway 2007; LeMasurier *et al.* 2016; Panter *et al.* 2021*b*). In Figure 6, this relationship also correlates broadly with K/Ta ratios, and can be modelled by mixing between the HIMU and lower-μ end members within the MBLVG. The K/Ta ratios of mafic samples plotted in Figure 6 are proportional to the magnitude of the K anomalies (K/K*) shown on the mantle normalized multi-element diagram in Figure 5c. The relationship also exists for Ce/Pb ratios that are also proportional to Pb anomalies shown in Figure 5c, where samples with lower Ce/Pb ratios (*c.* <30) and higher Pb/Pb* values (*c.* >0.5: a value of 1 represents a linear alignment of Ce–Pb–Pr on multi-element diagrams) have less radiogenic Pb isotopic signatures. It is important to note in Figure 6 that the MBLVG samples with lower Pb isotopic ratios (lower-μ source) and lower K/Ta ratios (and lower Ce/Pb ratios, not shown) approach back-arc and post-subduction mafic compositions from the Antarctic Peninsula, which supports the existence of a subduction-modified mantle component beneath Marie Byrd Land and

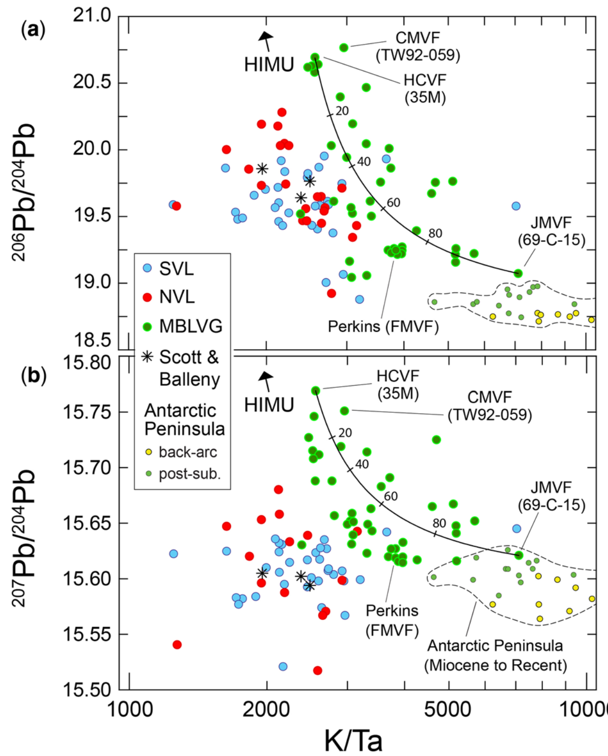

Fig. 6. Plots of K/Ta v. measured (**a**) $^{206}Pb/^{204}Pb$ and (**b**) $^{207}Pb/^{204}Pb$ ratios of mafic basaltic compositions from the West Antarctic Rift System (symbols are the same as those used in Fig. 5) and from the Antarctic Peninsula (back-arc and post-subduction magmatism; symbols and sources given in Fig. 2). Data from the Balleny and Scott islands, located north of the Ross Sea (Fig. 1), are from Hart *et al.* (1992) and Hart and Kyle (1994). MBLVG, Marie Byrd Land Volcanic Group; the other abbreviations are defined in Figures 1 and 3. Hypothetical curves of mixing between basanite (sample 35M) from the Hobbs Coast Volcanic Field (HCVF) and alkali basalt (sample 69-C-15) from the Jones Mountains Volcanic Field (JMVF) are marked at 20% increments. The curves illustrate that MBLVG compositions were likely to have been generated by the melting of a HIMU-like component (mantle plume?) and a lower-μ subduction-modified mantle component characterized by higher K/Ta (as well as higher K/Nb) and lower Ce/Pb ratios (*c.* <20). Alkali basalt sample TW92-059 (Panter *et al.* 2000) from the CMVF has the highest $^{206}Pb/^{204}Pb$ ratio (20.93) yet measured in West Antarctica. Also indicated are samples from Mount Perkins located within the Fosdick Mountains Volcanic Field (FMVF) (Gaffney and Siddoway 2007; Panter *et al.* 2021*b*). The FMVF and the JMVF lie approximately 1500 km apart on the periphery of the region that contains the MBLVG (Fig. 1).

western Ellsworth Land to supply volcanism (e.g. Hart *et al.* 1995; Panter *et al.* 2006; LeMasurier *et al.* 2016).

In northern Victoria Land, Rocholl *et al.* (1995) proposed three mantle source components to explain the geochemistry and isotopic compositions of mafic continental volcanism in this region: DMM, fossilized plume head (HIMU) and enriched mantle (EM). The enriched mantle is considered to reside within the subcontinental lithosphere. The authors envisage a pre-rift mantle that was stratified in these components (i.e. with depth from EM to HIMU to DMM) and that during rift development the rising asthenosphere progressively replaced the overlying sources to supply DMM-type mantle in greater proportions within the rift relative to the rift shoulder. An origin from metasomatized lithosphere without any plume influence is proposed for continental and oceanic (Adare Basin seamounts: Fig. 1) volcanism from this region (Rocchi *et al.* 2002; Nardini *et al.* 2009; Panter *et al.* 2018; Rocchi and Smellie 2021). Models for metasomatic origins are explained by a multistage process that begins with

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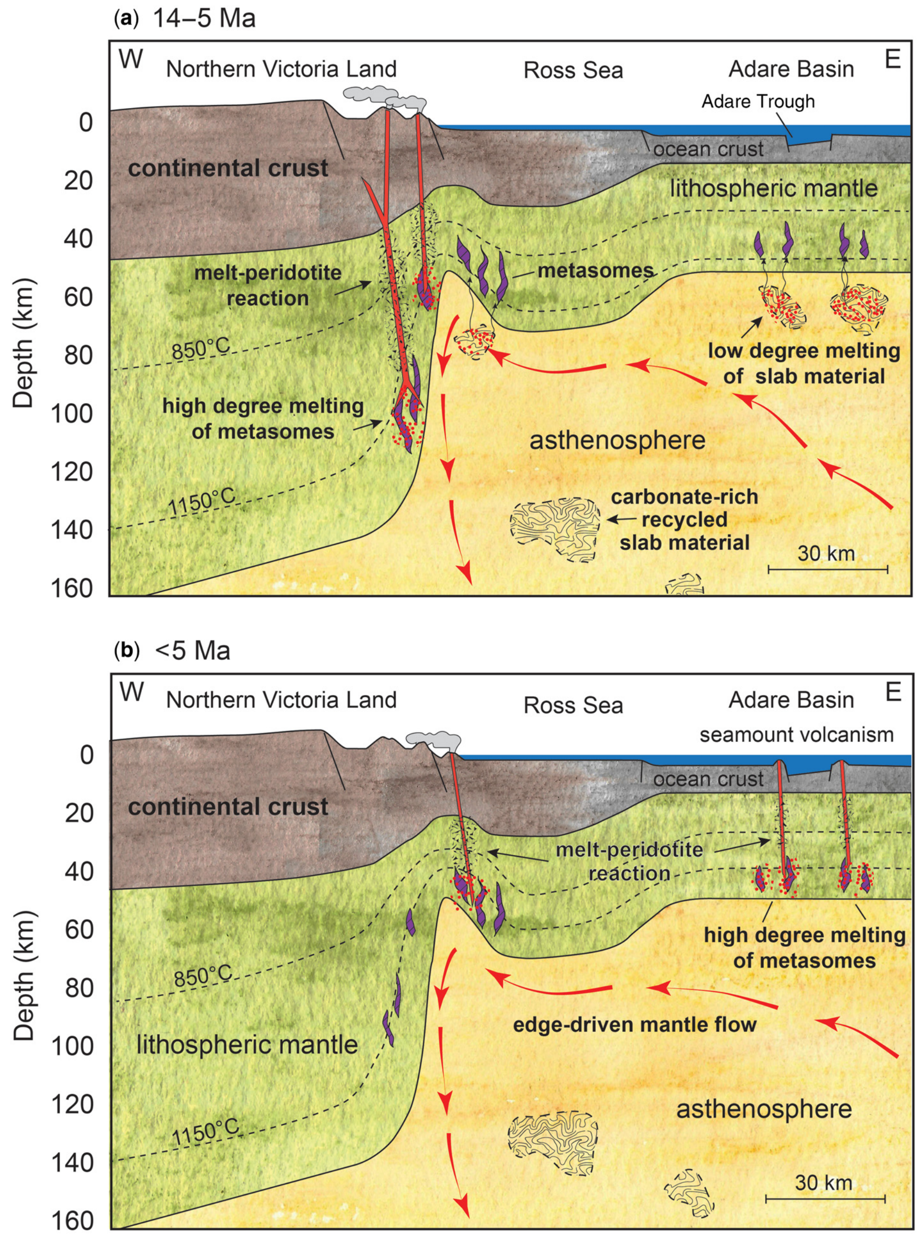

Fig. 7. Schematic model for the Late Oligocene–recent petrogenesis of alkaline volcanism in northern Victoria Land (Hallett Volcanic Province) and the oceanic Adare Basin seamounts (Fig. 1) modified from Panter *et al.* (2018). Plate architecture from craton to ocean in the northern Ross Sea region is shown for two time frames: 14–5 Ma and <5 Ma. Thinned lithosphere ('necked zone') beneath the rift boundary is considered to be a result of an earlier period (*c.* 80–40 Ma) of focused extension (Huerta and Harry 2007). The craton-directed edge-driven convective flow, depicted by red arrows, is considered to have been established in the Eocene (Faccenna *et al.* 2008). To explain the geochemistry and isotopic compositions of basalts and the time delay between rifting and volcanism, a multistage process is used: (**a**) decompression melting of upwelling subduction-derived materials produced carbonate-rich silicate liquids that rose and froze within the cooler lithosphere to form amphibole-rich veins ('metasomes'). Conductive heating at the base of the lithosphere by edge-driven flow eventually (*c.* 25 myr after focused extension) reached temperatures to melt metasomes (≥1150°C) and produce silica-undersaturated liquid. The reaction of this liquid with the surrounding peridotite modified the melt composition as it traversed the thicker continental plate and erupted to form large, elongated shield volcanoes along the continental coastline. (**b**) Thermal evolution of the lithosphere oceanwards reached the melting temperature of the earlier formed metasomes and produced the smaller Pliocene–Pleistocene volcanic islands (e.g. Possession Islands), and the seamounts located on the continental shelf and within the oceanic Adare Basin.

extension and/or transtension to initiate low degrees of melting of the asthenosphere (within either the garnet or the spinel stability fields). The melts rise and penetrate the base of the lithosphere to form a hydrous phase (pargasite-amphibole- and/or phlogopite-bearing cumulates) in veins (Fig. 7). Later, higher degrees of partial melting of these relatively small-volume, trace element and volatile-rich metasomatic veins, and the reaction of this silica-undersaturated liquid with peridotite (cf. Pilet *et al.* 2008; Pilet 2015) in the surrounding mantle during ascent (Fig. 7), is called upon to reproduce the major and trace elements, as well as the isotopic characteristics, of the mafic alkaline magmas from this region.

Overall, trace element concentrations of mafic compositions from the Ross Sea portion of the WARS (i.e. northern and southern Victoria Land (Fig. 1), which constitute the Western Ross Supergroup after Smellie and Martin 2021) show more restricted and uniform patterns relative to MBLVG samples on mantle-normalized plots, particularly with respect to elements Cs, K and Pb (Fig. 5a, b). The greater variability of the MBLVG mafic compositions may, in part, be controlled by partial melting processes (i.e. a greater range in the degree of melting) but it is also likely to be a consequence of differences in the proportions of plume and subduction-modified materials that are consumed during melting (e.g. Hart *et al.* 1995; LeMasurier *et al.* 2016). Another notable difference between MBLVG samples and those from the Ross Sea portion of the WARS in Figure 6 is that, on average, MBLVG compositions have higher K/Ta ratios and more radiogenic Pb isotope values. We propose that these compositional differences reflect a fundamental change in mantle-source domains somewhere between the Ross Sea portion of the WARS and the northern shoulder of the rift, which encompasses the MBLVG in Marie Byrd Land–western Ellsworth Land. It is possible that the change in mantle make-up may in some way be associated with the observed differences in crustal structure and composition across West Antarctica (Tinto *et al.* 2019; Jordan *et al.* 2020) (Fig. 1).

Secular changes in mantle domains across Antarctica

The past 200 million years of magmatism in Antarctica is intimately linked to its dynamic tectonic history. Over this period, igneous activity resulted from concurrent tectonic processes of continental fragmentation and subduction as the Gondwana

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supercontinent drifted southwards towards the Pole. Progressive disintegration of Gondwana changed the global continental configuration and eventually led to the creation of the Southern Ocean. By the Middle–Late Eocene, Australia had separated from Antarctica; and by the middle Oligocene, the opening of the Drake Passage established the Antarctic Circumpolar Current, isolating the continent of Antarctica from all other landmasses. Prior to continental rifting, the palaeo-Pacific margin of Gondwana, which consisted of conjugate continental blocks of Zealandia and what is now southeastern Australia and western Antarctica (Fig. 4), was impacted by subduction that occurred nearly continuously since the late Neoproterozoic. Contemporaneous subduction tectonics and an upwelling mantle plume are credited to have produced the Ferrar–Karoo LIP magmatism in the Jurassic (Heinonen *et al.* 2014; Luttinen 2018). Subduction shutdown progressively eastwards, beginning in the Early Cretaceous (Bradshaw 1989; Cawood 2005) and forming the Antarctic Peninsula volcanic arc by the Early Miocene (Leat and Riley 2021). Slow rates of subduction still occur at the Antarctic Peninsula's northernmost tip. Evidence from mafic igneous rocks and mantle xenoliths highlighted the widespread influence of long-lived subduction on upper-mantle sources for magmatism across West Antarctica.

Except for the Antarctic Peninsula and the isolated volcanoes of Gaussberg, Sheridan Bluff and Mount Early in East Antarctica (Fig. 1), all Cenozoic continental alkaline magmatism is associated with the post-subduction extensional tectonics of the WARS. The WARS was initiated during the break-up of Gondwana in the Late Cretaceous and developed in two main phases (e.g. Huerta and Harry 2007) ending in the Late Miocene (*c.* 11 Ma: Granot and Dyment 2018). However, most of the WARS magmatic activity is younger, occurring from the Middle Miocene (*c.* 14 Ma) through to the Holocene (Dunbar *et al.* 2021; Smellie and Martin 2021; Smellie and Rocchi 2021; Wilch *et al.* 2021). The significant time gap between tectonism and magmatism, as well as the absence of any Late Cretaceous–Cenozoic LIPs in West Antarctica, call into question a second plume-assisted Gondwana break-up event (e.g. Storey *et al.* 1999). However, Hoernle *et al.* (2020) made the case for a plume origin of Late Cretaceous (99–69 Ma) intraplate HIMU-like magmatism on and around the crustal blocks of Zealandia, which were landmasses outboard of Marie Byrd Land and Victoria Land (Fig. 4) before continental separation (>83 Ma). They propose that a Late Cretaceous plume rising beneath Zealandia impacted shortly after the collision between the oceanic Hikurangi Plateau and the active Gondwana margin (*c.* 110–100 Ma). Kipf *et al.* (2014) suggested that the plume beneath Zealandia underplated the adjacent oceanic lithosphere and, with seafloor spreading, became part of the Antarctica Plate. They contend that this source was melted by continental-insulation mantle flow in the Early Cenozoic (65–56 Ma) to produce the HIMU-like alkaline volcanism at the Marie Byrd seamounts (Fig. 1). Approximately 20–30 myr later in the Late Eocene–Early Oligocene, the earliest continental volcanism in Marie Byrd Land began (Wilch *et al.* 2021) and coincided with uplift of the Marie Byrd Land dome (LeMasurier and Landis 1996; LeMasurier 2006; Rocchi *et al.* 2006). The uplift may have occurred as much as 10–15 myr after the earliest volcanism, according to Spiegel *et al.* (2016), but this is still well before the onset of the phase of widespread and voluminous volcanic activity that occurred after 14 Ma (Wilch *et al.* 2021). The timing and spatial distribution of volcanism relative to domal uplift, the OIB HIMU-like compositions of erupted materials and the evidence for a low seismic velocity zone extending to at least the mantle transition zone (discussed previously) all support the influence of a mantle plume beneath this region. Whether there is an affiliation with the HIMU mantle imprinted upon the Late Cretaceous magmatism in Zealandia or the source reservoir for the Paleocene Marie Byrd seamount volcanism is uncertain. However, it is intriguing to note that tomographic models provided by Lloyd *et al.* (2020) show a broad region of slow shear-wave speeds beneath Marie Byrd Land that extend north of the coastline and underlie old oceanic lithosphere formed after the separation of Zealandia from Antarctica (see figs 6 and 11 in Wiens *et al.* 2021). This slow anomaly is relatively shallow (*c.* 75 km) beneath the Marie Byrd Land coastline but seawards connects at greater depths (*c.* 250 km) to a deeper (*c.* 400 km) low-velocity anomaly that is outboard of the Marie Byrd seamounts (Fig. 1). In addition, modelling of present-day bathymetic data (Sutherland *et al.* 2010) and residual basement topography (Wobbe *et al.* 2014) suggest that a lower-density upper mantle beneath this region may be long lived (*c.* 100 myr) in order to account for the subsidence history of the Campbell Plateau as Zealandia drifted away from West Antarctica. Setting aside the possible connections with Late Cretaceous magmatism in Zealandia, we conclude that melting of upwelling plume materials mixed with melts sourced from pre-existing subduction-modified mantle, in varying proportions, to account for the compositional array of Cenozoic magmatism that constitutes the MBLVG (Figs 5c & 6) (refer to Hart *et al.* 1995; LeMasurier *et al.* 2016; Panter *et al.* 2021*b*).

Applying a similar scenario to explain magmatism in the Ross Sea portion of the WARS is improbable. First, as discussed previously, mafic compositions in this region contrast with those of the MBLVG in that they have more uniform and restricted minor and trace element concentrations (e.g. Fig. 5) and have less of the HIMU-like Pb isotopic signature (Fig. 6). Tectonomagmatic relationships between the two regions also differ. For instance, magmatism in the Ross Sea region is not contemporaneous with Cenozoic uplift that occurred mostly in the Paleogene (Balestrieri *et al.* 2020; Goodge 2020 and references therein). In southern Victoria Land, localized domal uplift, which has been suggested to be plume initiated, is inferred to explain patterns of volcanism for Ross Island and nearby Mount Discovery. However, this is contrary to records for subsidence in this area caused by the growth of these volcanoes and the resultant loading of the crust over the past 5 myr (Naish *et al.* 2007; Johnston *et al.* 2008). Another complexity for plume models is how to account for the timing between magmatism and extension. Rilling *et al.* (2009) found that widespread Pliocene and Pleistocene volcanism along the Terror Rift in southern Victoria Land post-dates the major period of extension that occurred in the Miocene. Panter *et al.* (2018) also described significant stepwise time lags between major episodes of rifting and alkaline magmatism in the northwestern portion of the Ross Sea, which include plutons and volcanoes exposed in northern Victoria Land and the volcanic seamounts found within the oceanic Adare Basin (Fig. 1). In this region, the earliest alkaline magmatism, the Meander Intrusive Group (48–23 Ma), followed Gondwana break-up and a phase of broad WARS extension (105–80 Ma) by *c.* 30 myr. A focused phase of WARS extension (80–40 Ma) occurred *c.* 25 myr prior to the eruption of large alkaline shield volcanoes along the continental coastline (*c.* 14–5 Ma: Fig. 7a). In the final stage, monogenetic island and seamount volcanism located on the continental shelf and ocean floor of the Adare Basin (<5 Ma–<100 ka: Fig. 7b) followed extension and seafloor spreading (43–26 Ma) by *c.* 20 myr. The pattern of alkaline magmatism in northern Victoria Land has also shifted with time, indicating a change in tectonic conditions. Rocchi *et al.* (2002, 2005) and Rocchi and Smellie (2021) propose that the emplacement of Eocene–Oligocene plutons and

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dykes occurred along translithospheric dextral strike-slip faults, whereas younger volcanism (i.e. Miocene–recent) occurred along normal faults at the boundary of the WARS and above where the lithosphere has been locally thinned (‘necked’) by focused extension (Fig. 7).

Overall, the patterns and timing of alkaline magmatism in the Ross Sea portion of the WARS is best explained by plate dynamics and not by an upwelling plume or plumes. However, like Marie Byrd Land, a slow seismic wave anomaly also exists beneath the Ross Sea region (e.g. Heeszel *et al.* 2016; Shen *et al.* 2018; Lloyd *et al.* 2020; Wiens *et al.* 2021). The slow anomaly underlies areas of Cenozoic magmatism within the western Ross Sea and is almost continuous for nearly 3000 km from the southern Transantarctic Mountains, beneath the Sheridan Bluff and Mount Early volcanoes (Shen *et al.* 2017; Panter *et al.* 2021*a*), northwards to the Balleny Islands and further oceanwards where it is superimposed on transform fracture zones and the Pacific–Antarctic Ridge (Fig. 1; see also fig. 6 in Wiens *et al.* 2021). In contrast to the Marie Byrd Land anomaly, the mantle tomography of Lloyd *et al.* (2020) confined the slow anomaly to depths above 250 km (see fig. 6 in Wiens *et al.* 2021). This relatively shallow and linear seismic structure traces the continental margin defined by thinned WARS lithosphere against the thick cratonic lithosphere of East Antarctica. The juxtaposition of these features strongly suggests an origin controlled by Cenozoic extensional tectonics. It follows that the architecture of this lithospheric boundary promotes decompressive melting by passive asthenospheric upwelling and edge-driven mantle flow (Faccenna *et al.* 2008).

The uniformity of averaged trace element compositions (Fig. 5a, b), and the relatively narrow ranges in measured Sr (*c.* 0.7028–0.7038), Nd (*c.* 0.5128–0.5130) and Pb ($^{208}Pb/^{204}Pb$ *c.* 38.9–39.6: Fig. 6) isotopic ratios, strongly support a common origin for magmatism in the Ross Sea region of the WARS but one that is distinct from magmatism in the Marie Byrd Land region of the WARS. This distinction is further illustrated by data plotted on a Δ8/4Pb v. Δ7/4Pb diagram (Fig. 8). In Figure 8, the MBLVG samples define a linear array extending towards low Δ8/4Pb values of basalts

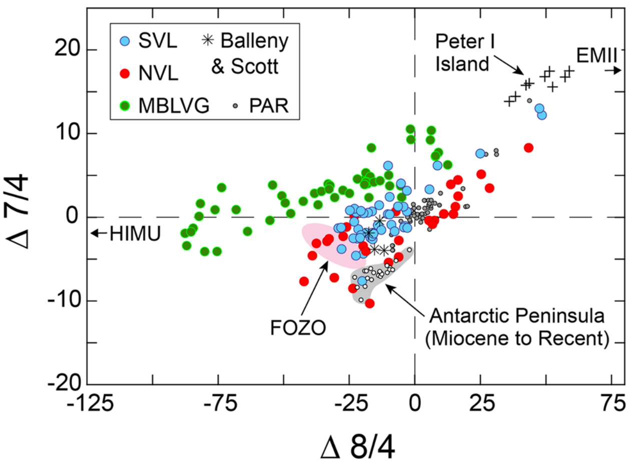

Fig. 8. Variation in Δ8/4Pb v. Δ7/4Pb for WARS mafic compositions in comparison with basalts from the Antarctic Peninsula (back-arc and post-subduction magmatism), nearby oceanic islands (Balleny, Scott and Peter I islands: Fig. 1) and the Pacific–Antarctic Ridge (PAR). Lead isotopic data used to calculate ΔPb values (i.e. variance of $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios from the Northern Hemisphere Reference Line (NHRL), after Hart 1984) for PAR samples are from Ferguson and Klein (1993) and Vlastélic *et al.* (1999). Samples from Peter I Island are from Prestvik *et al.* (1990) and Kipf *et al.* (2014). Other sources of data are the same as in previous figures.

sourced from HIMU mantle, whereas the Ross Sea array cluster closer to the origin point, and with oceanic compositions from the Balleny and Scott islands and MORB from the Pacific–Antarctic Ridge. Basalts from the Balleny Islands (Fig. 1) are considered by some researchers to be plume sourced (‘Balleny plume’: e.g. Lanyon *et al.* 1993; Weaver *et al.* 1994; Storey 1995; Hart *et al.* 1997) and were used by Hart *et al.* (1992) to help to define the isotopic signature of the FOZO mantle end member, which has since been redefined by Stracke *et al.* (2005) and is shown in Figures 3 and 8. Stracke *et al.* (2005) concluded that FOZO is a ubiquitous small-scale component in MORB sources and is likely to be found throughout the entire mantle. Castillo (2015), on the other hand, proposed that FOZO is previously subducted oceanic lithospheric mantle and, hence, represents older, uppermost sections of MORB sources; such sources are inherently quite heterogeneous as they contain small-scale enriched components to begin with. Either way, the MORB–FOZO source mixture (cf. Stracke *et al.* 2005) or FOZO domains (cf. Castillo 2015) can explain most of the array for magmatism in the Ross Sea region, including alkaline volcanism on the Australian–Antarctic Ridge (Yi *et al.* 2020). In contrast, the HIMU component, which is most strongly represented in the Marie Byrd Land region, and EM components, which are present in sources for Cenozoic alkaline magmatism from both regions of the WARS, are most likely to be artefacts of subduction-zone processes including subducted altered oceanic crust or marine carbonates (for HIMU) and sediments (for EMII: Fig. 8), respectively.

Summary and conclusions

The petrological study of mafic igneous rocks is critical to our understanding of the upper mantle. In addition, key information about the tectonic environment in which mantle partial melts are generated is revealed by geochemical and isotopic data gathered from mafic compositions. Based on this perspective, we have highlighted the state of our current understanding of the tectonomagmatic origins of mafic igneous rocks in West Antarctica since the Triassic:

- Ferrar–Karoo LIP rock compositions generated in the Jurassic (*c.* 183 Ma) plot coincident with arc basalt and within-plate tholeiitic flood basalt fields (Fig. 2), and have enriched Sr (Fig. 3) and positive Δ8/4Pb and Δ7/4Pb values similar to Peter I Island basalt that trend towards EMII (Fig. 8). Melting is likely to have occurred as a result of active subduction and active mantle pluming at *c.* 183 Ma (Fig. 4), resulting in variable Nb depletions (Fig. 2c) that also reflect mantle-source heterogeneity at this time.
- Along the Antarctic Peninsula, the main period of subduction occurred from the Early Cretaceous to the Early Miocene and persists at a slow rate to the present day. The mantle source has high $^{87}Sr/^{86}Sr$ ratios and low ε_{Nd} values (Fig. 3a) that are consistent with melting of either an enriched mantle (EM) source in the subducted slab material or melting of subduction-modified mantle wedge materials, or both. Variation in the mantle source of the Antarctic Peninsula subduction-related magmatism – for example, as seen by relatively depleted $^{206}Pb/^{204}Pb$ and Sr isotope ratios in some samples (Fig. 3b) – is attributed to variations in the mantle source or episodic arc extension. Post-subduction magmatism along the Antarctic Peninsula between the Miocene and present day is related to slab-rollback, slab-window or melting of slab-hosted pyroxenite, as shown by the transition in composition from calc-alkaline to tholeiitic compositions from subduction-related magmatism to mostly alkaline magmatism post-subduction

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(Fig. 2a). The chemical (Fig. 2) and isotopic (Sr–Nd: Fig. 3) composition of post-subduction magmatism is comparable to OIB or WARS primitive magmatism, although it is depleted with respect to isotopic Pb in WARS samples (Fig. 3b).

- In the Ross Sea and Victoria Land, primitive magmatic rocks have been emplaced since *c.* 50 Ma, with the majority of preserved volcanic activity occurring over the past 14 myr. Magmatism has occurred in a rift setting that is consistent with the alkaline whole-rock chemistry (Fig. 2a) and plotting in the within-plate field on trace element discrimination plots (Fig. 2b, c). The uniformity of averaged trace element compositions (Fig. 5) and the restricted range in isotopic composition (Figs 3 & 6) relative to other regions in this study supports a common mantle source that is characterized by a focal zone (FOZO) composition (Fig. 8). The trace element and isotopic patterns of primitive Victoria Land volcanic rocks and the timing of magmatism relative to major tectonic events is best explained by plate dynamics and not by an upwelling plume. In contrast, partial melting to produce Marie Byrd Land primitive volcanic rocks was induced by mantle-plume upwelling and mixed with melts from pre-existing subduction-modified mantle. This resulted in Pb isotopic ratios for Marie Byrd Land (Figs 6 & 8) that are distinct from either Victoria Land or the Antarctic Peninsula and represent a distinct mantle source.
- Through regional comparison in this study, mantle domains are defined by differences in chemical and isotopic signatures of mafic magmatism. These mantle-source differences reflect variability in bulk composition and mineral mode that will ultimately affect mantle rheology. The different mantle domains described here help to account for variations in geophysical studies of West Antarctica.

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