Chapter 1.2

Antarctic volcanism: volcanology and palaeoenvironmental overview

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Abstract: Since Jurassic time (*c.* 200 Ma), Antarctica has had a greater diversity of volcanism than other southern continents. It includes: (1) voluminous mafic and felsic volcanism associated with the break-up of Gondwana; (2) a long-lived continental margin volcanic arc, including back-arc alkaline volcanism linked to slab rollback; (3) small-volume mafic alkaline volcanism associated with slab-window formation; and (4) one of Earth's major continental rift zones, the West Antarctic Rift System (WARS), with its numerous large alkaline central volcanoes. Several of Antarctica's volcanoes are still active. This chapter is a review of the major volcanic episodes and their principal characteristics, in their tectonic, volcanological and palaeoenvironmental contexts. Jurassic Gondwana break-up was associated with large-scale volcanism that caused global environmental changes and associated mass extinctions. The volcanic arc was a major extensional arc characterized by alternating volcanic flare-ups and lulls. The Neogene rift-related alkaline volcanism is dominated by effusive glaciovolcanic eruptions, overwhelmingly as both pāhoehoe- and ʻaʻā-sourced lava-fed deltas. The rift is conspicuously poor in pyroclastic rocks due to the advection and removal of tephra erupted during glacial intervals. Volcanological investigations of the Neogene volcanism have also significantly increased our knowledge of the critical parameters and development of the Antarctic Ice Sheet.

The products of volcanism are widespread in Antarctica (Figs 1 & 2). Although this Memoir extends back to 200 Ma, older volcanism is also present but the outcrops are scattered, generally small, and their tectonic setting and volcanological and palaeoenvironmental significance are much more poorly known (e.g. Goodge 2019 and references therein). By contrast, the evidence for volcanism since Jurassic time is widespread and generally well exposed (Smellie 2020*b*). It is linked to an unusually diverse range of tectonic settings, which vary from large-scale mafic effusive outpourings and associated felsic explosive activity connected with supercontinent break-up, to small-volume mafic monogenetic edifices and volcanic fields associated with subducted-slab windows. A very long-lived (>200 myr) continental margin volcanic arc is also present, with related flood lava volcanism in a back-arc setting and numerous small, mainly submarine centres in a Quaternary ensialic marginal basin. Neogene alkaline volcanism is also widespread within the West Antarctic Rift System (WARS), one of the world's largest continental rifts. The tectonic diversity of Antarctica's volcanism is unmatched by any other southern hemisphere continent. It is used here as a convenient basis for this overview of Antarctica's volcanism and eruptive palaeoenvironmental record.

Early Jurassic break-up of Gondwana: flood lavas, phreatocauldrons and flare-ups

The fragmentation of Gondwana during the Early Jurassic is generally linked with the impact of a mantle plume (e.g. Storey 1995; Storey and Kyle 1997), although shallow, plate-driven processes are becoming seen as a plausible alternative hypothesis (e.g. Hastie *et al.* 2014; Peace *et al.* 2020) (Fig. 3). The break-up was associated with widespread and voluminous volcanism and associated hypabyssal intrusions. In addition to outcrops in Antarctica, the episode is also represented in South Africa, southern South America, Australia and New Zealand. Cumulatively, it represents a large igneous province (LIP) sometimes informally called the Gondwana LIP (Storey and Kyle 1997), which is one of the largest continental LIPs on Earth (Sensarma *et al.* 2018). The volcanism has two parts: mafic and felsic. The earliest-formed volcanic units are mafic tholeiitic dolerite sills and coeval flood lavas. The outcrops in Antarctica (Transantarctic Mountains; excluding Dronning Maud Land) are called the Ferrar Dolerite Formation (intrusions) and Kirkpatrick Basalt Formation (mainly lavas), and they are collectively called the Ferrar Supergroup (Elliot *et al.* 2021). The age of the Ferrar Supergroup is 183–182 Ma and it may have been intruded over less than 0.4 myr, similar to estimates for the coeval Karoo volcanism in South Africa (Svensen *et al.* 2007, 2012; Burgess *et al.* 2015). The total volume of mafic magma involved is >0.5 × 10^6 km^3 (Elliot *et al.* 2021; Luttinen 2021) and an even greater volume can be inferred if extensive geophysically detected subsurface outcrops under the East Antarctic Ice Sheet and offshore, interpreted as early break-up magmas, are taken into account (Studinger *et al.* 2004; Leat 2008; Ferraccioli *et al.* 2009; Paxman *et al.* 2019). The magmatism probably had a global environmental impact as it was coeval with the significant Toarcian mass extinction event (Burgess *et al.* 2015; Ernst and Youbi 2017; Elliot *et al.* 2021). It probably influenced extinctions by mediating global climate and environmental change: for example, perturbations in pCO_2, CH_4, SO_2 and halogens, sea-level changes, oceanic anoxia, calcification crises, evolutionary radiations, the release of gas hydrates, and rapid global warming and cooling crises (Svensen *et al.* 2007; Storey *et al.* 2013).

The Ferrar sills are typically 100–300 m thick. Associated dykes are much thinner (<2 m) and inconspicuous. The sills probably have a local cumulative thickness of *c.* 1500 m and a total volume of *c.* 1.7×10^5–2.0×10^5 km^3, larger than sills in the Karoo (3000 km^3: Svensen *et al.* 2007). Some sills are extremely extensive. For example, the Basement Sill in Victoria Land has an estimated outcrop area of *c.* 10 000 km^2 (Marsh 2007) and the Peneplain Sill may be even larger (*c.* 19 000 km^3: Gunn and Warren 1962). Two distinctive compositional types of sills and lavas are recognized in the Transantarctic Mountains, and their compositional uniformity over large distances has been used to suggest that the magma flowed laterally for *c.* 4000 km from their source, which was assumed to be a large plume-head centre situated between Dronning Maud Land and South Africa (e.g. Leat 2008). This is the longest interpreted lateral flow of magma on Earth. The sills intruded the Beacon Supergroup, an unusually long-lived intermontane succession of continental sedimentary rocks with ages

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Fig. 1. Map showing the locations of places mentioned in the text. Abbreviations: AI, Anvers Island; BI, Brabant Island; CM, Crary Mountains; D, Mount Discovery; DI, Deception Island; E, Mount Erebus; Ea, Mount Early; ECG, Elephant and Clarence Islands Group; EM, Ellsworth Mountains; HC, Hobbs Coast; HM, Hudson Mountains; HP, Hallett Peninsula; JRI, James Ross Island; JM, Jones Mountains; KGI, King George Island; LC, Lassiter Coast; M, Mount Melbourne; MB, Mount Berlin; MM, Merrick Mountains; Mp, Mount Murphy; MS, Mount Siple; MT, Mount Takahe; O, Mount Overlord; P, The Pleiades; Pt, Mount Petras; R, Mount Rittmann; Sd, Mount Sidley; Sh, Sheridan Bluff; TM, Toney Mountain; W, Mount Waesche.

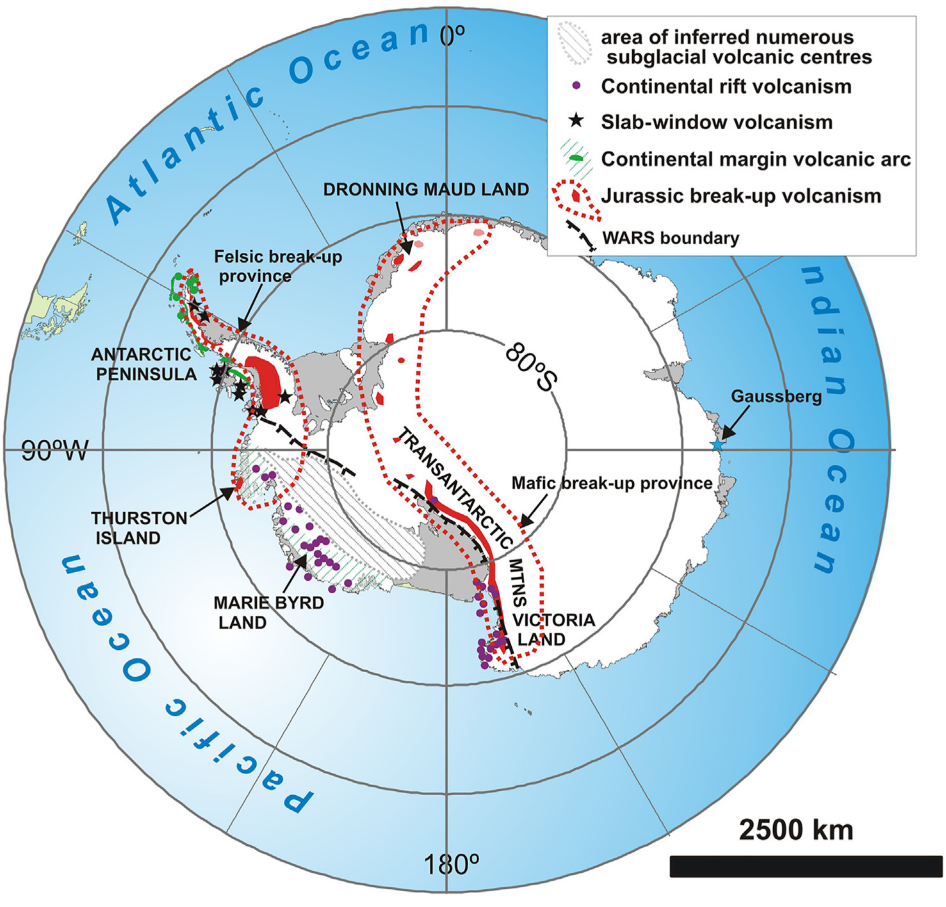

Fig. 2. Map showing the distribution of volcanic outcrops in Antarctica, going back 200 myr. The West Antarctic Rift System (WARS) boundary is after LeMasurier (2008).

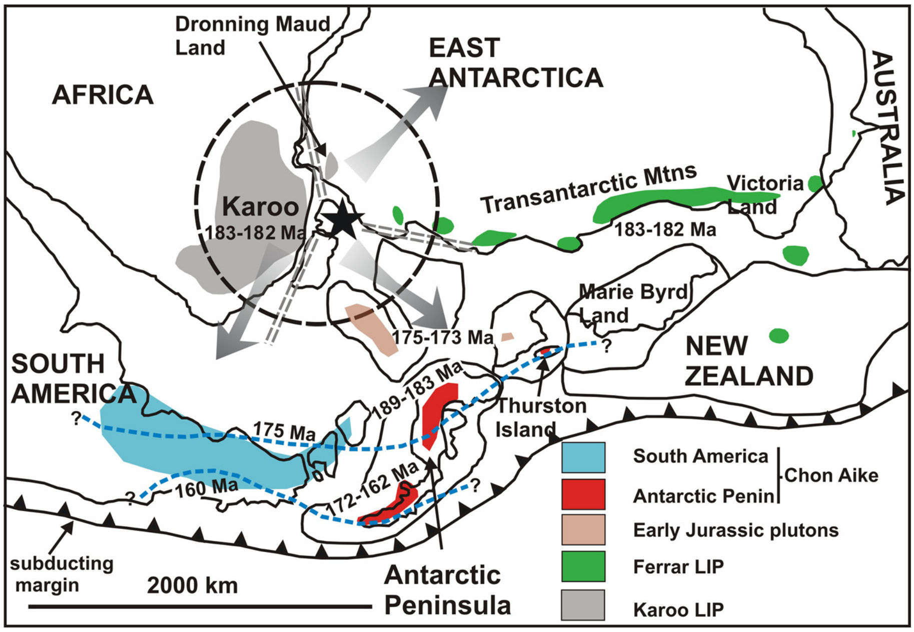

Fig. 3. Reconstructed Gondwana continent showing the mantle plume thought to be responsible for subsequent break-up, and the distribution and ages of associated volcanism forming the Ferrar and Chon Aike LIPs (adapted from Smellie 2020*b*).

spanning the Devonian–Triassic (Barrett 1991; Isbell 1999). Intrusion and inflation of the sills may have contributed to the final physiographical closure of the Beacon Basin(s), which may already have been shallowing due to progressive crustal thickening (Bialas *et al.* 2007; but see Lisker and Läufer 2013 for an alternative view).

Some sills merge and others terminate in dykes but no feeder dyke swarm has been identified in the Transantarctic Mountains, or any Strombolian deposits representing possible vent locations (cf. Pedersen *et al.* 2017). Volcanic plugs at a few localities in Victoria Land are potential feeders, but on a very small scale (Ross *et al.* 2008). However, the Ferrar LIP has been interpreted as a possible example of a flood lava system characterized by sill-driven feeder dykes in an absence of significant regional tectonic stresses (Muirhead *et al.* 2014). Known as the 'cracked lid' model, the emplacement and inflation of the Ferrar sill network generated fractures in the overlying country rock that were intruded by a plethora of narrow cross-cutting dykes with widely varying orientations (Fig. 4). Conversely, sills are uncommon in Dronning Maud Land and the dykes present there, although small (typically <2 m wide, although sometimes a few tens of metres thick: Riley *et al.* 2005; A. Luttinen pers. comm.), are presumed to have acted as feeders (Luttinen 2021). The Dronning Maud Land occurrences are linked genetically to the Karoo province in South Africa. The Karoo also includes feeder dyke swarms, although on a larger scale and generally wider than those in Dronning Maud Land (typically 18 m wide: Le Gall *et al.* 2002; Hastie *et al.* 2014). Dykes in Palmer Land (Antarctic Peninsula), interpreted as possible Ferrar-age equivalents by Vaughan *et al.* (1999), may be mafic feeders for the bimodal but mainly felsic Palmer Land Volcanic Group, part of the Chon Aike province (see later).

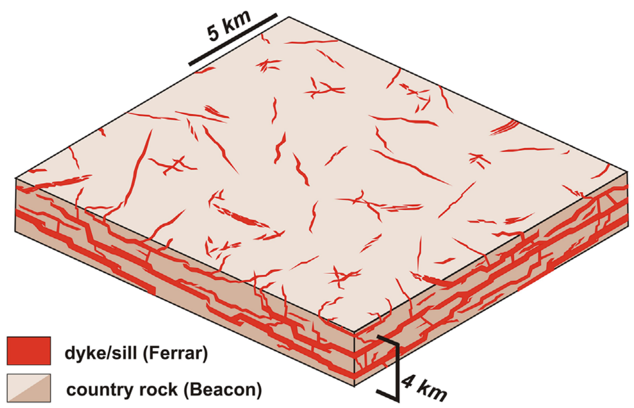

Fig. 4. Schematic depiction of the 'cracked lid' model of multiple small dykes genetically linked to inflation of subjacent Ferrar sills intruding Beacon Supergroup sedimentary strata. The dykes, whose widths are exaggerated in the diagram for clarity, are envisaged feeding flood lava effusion in the overlying coeval Kirkpatrick Basalt Formation. The essentially decussate pattern of dyke intrusion suggests that regional stresses were negligible. After Muirhead *et al.* (2014).

The Ferrar sills were associated with a widespread coeval cover of subaerial flood lavas (Kirkpatrick Basalt Formation). However, the earliest volcanic events, represented by the Prebble and Mawson formations and Exposure Hill rocks, include large-scale chaotic assemblages of phreatomagmatic pyroclastic deposits (mainly products of pyroclastic density currents) with rafts of lava and Beacon sedimentary rocks, intimately intruded by Ferrar dolerite sills and dykes. Those outcrops are interpreted as the infills of multiple coalesced maar–diatreme vent complexes, collectively called phreatocauldrons in recognition of their likely cumulative negative relief (Fig. 5). They represent explosive volcanic activity prior to effusion of the flood lava sequences. Similar explosively-generated deposits are a less well-known but important component of the basal stages of several flood lava provinces elsewhere (White and McClintock 2001; Ukstins Peate *et al.* 2003; Ross *et al.* 2005, 2008; McClintock and White 2006; Ross and White 2006; McClintock *et al.* 2008). They may have played a significant role in triggering climate change and global mass extinctions because of their mafic compositions, which are associated with higher volatile contents, especially CO_2, F, Cl and sulfur species, and their ability to send ash and volatiles directly into the stratosphere (Thordarson *et al.* 2003; Jolley and Widdowson 2005; Ross *et al.* 2005; McClintock *et al.* 2008). Water clearly played a significant part in the pyroclastic eruptions of the Ferrar province. However, the source was stored and recycled groundwater, and they were not erupted subaqueously, thus providing possible indirect confirmation that the precursor Beacon sedimentary basin(s) were largely infilled by the time Ferrar volcanism took place (cf. Bialas *et al.* 2007).

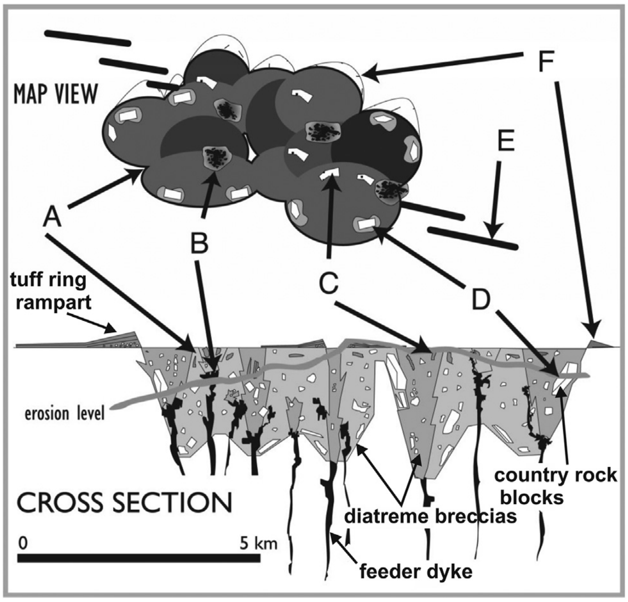

Fig. 5. Sketch showing map and cross-sectional views of multiple coalesced maar–diatreme volcanoes in the Coombs Hills area of the Transantarctic Mountains envisaged by White and McClintock (2001; modified). Coalescence of the centres led to a wide area of negative relief, termed a phreatocauldron.

The succeeding Kirkpatrick lavas may have had a minimum volume of 7000 km^3 but they are restricted by erosion to relatively small outcrops in Victoria Land, central Transantarctic Mountains and equivalents in Dronning Maud Land (Fleming *et al.* 1995; Elliot *et al.* 2021; Luttinen 2021). The individual lavas are pāhoehoe, commonly 500 m in cumulative thickness but locally exceeding 750 m, and they reach 2500 m in the Karoo-related province of Dronning Maud Land (Luttinen 2021). The individual lava lobes range in thickness from decimetres to several metres, and have widths of a few metres to several hundred metres. A few are associated with substantial thicknesses of ‘hyaloclastite’ (probably tuff breccia, *sensu* White and Houghton 2006) and pillow lava, suggesting that some of the lavas may have migrated into lakes as lava-fed deltas, similar to Paleocene flood lavas in Greenland (Pedersen *et al.* 2018). However, the proportion of volcaniclastic rocks in the Kirkpatrick Basalt Formation generally is small (*c.* 60 km^3: Elliot *et al.* 2021). Tabular sheet lavas several tens of metres to >100 m in thickness and tens of kilometres across are also present (Luttinen 2021). In Dronning Maud Land they have been divided up into flow fields based on contact relationships, associated interbeds, type of flow unit, colour and geochemical composition (Luttinen 2021); most are compound-braided pāhoehoe types (*sensu* Jerram 2002). Overall, the characteristics of the pāhoehoe lavas are those of inflated pāhoehoe (cf. Self *et al.* 1996; Keszthelyi *et al.* 2006). ‘A‘ā lavas have not been unequivocally identified but some lavas have brecciated surfaces and may be rubbly pāhoehoe (Luttinen *et al.* 2010; cf. Rowland and Walker 1990). The lava outcrops are comparatively small relicts of what was probably once a very extensive volcanic field.

The Kirkpatrick Basalt Formation also contains epiclastic interbeds sometimes associated with pillow lava and generally assigned a lacustrine origin (Elliot *et al.* 2021; Luttinen 2021). Additionally, red and yellowish-green to grey-green boles are present and probably represent palaeosols formed under a variety of oxidizing and reducing surface weathering conditions during substantial breaks in activity (e.g. Retallack 2001).

The Early Jurassic break-up magmatism also included widespread felsic volcanism known collectively as the Chon Aike province. It crops out throughout the Antarctic Peninsula (Fig. 2) and into southern South America, and it may also be represented in the central Transantarctic Mountains by fine tuffs in the Hanson Formation, an Early Jurassic felsic tuff unit (Elliot 1996). The Hanson Formation tuffs are interpreted as distal Plinian fall deposits and they lack known vents (Elliot 2000; Elliot *et al.* 2017). They may thus be the far-travelled stratigraphical equivalent of the earliest (Palmer Land) eruptive phase of the Chon Aike province, although they have been compared compositionally with arc magmas (Elliot *et al.* 2017). Three major pulses of felsic volcanism are documented during which the volcanic loci migrated towards the Pacific margin of the continent from the supposed plume centre responsible for the Ferrar and Karoo mafic volcanism (Pankhurst *et al.* 2000). The oldest felsic pulse took place at 189–183 Ma in the Palmer Land Formation, with a further pulse at 172–162 Ma represented by the Graham Land Formation. Younger volcanism (to 153 Ma) occurred in southern South America, where much of the outcrop is subsurface (Pankhurst *et al.* 2000; Riley *et al.* 2001). Comparable felsic volcanism probably also took place in Marie Byrd Land and may be hinted at by Early Jurassic (175–173 Ma) plutons in flanking areas (Jones Mountains and Ellsworth Mountains: Storey *et al.* 1988; Riley *et al.* 2017*b*). Any evidence is either obscured by the extensive ice cover or else has been removed by erosion.

The Chon Aike is a felsic province regarded as a volcanic flare-up (i.e. a period of unusually high magma flux: Paterson and Ducea 2015). It is linked to crustal anatexis caused by the migration of the Ferrar–Karoo plume head (Pankhurst *et al.* 2000) (Fig. 3). The presence of a coeval subduction zone along the Pacific margin probably acted as a self-limiting factor on the geographical spread of the plume and which intensified the effects of sublithospheric heating. The estimated volume of magma erupted, *c.* 0.5×10^6 km^3, is comparable with the volume of mafic magma involved in the Ferrar LIP (Pankhurst *et al.* 2000). The Chon Aike was a bimodal volcanic episode with a total thickness of *c.* 1 km of volcanic products, mainly rhyolitic ignimbrites and fewer rhyolite lavas, with minor mafic lavas (Hunter *et al.* 2006; Riley *et al.* 2010; Riley and Leat 2021). Eruption probably took place from multiple calderas associated with large stratovolcanoes. The felsic flare-ups probably contributed an atmospheric loading similar to that associated with the mafic (Ferrar) LIP and, from the coincident timing, they may also have influenced at least two younger, lesser mass extinction episodes (Smellie 2020*b*). Eruptions of such felsic magmas, although likely to have a significant stratospheric impact, are unlikely to be sulfur-rich, so the mechanism of their impact on climate and Life is more probably due to the atmospheric effects of a high ash-loading, or possibly high fluorine aerosols (cf. McConnell *et al.* 2017). Regardless of the mechanism(s) involved, it is evident that, cumulatively, the Jurassic volcanism in Antarctica had a major palaeoenvironmental impact far outside of the continent itself.

Pacific margin volcanism: development and sequential cessation of a major continental margin volcanic arc

The timing of the initiation of subduction-related magmatism along the Pacific margin of Gondwana is uncertain but preceded 200 Ma (see Smellie 2020*a*, *b* for a synthesis). Moreover, whether volcanic activity in the arc was subsequently continuous or episodic is unclear. Early Jurassic plutons in the central and southern Antarctic Peninsula may be subduction-related (Riley *et al.* 2017*a*) and could have fed coeval volcanism. Alternatively, the Early Jurassic magmatism may have been related to extension, and subduction (or, perhaps, its latest phase?) did not commence until Late Jurassic time, with the arc becoming a prominent established feature in the Early Cretaceous (Leat and Riley 2021*b*). However, if the Hanson Formation is indeed arc-derived and it overlapped in age with the Kirkpatrick Basalt Formation (Elliot *et al.* 2017), then it provides evidence for Early Jurassic subduction. The arc could have been a prominent orographical feature extending along the length of the Pacific margin of Gondwana (Fig. 2), including South America, the Antarctic Peninsula, Marie Byrd Land and New Zealand. Early Cretaceous granitoids in the Lassiter Coast, southern Palmer Land, have been interpreted as evidence for high magma flux in the arc represented by three discrete episodes of pluton emplacement, at 130–126, 118–113 and 108–102 Ma (Riley *et al.* 2017*a*, 2018). The plutons are mainly tonalite to granodiorite in composition (i.e. relatively felsic) and any associated volcanism is likely to have been mainly pyroclastic rather than effusive, with eruptions probably from large calderas similar to those associated with the Chon Aike. Together, they have been interpreted as a succession of volcanic flare-ups. However, unlike the Chon Aike, the impact on mass extinctions of the three Early Cretaceous volcanic episodes is much less obvious and may not be significant (Smellie 2020*b*).

Following the mid-Cretaceous separation of New Zealand from Marie Byrd Land at *c.* 90–80 Ma (Lawver and Gahagan 1994), offset sections of the Phoenix–Antarctic spreading centre collided with the coeval trench and subduction shut down progressively in a northerly direction (Larter *et al.* 2002). The collision ages are best defined for the Antarctic Peninsula where they began *c.* 50 myr ago offshore of southern Alexander Island (Hole *et al.* 1995). Subduction ceased following each collision and the arc-related magmatism stopped *c.* 10–20 myr ahead of each ridge collision (Barker 1982; McCarron and Larter 1998). The most recent collision took place opposite northern Graham Land at *c.* 3 Ma. However, it did not occur at the South Shetland Trench, and subduction is still taking place there at a very slow rate (Larter 1991; Maldonado *et al.* 1994). In addition, the axis of active arc magmatism migrated trenchwards from Late Cretaceous time (*c.* 70 Ma) and relocated to Alexander Island and Adelaide Island, but whether a similar relocation occurred in the South Shetland Islands is less certain (Leat and Riley 2021*a*; see also Smellie 2020*a*). The reason for the migration is unknown but the width of the forearc is substantially greater opposite Alexander Island and Adelaide Island compared with that opposite the South Shetland Islands, which may imply that the active axis of volcanism, linked as it is to slab depth, simply followed the oceanward migration of the trench (and subjacent slab) because of time-integrated growth of the accretionary prism. Moreover, essentially orthogonal subduction and associated accretion may have characterized much of the region south of the South Shetland Islands. Because of the oroclinal bend of the Antarctic Peninsula, the subduction trajectory was more oblique opposite the South Shetland Islands (cf. McCarron and Larter 1998). It may thus have triggered tectonic erosion of the forearc there (cf. Maldonado *et al.* 1994), thus counteracting any potential trenchward migration (also see below).

The most extensive outcrops of subduction-related volcanic rocks are present in the Antarctic Peninsula. However, most are pervasively hydrothermally altered by coeval intrusions of the Antarctic Peninsula batholith, contact metamorphism, and regional metamorphism to zeolite and prehnite–pumpellyite facies (Burn 1981; Smellie *et al.* 1984; Leat and Riley 2021*b*). The alteration obscures many volcanological details, and makes tracing and matching volcanic units exceedingly difficult. Although the outcrops are often well exposed in coastal cliffs, access is challenging or impossible because of the scarcity of beaches and the lack of sea ice in the region during the austral summer. Inland, the snow-covered alpine topography can also make overland access problematic. Conversely, beaches are common in the South Shetland Islands and the topography is much more subdued. Together with a lack of pervasive alteration in most of the outcrops, the South Shetland Islands contain the most intensively investigated outcrops of subduction-related volcanic rocks in Antarctica (e.g. Smellie *et al.* 1984; Birkenmajer 2001; Machado *et al.* 2005; Haase *et al.* 2012; Leat and Riley 2021*a*).

With its well-developed forearc and back-arc basins (Macdonald and Butterworth 1990), subdued elevation (mostly <2 km), lack of a back-arc fold-and-thrust belt, and overall relatively thin crust, the Antarctic Peninsula most resembles an extensional continental arc (Ducea *et al.* 2015). However, the volcanism in the South Shetland Islands is overwhelmingly mafic–intermediate and occurrences of felsic rocks (rhyolites and dacites) are rare (Smellie *et al.* 1984; Smellie 2020*a*; Leat and Riley 2021*b*). Continental margin arcs are characteristically poor in mafic volcanic products (Ducea *et al.* 2015). The mafic, partly tholeiitic, compositions in the South Shetland Islands are characteristic of arcs founded on thin crust (Smellie 2020*a*). Indeed, their petrological characteristics, especially the lack of crustal contamination, have led to some authors referring to the South Shetland Islands as typical island arc rocks (Birkenmajer *et al.* 1990; Machado *et al.* 2005). Geophysical studies suggest that crustal thicknesses vary from 36–42 km beneath Graham Land to 25–30 km beneath the South Shetland Islands (Grad *et al.* 2002). The volcanism in the South Shetland Islands may thus correspond to a so-called transitional continental arc (*sensu* Ducea *et al.* 2015).

The subduction-related outcrops are grouped together as the geographically extensive feature called the Antarctic Peninsula volcanic arc (Leat and Riley 2021*b*). Because of the relatively easy access, stratigraphic details of volcanic rocks on Alexander Island, Adelaide Island and the South Shetland Islands are comparatively well described (summarized by Leat and Riley 2021*a*). Because of some distinctive lava compositions corresponding to high-magnesian andesites formed by the melting of young hot lithosphere associated with ridge subduction (McCarron and Smellie 1998) and an incorrect assumption that coeval arc volcanism was present in Palmer Land, the Alexander Island Volcanic Group was interpreted as genetically distinct from the rest of the Antarctic Peninsula volcanic arc. However, such unusual compositions are occasionally found in arcs under certain circumstances (e.g. Kelemen 1995; Goss *et al.* 2013). The Alexander Island volcanism is now considered to be a consequence of the trenchward migration of the active arc volcanism away from Palmer Land during the Late Cretaceous (Leat and Riley 2021*a*). Alexander Island volcanism is predominantly effusive, with mainly mafic–intermediate lava compositions (rhyolitic and dacitic ignimbrites are common in the Colbert Mountains: McCarron and Millar 1997). Ages range from *c.* 80 to *c.* 46 Ma, and there is a pronounced northerly migration of the volcanism that was linked to the effects of the progressive collision and subduction of three offset spreading ridge segments (McCarron and Larter 1998; McCarron and Smellie 1998). Adelaide Island, 200 km to the north of Alexander Island, also contains substantial thicknesses (up to *c.* 2 km) of volcanic rocks in three formations that vary from basaltic andesite and andesite lavas, to rhyolitic tuffs and ignimbrites (Riley *et al.* 2012). As on Alexander Island (Burn 1981), all are intensely hydrothermally altered and they have latest Cretaceous ages (*c.* 75–67 Ma) overlapping with volcanism on Alexander Island. However there is no age migration, probably because subduction was continuous (and orthogonal) offshore of Adelaide Island until only a single long Phoenix–Antarctic ridge segment collided at the adjacent trench, rather than multiple offset ridge segments arriving at different times.

The Cretaceous–Miocene volcanic stratigraphy of the South Shetland Islands is the most frequently described part of the magmatic arc. From studies particularly by Polish geologists (e.g. Birkenmajer 2001), King George Island has the most complicated stratigraphy in Antarctica, despite encompassing a period just 30 myr in duration, and for an island just 90 km long and 25 km wide (Fig. 6). It illustrates how the easier access and generally lesser alteration has enabled much more frequent detailed stratigraphic investigations of the volcanic rocks there than elsewhere in Antarctica. King George Island also contains the only exposed Paleogene terrestrial environmental record, with an internationally important glacial–interglacial stratigraphy (Fig. 7). At least five glacial periods have been described, together with four interglacials (Birkenmajer 1996); although, of the putative Eocene glacials, one (Krakow) has been disproved (Dingle and Lavelle 1998) and the other (Ezcurra: Birkenmajer *et al.* 2005) has yet to be substantiated. The two best-known and verified glacial episodes (Polonez and Melville) are dominated by marine sedimentary rocks, but all the other units are volcanic. The volcanic sequences are well exposed and have been subject to several detailed investigations but few included volcanological–palaeoenvironmental aspects (Porebski and Gradzinski 1987, 1990; Smellie *et al.* 1998; Troedson and Smellie 2002).

Like Alexander Island, the South Shetland Islands show a prominent along-arc migration of the volcanism (and plutonism), with the inferred younging to the NE interpreted to indicate the progressive shutting down of volcanic centres rather than recent tilting and enhanced erosion of westerly areas (Pankhurst and Smellie 1983; Smellie *et al.* 1984). Since these studies, the number of K–Ar and (increasingly) $^{40}Ar/^{39}Ar$ isotopic ages determined on the volcanic rocks has expanded substantially; it is the largest dating dataset for any part of the magmatic arc (see Leat and Riley 2021*a* for a compilation). When the entire dataset is considered, it is now evident that the published migration model was simplistic (see also Willan and Kelley 1999). It is clear that the main volcanic axes associated with each eruptive phase have prominent northeasterly orientations and there is an overall migration to the *SE*, a trend that is continued into the marginal basin where most of the youngest volcanism is present (Fig. 8) (cf. Leat and Riley 2021*a*). The width of the different-aged volcanic zones, *c.* 20 km, is similar to typical widths of active magmatism in continental arcs at any time, which is caused by magma focusing (Ducea *et al.* 2015). However, the presence of, admittedly rare, inliers of Cretaceous rocks among the Paleogene outcrops suggests that the distribution of Cretaceous volcanic centres, at least, may have been geographically more widespread. The Cretaceous volcanic zones, particularly the Early Cretaceous one but not the Paleogene zone, also show a prominent geographical coincidence with the Pacific Margin Anomaly (PMA). The PMA is a prominent linear belt of positive long-wavelength magnetic anomalies that runs down the west side of the Antarctic Peninsula and is attributed to Cretaceous mafic plutons in the Antarctic Peninsula Batholith (Garrett *et al.* 1987; Parra *et al.* 1988; Soloviev *et al.* 2018). Its displacement to the NW of the islands emphasizes that a southeasterly migration of the volcanic axis, *away from* the South Shetland Trench, occurred during the Paleogene. Younger volcanism, of Oligocene age, is confined to southeastern King George Island (Smellie *et al.* 1984, 1998; Birkenmajer *et al.* 1986; Troedson and Smellie 2002). The youngest arc

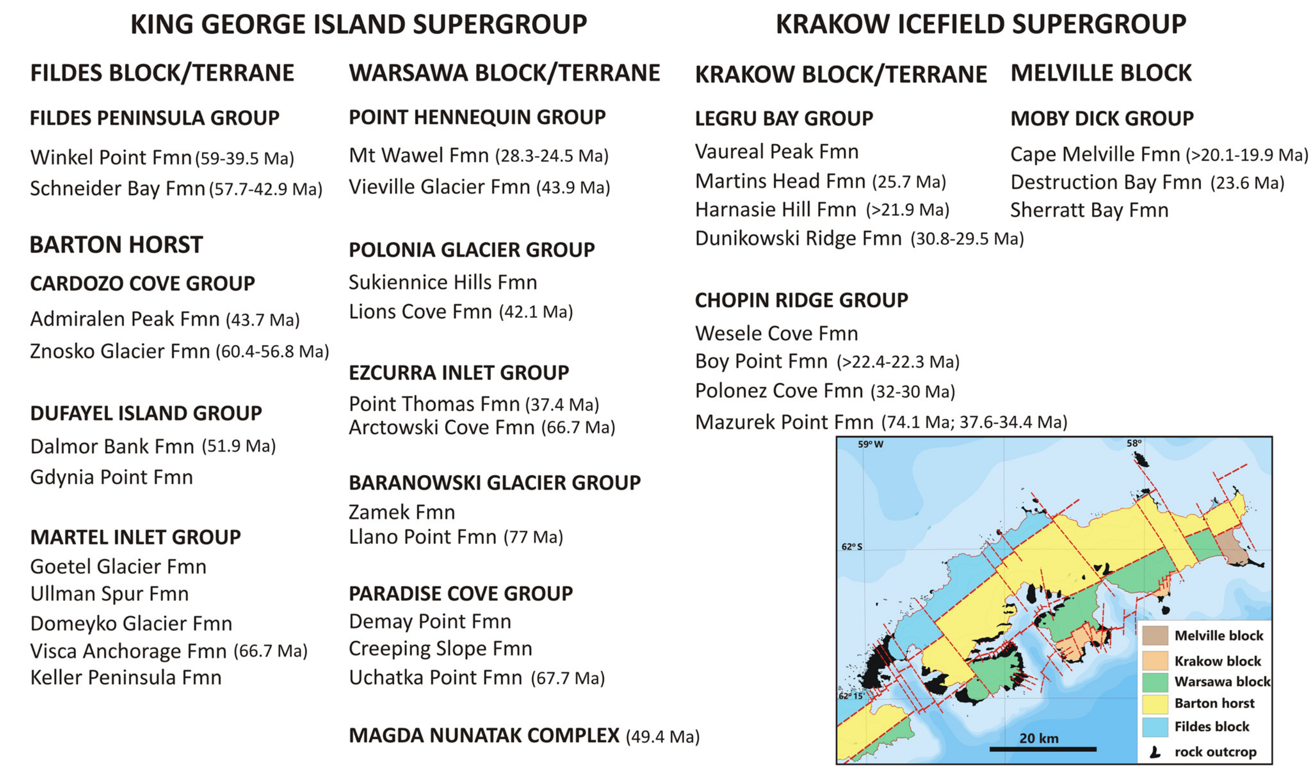

Fig. 6. Stratigraphy of King George Island constructed by Birkenmajer (2001). The ages shown are by K–Ar and have high errors (1–5 myr) and some ages have been disproved. Despite covering a period of just 30 myr, this is the most complicated stratigraphy in Antarctica, and was facilitated by the relatively easy access and generally low alteration of the rocks. The inset shows the distribution of structural blocks (also called 'terranes': Birkenmajer 2001) used as a framework for the stratigraphy. Note that many of the faults shown are conjectural but the main NE-trending faults have some topographical and geological support.

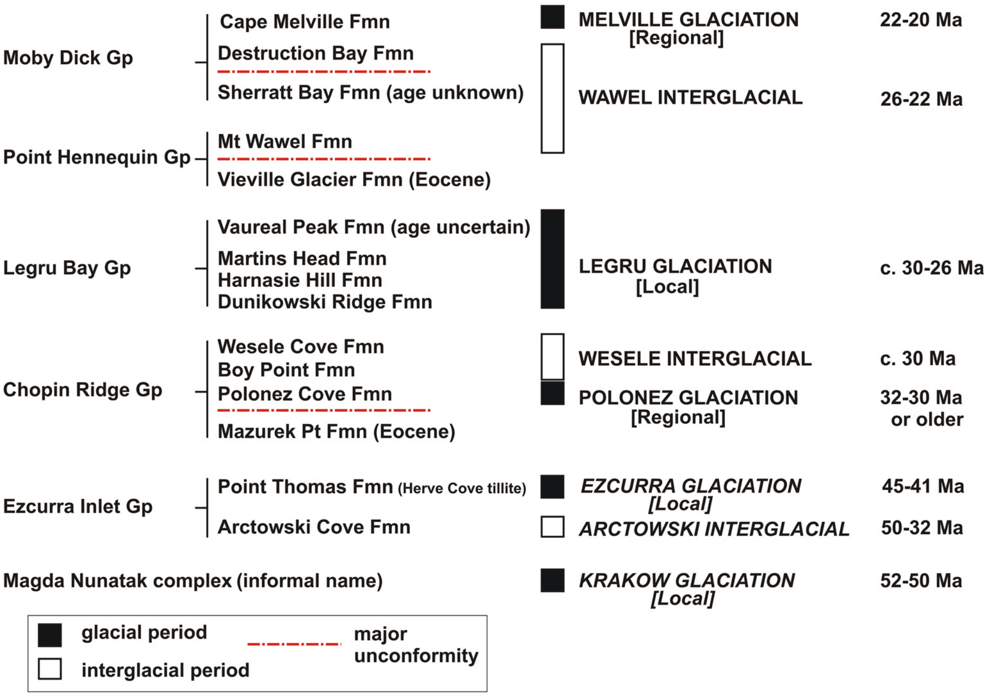

Fig. 7. Summary of glacial and interglacial periods on King George Island recognized by Birkenmajer (1996) and local stratigraphical names. The text in italics indicates environmental episodes either disproven ('*Krakow Glaciation*', '*Arctowski Interglacial*') or unconfirmed ('*Ezcurra Glaciation*').

volcanism may be represented by a small basalt volcano on King George Island at Melville Peak (<300 ka) and a submerged basaltic andesite–andesite volcano with a very young age (less than a few million years?) in the Eastern Basin of the Bransfield Strait (Smellie 2021). However, in general, evidence for arc volcanism in the South Shetland Islands is essentially absent after *c.* 20 Ma. This is probably due either to subduction of young buoyant oceanic crust switching off arc volcanism, as happened further south in the Antarctic Peninsula (Barker 1982), or to later subsidence of any arc volcanics in Bransfield Strait (Smellie 1990; Fretzdorff *et al.* 2004).

Migrations of the active volcanic axis, both toward and away from the trench, are well known in magmatic arcs and are usually ascribed to changes in slab dip (Ducea *et al.* 2015). There is currently no published explanation for why the slab dip should have changed over time beneath the South Shetland Islands. In another example, in the sub-Antarctic

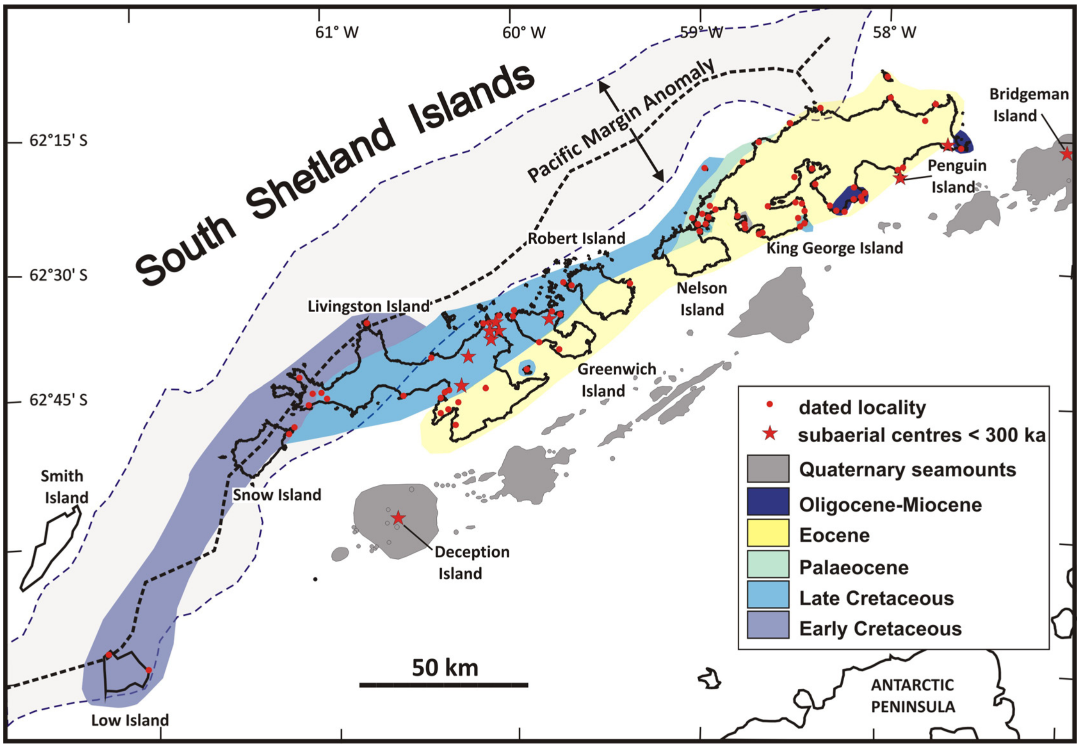

Fig. 8. Map of the South Shetland Islands showing the distribution of ages of volcanism. The ages form discrete NE-trending bands which migrate (get younger) in a southeasterly direction. The youngest volcanism is associated with the opening of Bransfield Strait as a young ensialic marginal basin (seamount centres shown). The location of the Pacific Margin Anomaly is also indicated, with its axis shown as a black dashed line (after Parra *et al.* 1988). It appears to coincide mainly with early Cretaceous-age volcanic outcrops.

South Sandwich Islands, an active intra-oceanic island arc in the eastern Scotia Sea, the magmatic axis has migrated *c.* 70 km away from the trench in the past 15 myr and this was attributed to tectonic erosion of the forearc (Vanneste and Larter 2002). For the South Shetland Islands, subduction erosion may be linked to oroclinal bending of the northernmost Antarctic Peninsula, which resulted in an oblique subduction trajectory and frontal compression. This suggestion may be supported by the presence of enigmatic folding in the associated Mesozoic–Cenozoic accretionary Scotia Metamorphic Complex, which crops out principally in the Elephant and Clarence Islands Group and South Orkney Islands (Fig. 1). The folding verges away from the trench, which is anomalous in an accretionary prism (they should verge towards the trench), although the structures have been speculatively explained as a result of sinistral strike-slip movements along the Shackleton Fracture Zone, which cuts across the South Shetland Trench at its NE end (Trouw *et al.* 2000). Uplift associated with oblique convergence and tectonic erosion might also explain why the accretionary complex is now exposed above sea-level (see also Maldonado *et al.* 1994). Shearing and strike-slip faulting would be a natural consequence of oblique subduction and may additionally be responsible for open folding of Cretaceous sequences on islands SW of King George Island (Smellie *et al.* 1984), which does not affect younger rocks.

Finally, four major pulses (i.e. flare-ups) of arc volcanism have been identified in the South Shetland Islands, at 130–110, 90–70, 60–40 and 30–20 Ma (Willan and Kelley 1999; Fretzdorff *et al.* 2004; Haase *et al.* 2012; Smellie 2020*a*; Leat and Riley 2021*a*). Haase *et al.* (2012) suggested that, within the limitations of the dataset of published ages, each flare-up may have lasted for *c.* 10 myr and might have been even shorter (e.g. just 2–3 myr) in some areas. The erupted products of each episode probably dominated the mass budget of the South Shetlands arc. However, the presence of isolated ages falling between the major pulses indicates that activity continued sporadically, probably throughout the entire period. Thus, the behaviour of the South Shetland Islands arc can be described as non-steady state and composed of alternating flare-ups and lulls (*sensu* Paterson and Ducea 2015; see also Ducea *et al.* 2015). It is a likely microcosm for arc volcanism throughout the Antarctic Peninsula.

Ensialic marginal basin: Bransfield Strait

As subduction slowed and almost ceased along the Antarctic Peninsula, a small ensialic marginal basin opened up in Bransfield Strait, from *c.* 4 Ma or possibly as early as *c.* 22 Ma (Barker 1982; Birkenmajer 1992). Its tectonic setting is disputed, with hypotheses ranging from extension due to rollback at the South Shetland Trench following the cessation of spreading in the Drake Passage (after *c.* 4 Ma; or possibly 6.7 Ma based on a rapid reduction in convergence rates at the South Shetland Trench at that time: Maldonado *et al.* 1994), to oblique extension linked to sinistral transcurrent movement of the Antarctic and Scotia plates (e.g. González-Casado *et al.* 2000; Fretzdorff *et al.* 2004; Solari *et al.* 2008). The basin may be propagating southwards, which could help to explain the occurrence of young (<3 Ma) volcanism on the Brabant and Anvers islands (Smellie *et al.* 2006), but northerly propagation has also been proposed (Gràcia *et al.* 1996; Barker and Austin 1998; González-Casado *et al.* 2000; Christeson *et al.* 2003; Fretzdorff *et al.* 2004). Swath studies in Bransfield Strait have shown that the marginal basin floor is characterized by numerous small submarine volcanic ridges and seamounts. They are mainly mafic pillow mounds but rare rhyolite is also present (Keller *et al.* 2002) and at least one of the edifices ejected Pele's hair explosively at a depth of *c.* 1200–1500 m (Smellie 2021). From morphometric studies, the volcanic mounds and ridges are thought to have formed progressively in phases involving eruptive construction followed by splitting caused by marginal basin extension (Gràcia *et al.* 1996). By comparison with seamount volcanism associated with slow spreading mid-oceanic ridges, which is characterized by abundant small edifices typically <150 m high, the seamounts in both Bransfield basins contain a greater proportion of larger examples (2–7 km in basal diameter but up to 16 km) and they are more widely spaced. The differences are attributed to the essentially continental rather than oceanic nature of the underlying crust and its ability to geographically focus the effects of the regional extension.

The marginal basin also contains Deception Island, a large active volcano and the only Antarctic volcano with a hazard assessment (Smellie *et al.* 2002; Martí *et al.* 2013; Bartolini *et al.* 2014; Geyer *et al.* 2021). In addition to numerous eruptions during the past few tens of thousands of years and particularly during the nineteenth century (Moreton and Smellie 1998; Smellie *et al.* 2002), Deception underwent a major caldera-forming eruption *c.* 4 kyr ago. It was the largest Holocene eruption to occur in Antarctica and vented a bulk volume of *c.* 90 km^3, which deposited ash more than 4000 km across the Scotia Sea and East Antarctica (Antoniades *et al.* 2018). Although the well-documented 1969 eruption of Deception was glaciovolcanic (but through very thin ice: Smellie 2002), and ice still covers half of the island during the current peak interglacial conditions, the deposits preserved on the island show no obvious evidence for glaciovolcanism.

Voluminous back-arc alkaline volcanism and Neogene cryosphere evolution: the James Ross Island Volcanic Group

Back-arc volcanism in the James Ross Island region is situated *c.* 250 km SE of the South Shetland Trench. It is a large mafic (basaltic) volcanic field and the products are known as the James Ross Island Volcanic Group (JRIVG: Smellie 2021). The JRIVG is probably still active, although it characteristically exists in a very long-lived dormant state (Smellie *et al.* 2008, 2013*a*). The volcanism varies from alkaline to less commonly tholeiitic in composition (Haase and Beier 2021). It has been attributed to rollback effects of the slowly subducted slab drawing in a shallow 'plume' of pristine mantle (i.e. unaffected by slab-related metasomatism) from the Weddell Sea, which then underwent upwelling and associated decompression melting on the SE side of the Antarctic Peninsula (Hole *et al.* 1995). JRIVG volcanism may extend back to *c.* 12.5 Ma (Marenssi *et al.* 2010). That age considerably predates the most usually stated age for the commencement of slab rollback (i.e. from *c.* 4 or 6.7 Ma). The conflict in timing may be resolved if the proposal by Birkenmajer (1992) is correct: that is, that extension (reflected by rifting and basin formation in Bransfield Strait) might date back to latest Oligocene–earliest Miocene time (*c.* 22 Ma). That proposal was based on the identification of a 'thermal event' and extensional faulting with associated dykes, dated at between 26 and 20 Ma. However, the suggestion remains unsubstantiated given that there is no known association with regional tectonics (e.g. plate convergence rates; see below). The conflict also relies on the reliability of the dating of JRIVG basalts found as clasts in tills, which were mostly determined by the K–Ar method (including ages of 12.4 and 7.13 Ma: Sykes 1988; Marenssi *et al.* 2010); however, a relatively old age of 9.2 Ma was determined (also on a lava clast in till) using

$^{40}Ar/^{39}Ar$ and may be more reliable (Jonkers *et al.* 2002). *In situ* rocks date back to only 6.2 Ma, consistent with an age for rollback commencing at *c.* 6.7 Ma, although the presence of a deep 'keel' of likely JRIVG rock beneath Mount Haddington implies an even older volcanic history (Smellie *et al.* 2008; Jordan *et al.* 2009). Notably, neither the compositional nature nor the eruptive periodicity of the JRIVG volcanism changed across the transition from active to passive subduction (i.e. associated with slab rollback or transtensional effects). The evolution of the Cenozoic convergence rate of the Phoenix/Aluk slab is relatively well constrained. Two early stages of slowing are known, at 52.3 and 47.3 Ma. Both could have had profound effects on the overriding plate and might have been associated with slab rollback (McCarron and Larter 1998), although they had no apparent effect on the axis of active arc volcanism in the South Shetland Islands (Fig. 8). A further slowing of the convergence rate at *c.* 13 Ma could have created sufficient slab pull to initiate or enhance corner flow of pristine Weddell Sea mantle into an arc-rear 'thinspot', as postulated by Hole *et al.* (1995). However, the history of plate convergence does not show any rapid slowing until *c.* 6.7 Ma (from 40–60 to <10 mm a^{-1}), which is the earliest time that slab rollback is thought to have been initiated (Maldonado *et al.* 1994).

Although a significant role for the resulting magmatism, involving the melting of the subducted slab, is now being considered (Hole 2021), it is unclear yet how the new explanation might help to resolve either the timing of the JRIVG or the mechanism of its occurrence. Perhaps significantly, tholeiitic–alkaline mafic volcanism is also present in a similar arc-rear position in southern South America. Volcanic activity in the extra-Andean Patagonian basalt province mostly took place between 30 and 20 Ma but recurred in the Plio-Pleistocene. It consists mainly of 'plateau lavas', which are voluminous eruptions of basalt that cover a wide area, but includes numerous small volcanic centres in the southernmost, much younger outcrops (in the Pali Aike Volcanic Field: D'Orazio *et al.* 2000; Muñoz *et al.* 2000; de Ignacio *et al.* 2001; Ross *et al.* 2011). Although a connection with slab windows has been postulated for the volcanism, other workers prefer a slab rollback model linked to plate convergence processes, which initiated variable slab dips and caused corner flow of pristine mantle. However, both models may be correct. The field relationships and ages of the volcanism indicate that the much more widespread plateau basalt volcanism is older (Oligocene–Miocene), whereas the younger volcanism (Plio-Pleistocene) consists of numerous small-volume monogenetic volcanic centres (tuff cones, maars and scoria cones). Ridge–trench collision also did not occur until 14 Ma, placing a maximum age on the formation of slab windows. Thus, the older plateau basalt volcanism is plausibly related to a combination of slab rollback and shallow asthenospheric upwelling of pristine mantle (associated with more rapid plate convergence rates, the opposite to the situation in the Antarctic Peninsula), whilst the younger much smaller-volume volcanism can be linked to slab-window formation. The similarities with the contrasting models for volcanism in the JRIVG (flood lava eruptions (Smellie 2021); i.e. corner flow in the mantle wedge driven by slab rollback) and further south in the Antarctic Peninsula (i.e. small-volume monogenetic volcanic fields (Smellie 1999; Hole *et al.* 1995; Smellie and Hole 2021); slab-window-related) are self-evident but have not been highlighted previously.

An unusual feature of JRIVG volcanism is that it remained basaltic throughout its *c.* 12 myr duration (Smellie 1987; Košler *et al.* 2009; Haase and Beier 2021). However, the Antarctic Plate has been stationary since Late Cretaceous times. Under a model involving long-lived shallow diapiric upwelling and decompression melting of Weddell Sea mantle, the static conditions (i.e. no plate migration) would have favoured the construction of a substantial edifice (i.e. Mount Haddington, probably Antarctica's largest volcano). This is similar to the way very large volcanoes were constructed on Mars, a planet lacking plate tectonics and characterized by very long-lived stationary mantle plumes, whether internally generated or impact induced (e.g. Carr 1974; Reese *et al.* 2004). What triggered the repeated episodes of melting and eruption of large volumes of (only) mafic magma in the JRIVG is uncertain but two possible options are: (a) regional plate-tectonic effects (plate 'jostling') triggering short-lived diapiric upwelling episodes in the mantle; or (b) melting in response to glacial–interglacial fluctuations in the thickness of ice overburden. Both suggestions are speculative but, on a geological timescale, the periods between eruptions (i.e. few tens of thousands of years to >100 ka: Smellie *et al.* 2008) are probably rather too short to be related to large-scale plate effects. The other suggestion is a climate modulation similar to that documented for volcanic eruptions in Iceland, which are also situated above upwelling mantle (e.g. Jull and McKenzie 1996). The characteristically long repose periods between JRIVG eruptions more closely resemble a climate modulation as they are on a scale that resembles Milankovitch cyclicity (i.e. peaks at 26, 41 and *c.* 125 ka). Further (and more precise) dating of eruptions may help to verify this suggestion.

The JRIVG covers an area of 7000 km^2 and has an estimated volume of erupted products of >4500 km^3 (Smellie *et al.* 2013*a*). It is dominated by the huge volcanic shield of Mount Haddington, with a basal diameter of 60–80 km. Despite a summit elevation of just 1600 m, the volcano has a substantial root extending to 5 km with a volume below sea-level of *c.* 3000 km^3. Volcano spreading (i.e. settling and accompanying lateral displacement) has deformed the soft underlying Cretaceous sediments (Oehler *et al.* 2005; Jordan *et al.* 2009). The resulting deformation is particularly evident on the west side of the island facing Graham Land, where beds are steeply dipping on the coast, with thrust faults and anticlines, and give way inland to less steeply dipping younger Cretaceous strata. The Mio-Pliocene volcano-related deformation may be an alternative explanation for the deformation of the Cretaceous strata, which are currently interpreted using a model of progressive syndepositional basin subsidence (Whitham and Marshall 1988; Hathway 2000).

Mount Haddington and most of the satellite centres in the JRIVG are constructed principally of the products of multiple pāhoehoe lava-fed deltas, many of which were very voluminous (a few tens of cubic kilometres to 100 km^3) and correspond to flood lavas (Smellie *et al.* 2013*a*). By comparison with the most voluminous historical effusive flood lava eruption, Laki (Iceland) in 1873–74, which produced *c.* 15 km^3 of magma over 14 months, the individual and much larger effusive eruptions on Mount Haddington must have taken years to decades to be emplaced. This is comparable with flood basalt eruptions in LIPs and, similarly, the Mount Haddington eruptions were followed by substantial periods of repose (cf. Self *et al.* 1997; Muirhead *et al.* 2014), although the JRIVG is not a LIP.

Most of the JRIVG eruptions occurred in a glacial setting, and their features have been used to significantly improve our knowledge of glaciovolcanic edifice construction and eruptive processes (Skilling 1994, 2002; Smellie 2006; Smellie *et al.* 2008; Calabozo *et al.* 2015; Nehyba and Nývlt 2015). The JRIVG has also been the principal source of information about critical parameters of the northern part of the terrestrial Antarctic Peninsula Ice Sheet (APIS) from 6.2 Ma. The evidence indicates that the ice cover was comparatively thin (a few hundred metres) and wet-based (polythermal) throughout its history, apart from during the last glacial when it was much thicker and probably cold-based (Hambrey *et al.* 2008; Smellie *et al.* 2008, 2009; Nelson *et al.* 2009; Davies *et al.* 2012, 2013). Nývlt *et al.* (2011) suggested that the evidence for wet-based conditions may be an artefact caused by thermal activity of the JRIVG. However, active volcanism is only likely to change the climate-based thermal regime of a glacial cover in a comparatively narrow region on the summit of a volcano, within a zone approximately three times the width of any associated magma chamber (Smellie and Edwards 2016; Smellie 2018). Mount Haddington lacks a crustal magma chamber (Jordan *et al.* 2009), so the precise width of the thermally affected zone is uncertain but unlikely to be unusually large. Moreover, the evidence for wet-based conditions comes from volcanic outcrops situated variably 20–40 km from the Mount Haddington summit (i.e. well beyond any plausible volcano-related thermal effects). Therefore, it is highly unlikely that the thermal regime of the glacial cover on James Ross Island (away from the summit region) was influenced by the volcanism.

The thickest ice conditions (*c.* 700–800 m) appear to have occurred during the late Quaternary. The thickest ice was probably associated with the Last Glacial Maximum (LGM), as indicated by a glaciovolcanic lava-fed delta >650 m thick at <0.08 Ma and erratics on the 600 m asl (above sea-level) summit of Terrapin Hill, a Quaternary (*c.* 0.66 Ma) tuff cone on the north side of James Ross Island. Such an ice sheet would have been capable of largely drowning topography in the northern Antarctic Peninsula (Smellie *et al.* 2008, 2009), although it was much thinner than the 'giant', 2 km-thick APIS envisaged by others (Denton *et al.* 1991; Denton and Hughes 2002; cf. Nývlt *et al.* 2011). Moreover, the ice was probably comparatively resistant to global warming, up to mean global temperatures 4.5° above present (Smellie *et al.* 2009). Thus, the Peninsula region was ice-poor rather than ice-free during interglacials (Johnson *et al.* 2009; Salzmann *et al.* 2011). This is probably because, although the APIS comprises just 3% of the grounded ice-sheet area of the Antarctic continent, precipitation is three–four times greater than elsewhere and it receives *c.* 13% of the total mass input (Drewry and Morris 1992; van Lipzig *et al.* 2004).

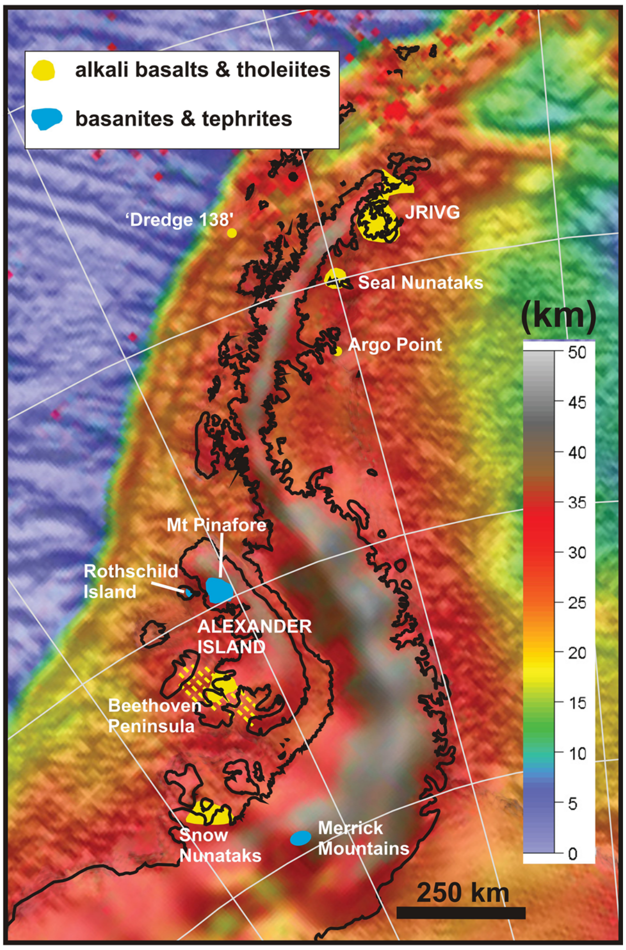

Fig. 9. Map of crustal thicknesses in the Antarctic Peninsula, based on gravity inversion (image: Nick Kusznir, reproduced with permission). The locations of alkaline slab-window basalts and similar-age compositionally indistinguishable back-arc basalts of the JRIVG are also shown. Note the prominent correlation between crustal thickness and compositions of the basalts. 'Dredge 138' indicates the location of a small submarine volcano formed of slab-window basalt (Hole and Larter 1993).

Monogenetic glaciovolcanism associated with post-subduction slab-window formation

Following the progressive collision of offset sections of the Phoenix–Antarctic spreading centre with the Antarctic Peninsula trench from Eocene time, subduction ceased but a northerly propagating slab window opened up due to the continued sinking of the leading oceanic plate (the Phoenix or Aluk slab: Hole *et al.* 1995). This has been considered as the trigger for the uprise and decompression melting of pristine mantle drawn up from beneath the slab (see also Hole 2021). The resulting small-volume melts were erupted at the surface as numerous monogenetic volcanoes forming extensive volcanic fields (Fig. 9).

Eruptions took place from 7.7 Ma (Smellie 1999) and rapidly became widespread in southern areas. They were joined by volcanism in northern Antarctic Peninsula from *c.* 4 Ma, with a volcano-free gap of *c.* 500 km between the two outcrop regions. Despite the opening up of slab windows at progressively younger times in a northerly direction, there is no similar progression of eruptive ages seen in the slab-window-related volcanism, an enigma that still requires an explanation (Hole 2021; Smellie and Hole 2021). The edifices vary from a few hundred metres to *c.* 7 km in diameter and are *c.* 100–800 m high. They range from rare isolated scoria cones to (mainly) glaciovolcanic tuyas and a few sheet-like sequences (Smellie and Hole 2021). Most crop out in monogenetic volcanic fields with areas ranging from 1400 to >2000 km^2 (possibly >7000 km^2 in one example: Smellie 1999).

From the distribution of the outcrops, it is clear that, apart from two tiny isolated outcrops in Merrick Mountains (central southern Palmer Land), all of the Neogene alkaline volcanic rocks, including the compositionally similar JRIVG, occur on the flanks of the Antarctic Peninsula where crustal thicknesses can be expected to be relatively thin (Fig. 9) (Renner *et al.* 1985; Kusznir *et al.* 2018; Pappa *et al.* 2019). The implication is that greater crustal thicknesses generally prevented the alkaline magmas from being erupted. There is also a significant correlation between the erupted compositions and crustal thicknesses: viz. the more undersaturated, more alkaline lavas in northern Alexander Island and Merrick Mountains, composed of tephrites and basanites with locally abundant ultramafic nodules, crop out above thicker crust; the more common outcrops of lavas with less undersaturated compositions, including the JRIVG, composed of olivine basalts, alkali basalts and tholeiites generally lacking nodules, crop out above much thinner crust (Fig. 9). The more alkaline group was also formed by lower degrees of melting, consistent with its smaller erupted volumes (Hole 1988, 1990; Smellie 1999). The Moho would have acted as a density barrier where the magmas were temporarily stored and underwent the small degrees of fractionation observed. Moreover, the alkali basalts, olivine basalts and tholeiites consistently have slightly higher $^{87}Sr/^{86}Sr$ ratios and lower $^{143}Nd/^{144}Nd$ ratios than the basanites, interpreted as the incorporation of a variable subduction-zone component in the mantle wedge traversed by the magmas (Hole 1988, 1990). Moho depth differs by *c.* 10–15 km between the occurrences of the two magma types (Fig. 9) and the incorporation of the subduction component would be enhanced by migration over a greater vertical distance. Thus, greater degrees of melting (and erupted volumes) for the alkali/olivine basalt and tholeiitic occurrences may be explained by the greater vertical distance travelled to reach the Moho, and the correspondingly shallower equilibration pressures. It is therefore suggested that the high-relief subcrustal topography of the Antarctic Peninsula exerted an important control on the location, compositions and erupted volumes of the Neogene slab-window volcanism.

Practically all of the slab-window-related centres were erupted in association with a glacial cover. Together with erupted units in the JRIVG, they have been used to advance our knowledge of glaciovolcanism generally, including: the relationship between sequence types and ice thickness (Smellie and Skilling 1994); the characteristics of sheet-like sequences and their mode of formation (Smellie *et al.* 1993; Smellie 2008); improved lithofacies-based models for tuya (Surtseyan) edifice construction (Skilling 1994, 2002; Smellie and Hole 1997); and the hydraulics of tuya eruptions (Smellie 2006). Palaeoenvironmentally, the outcrops have also been a major source of information on the critical parameters and evolution of the terrestrial APIS. As a result, more is known about the history and evolution of the terrestrial APIS from Late Miocene time (<7.7 Ma) than is known for most other pre-Quaternary ice sheets on Earth (e.g. Smellie *et al.* 2006, 2008, 2009; Hambrey *et al.* 2008; Nelson *et al.* 2009). The studies have demonstrated that a relatively thin (<*c.* 400 m), wet-based draping ice cover was present throughout the Antarctic Peninsula most of the time. The APIS therefore mainly resembled an ice field, although there were also occasional episodes of relatively thick ice (e.g. at *c.* 5.5 and 3 Ma, and LGM). It is also noticeable that typical ice thicknesses in the Antarctic Peninsula were significantly thicker (mainly 200–400 m, and at times much thicker (up to 750–800 m): Smellie *et al.* 2009) than inferred for the East Antarctic Ice Sheet in northern Victoria Land during the Late Miocene–Pliocene (mostly <200 m: Smellie *et al.* 2011*b*). This is probably due to the warmer and wetter conditions causing greater precipitation in the narrow high peninsula, with its more northerly position flanked by large oceanic masses, and greater exposure to large numbers of cyclonic weather systems tracking across it (Turner *et al.* 1998).

Alkaline continental rift volcanism (West Antarctic Rift System): influence of the West Antarctic Ice Sheet

Antarctica is also host to one of the world's great continental rift zones, known as the West Antarctic Rift System (WARS). It is *c.* 3000 km long and 750–1000 km wide, comparable with the East African Rift and the Basin and Range province. Conversely, its floor is substantially lower and large areas of the WARS are well below sea-level (down to *c.* 2555 m bsl (below sea-level): LeMasurier 2008). Although the earliest age of volcanism in the rift (Eocene: Wilch and McIntosh 2000; Smellie and Rocchi 2021; Wilch *et al.* 2021) might suggest that the WARS formed primarily during Cenozoic rifting, much of West Antarctica was affected by a much more significant precursor episode of extension and crustal thinning associated with the separation of New Zealand from Marie Byrd Land during the Late Cretaceous (from *c.* 105 Ma: Lawver and Gahagan 1994; Siddoway 2008). Perhaps as a result, the West Antarctic Plateau, a postulated high topographical area that may have formed the Pacific flank of the long-lived (Devonian–Triassic) Beacon Supergroup sedimentary basin(s), subsided close to or somewhat below sea-level (Bialas *et al.* 2007; Fitzgerald *et al.* 2007; but see also Elliot 2013). A regionally extensive, generally low-relief erosion surface, known as the West Antarctic Erosion Surface (WAES), was created in Marie Byrd Land and Ellsworth Land (Jones Mountains), principally between *c.* 85 and 75 Ma (LeMasurier and Landis 1996). A likely temporal equivalent is also present in New Zealand (the Waipounamu Erosion Surface). The extensive crustal thinning during this period is often described as amagmatic but alkaline dykes and plutons with ages of 107–95 Ma are present in Marie Byrd Land and may have fed volcanic activity, now removed by erosion associated with the formation of the WAES. The Cretaceous alkaline magmatism has been assigned a plume origin linked to the break-up episode (Storey *et al.* 1999). The presence of a weak marine mass extinction at the Cenomanian–Turonian boundary (*c.* 90 Ma: Ernst and Youbi 2017) provides possible support for suggesting that volcanic activity was associated with the Late Cretaceous intraplate magmatism in Marie Byrd Land (and Zealandia: Hoernle *et al.* 2020), since volcanic emissions of carbon dioxide and associated climate change have been identified as likely culprits. However, the Antarctic magmatism also broadly coincided with several LIP events (e.g. Caribbean–Colombian, Kerguelen Plateau and Madagascar: Storey *et al.* 2013), and they probably played the leading role.

Extension and rifting were renewed between *c.* 50 Ma and present, although the episode involved significantly less extension than during the Late Cretaceous and was largely confined to the western Ross Sea, adjacent to the Transantarctic Mountains. The earliest alkaline magmatism associated with the Cenozoic extension consisted of alkaline plutons and dykes of mainly Eocene age. They included a single pluton in eastern Marie Byrd Land (the Dorrel Rock gabbro close to Mount Murphy: 35–34 Ma); volcanism also occurred at 37 Ma (at Mount Petras: Rocchi *et al.* 2006; Wilch *et al.* 2021). However, the episode is best represented by numerous plutons and dykes in northern Victoria Land known as the Meander Intrusive Group (52–18 Ma: Rocchi *et al.* 2002; Ross *et al.* 2002; Smellie and Rocchi 2021). Emplacement of the Meander Intrusive Group coincided in time with oceanic crust formation in the Adare Basin and continental rifting in the Northern Basin offshore of northern Victoria Land (*c.* 43–26 Ma: Cande and Stock 2006), which implies a genetic link with tectonism outside of the WARS (i.e. seafloor spreading between Australia and Antarctica: Davey *et al.* 2016). It is generally unknown if the Meander Intrusive Group plutonic episode also fed volcanic activity as erosion has removed virtually the entire record. However, possible evidence for an associated volcanic suite is present at one locality in northern Victoria Land, Vulcan Hills (between Mount Melbourne and Mount Overlord: Fig. 1), and more widespread associated volcanic activity is inferred (Smellie and Rocchi 2021). The intrusive activity overlapped in time with alkaline volcanism, which began at *c.* 37 Ma in Marie Byrd Land and became voluminous after *c.* 14 Ma, and which constructed numerous large, shield-like, composite central volcanoes throughout the WARS, (Hamilton 1972; LeMasurier and Thomson 1990; Smellie *et al.* 2011*a*, *b*; LeMasurier 2013; Smellie and Rocchi 2021; Smellie and Martin 2021; Wilch *et al.* 2021). The unusual terminology used to describe these large polygenetic volcanoes (discussed by Wilch *et al.* 2021) reflects the fact that, despite being formed of alternating massive (effusive) and fragmental products and developing evolved compositions similar to stratovolcanoes (i.e. composite volcanoes), the individual volcanoes generally have relatively low gradients (*c.* 5°–10°) like shield volcanoes. The low gradients reflect a predominantly effusive origin, but with emplacement overwhelmingly as lava-fed deltas, particularly in Victoria Land (Smellie *et al.* 2011*a*, 2014; and unpublished information of the author). The same probably also applies to volcanoes in Marie Byrd Land (at Mount Murphy and Crary Mountains, at least: Wilch *et al.* 2021; and unpublished information of the author) but the erosional dissection of most of the volcanoes is minor and their internal structure is largely unknown. The lava-fed delta sequences are dominated by alternating massive subaerial lava and subaqueous fragmental (non-explosively-formed) tuff breccia lithofacies, in cogenetic couplets (e.g. LeMasurier 2002; Smellie *et al.* 2011*a*, *b*, 2013*b*). By contrast, some of the central volcanoes in Victoria Land are simple stratovolcanoes, with steep flank gradients (e.g. Mount Erebus, Mount Discovery, Mount Melbourne, Mount Overlord, Mount Lubbock and Mount Harcourt); most of those in northern Victoria Land are unusually small.

Volcanism in the WARS is widespread throughout Marie Byrd Land and Victoria Land. It is likely that a significant amount of the volcanic activity in Marie Byrd Land is hidden by the West Antarctic Ice Sheet, as numerous subglacial volcanoes have been tentatively identified aerogeophysically (Fig. 2) (e.g. Behrendt *et al.* 1994, 2002; van Wyk de Vries *et al.* 2018; but see also Quartini *et al.* 2021). Behrendt *et al.* (1994) speculated that the volcanism in the WARS, which they considered included comparatively large centres (2 km thick and >10 km in basal diameter), potentially had an erupted volume of 10^6 km^3, which is similar to areas of flood basalts (e.g. in LIPs). However, given a lifetime of >30 myr for the volcanism, the time-integrated magma discharge rate is far lower than in LIPs. Moreover, the absence of basalt clasts of appropriate age in subglacial sediments from the WARS suggests that subglacial volcanism is either not widespread or is covered by a sedimentary drape in the region sampled (Vogel *et al.* 2006). The Victoria Land volcanism is included in the McMurdo Volcanic Group, which is divided into several volcanic provinces and volcanic fields (Smellie and Rocchi 2021) (Fig. 10), whereas that in Marie Byrd Land and Ellsworth Land is included in the Marie Byrd Land Volcanic Group, with two subdivisions (Marie Byrd Land and Thurston Island volcanic provinces: Wilch *et al.* 2021). There are also several active (dormant) and potentially active volcanoes within the WARS, including Mount Takahe, Mount Berlin and Mount Waesche in Marie Byrd Land; Mount Erebus in southern Victoria Land; and Mount Melbourne, Mount Rittmann and The Pleiades in northern Victoria Land, together with candidate subglacial volcanoes inferred to be active (Smellie and Rocchi 2021; Dunbar *et al.* 2021; Quartini *et al.* 2021; Sims *et al.* 2021; Smellie and Martin 2021; see also Geyer *et al.* 2021).

Two principal contrasting origins are inferred for volcanoes in the WARS (Panter 2021; Panter *et al.* 2021*b*). Those in Marie Byrd Land (Marie Byrd Land Volcanic Group: Wilch *et al.* 2021) and in southern Victoria Land (Erebus Volcanic Province: Smellie and Martin 2021) may be related to mantle plumes. Many of the individual volcanoes are very large. They include Mount Erebus, which is 40 km in basal diameter and rises to 3794 m, and Mount Sidley, the highest volcano in Antarctica, rising to 4181 m. Additionally, Toney Mountain may be Antarctica's tallest volcano (*c.* 6595 m; it has a summit elevation of 3595 m asl and rests on basement at 3000 m bsl: LeMasurier 2013). The plume model is supported by: (a) a radial distribution of volcano ages and associated synvolcanic updoming in Marie Byrd Land; (b) the three-fold radial symmetry of major edifices in the Erebus Volcanic Province; (c) seismic tomography studies that show distinct low-velocity shear-wave anomalies below Ross Island and Marie Byrd Land extending down to 800–1200 km (Fig. 11); and (d)

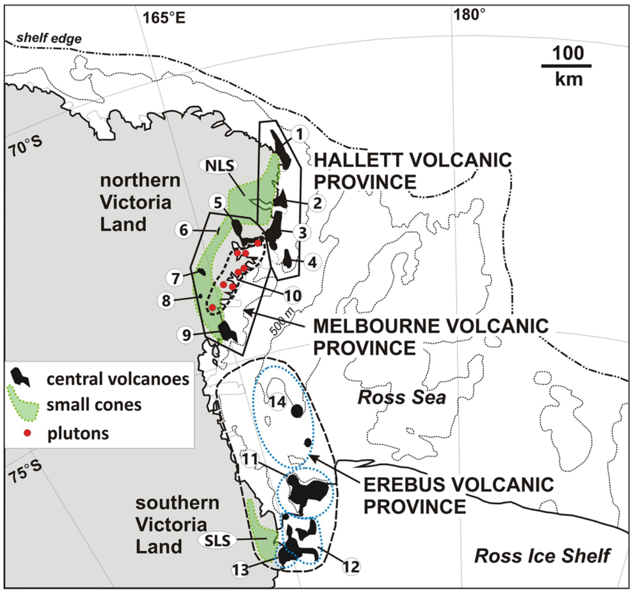

Fig. 10. Map showing the distribution of the McMurdo Volcanic Group (excluding the Scott Glacier Volcanic Field of the southern Transantarctic Mountains). The plutons shown are contained in the Meander Intrusive Group. Note also the widespread distribution of small pyroclastic cones (SLS, Southern Local Suite (volcanic field); NLS, Northern Local Suite (volcanic field)). See Smellie and Martin (2021) and Smellie and Rocchi (2021) for descriptions of the numbered volcanic fields.

spatially variable high heat flow; as well as petrological studies that have documented ocean island basalt compositional affinities and high U/Pb ratios (HIMU (high $^{238}U/^{204}Pb = \mu$): LeMasurier and Rex 1982, 1989; Hansen *et al.* 2014; Schroeder *et al.* 2014; Brenn *et al.* 2017; Seroussi *et al.* 2017; Phillips *et al.* 2018; Panter 2021; Martin *et al.* 2021; Panter *et al.* 2021*b*; Quartini *et al.* 2021). By contrast and despite essentially identical compositions throughout the WARS, it has been suggested that the origin of volcanism in northern Victoria Land is better explained by melting and craton-directed edge flow of a prominent shallow mantle thermal anomaly (Fig. 11) (Graw *et al.* 2016; Panter *et al.* 2018; Rocchi and Smellie 2021). The low-wave-speed shallow anomaly is one of several identified in the Balleny–Tasman Belt, a strike-slip zone extending between Victoria Land and Australia that may be an incipient (diffuse) intraplate boundary (Danesi and Morelli 2000; Storti *et al.* 2007). The northern Victoria Land volcanoes are further distinguished into two types: inland stratovolcanoes, which are few, relatively small and little eroded, including Mount Overlord which is only 7 km in basal diameter and rises just 800 m above the surrounding land surface; and numerous large coalesced shield volcanoes that form a prominent linear zone along the coast. Individual volcanoes in the latter are commonly 25–>35 km in original diameter (although much modified, mainly by marine erosion) and rise to 2 km (Smellie and Rocchi 2021). Although stratovolcanoes are also present in the coastal zone, they are rare and small, and just two are known (Mount Lubbock and Mount Harcourt, both with basal diameters of *c.* 15 km). The coastal volcanism probably erupted from north–south-trending faults that are conjugate with a series of prominent NW–SE-trending strike-slip faults genetically linked to the Balleny–Tasman strike-slip belt (Salvini *et al.* 1997; Rossetti *et al.* 2006; Rocchi and Smellie 2021). The coastal volcanism has also been modelled to show that Cenozoic extension of crust previously thinned during Cretaceous extension would cause necking in a narrow zone at the junction between thick East Antarctic crust and much thinner

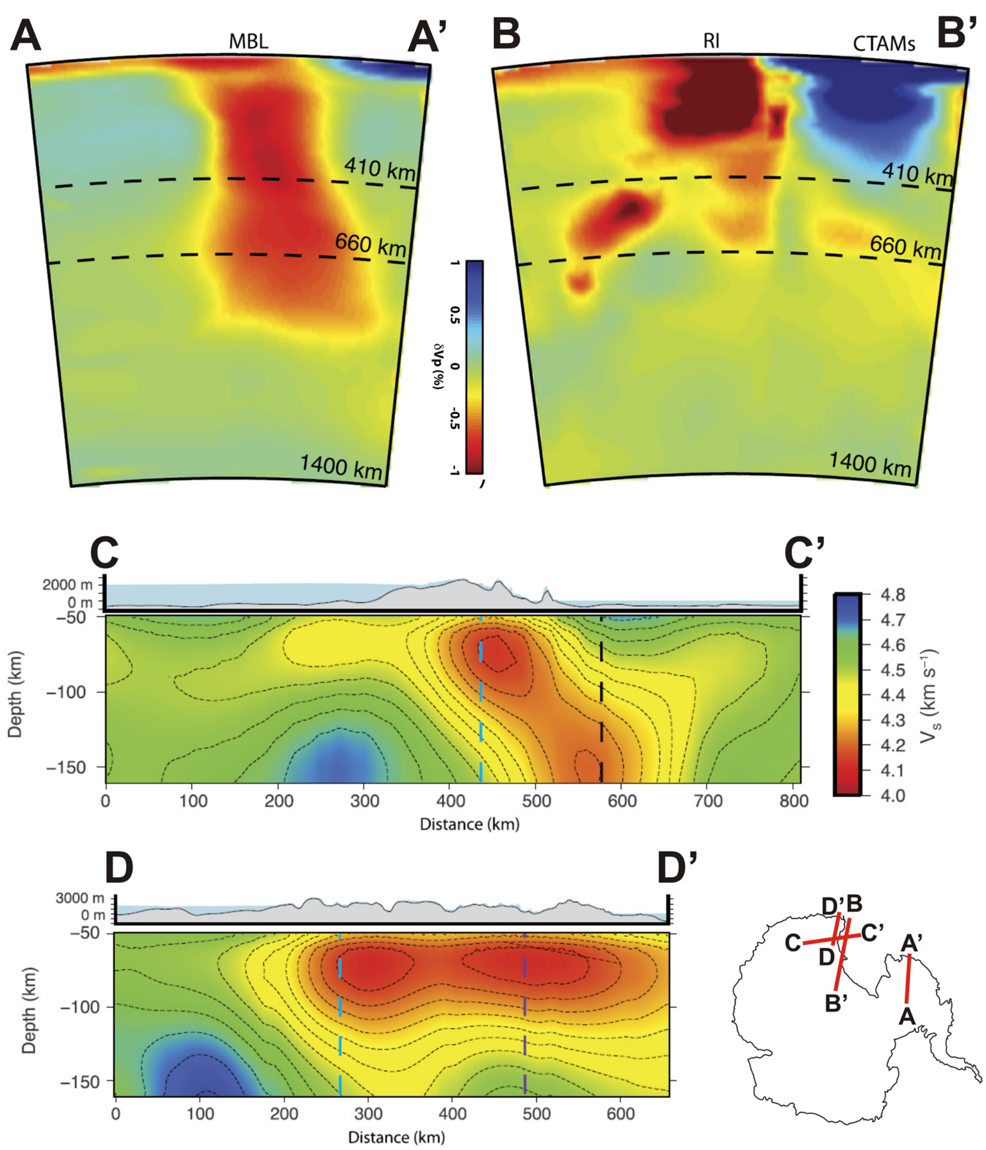

Fig. 11. Seismic tomographic profiles through Marie Byrd Land (MBL: A–A′), Ross Island (RI: B–B′) and northern Victoria Land (C–C′ and D–D′) showing the shear-wave structure. Zones with low velocity (orange and yellow colours) are interpreted as being due to mantle upwelling with associated melting. Note the different vertical scales between sections A–A′ and B–B′ v. C–C′ and D–D′. The basal boundary for upwelling is much shallower beneath northern Victoria Land compared with southern Victoria Land and Marie Byrd Land. Diagrams are from Hansen *et al.* (2014) and Graw *et al.* (2016). See also Phillips *et al.* (2018). CTAMs, central Transantarctic Mountains.

West Antarctic crust (Huerta and Harry 2007), and in which melting became focused (Rocchi *et al.* 2002; Panter *et al.* 2018). The coastal volcanic belt thus marks the junction between thick and thin crust, and is the structural margin of East Antarctica.

Volcanism in the coastal belt of northern Victoria Land is much more voluminous than that inland and it differs in broad geochemical characteristics. It is dominated by mafic compositions, whereas the inland volcanoes include a greater proportion of differentiated compositions. The latter also evolved to high-silica rhyolites that mostly reached peralkalinity consistent with the presence of substantial cooling and fractionating crustal magma chambers (Rocchi and Smellie 2021). The differences may be ascribed to variable magmatic fluxes, with the coastal volcanism experiencing a much higher flux than the inland volcanism. Thus, magma flux along the coast kept the crust hot and the magmas remained as gabbros for a much longer period, whereas the lower flux inland led to isolated magma chambers, more rapid cooling and fractionation. The coastal volcanic sequences have also been likened broadly to proto-seaward-dipping reflectors formed by volcanism at a ‘non-volcanic’ rifted margin (*sensu* Menzies *et al.* 2002), but which stalled essentially at a pre-rift stage (Rocchi and Smellie 2021). An oceanic basin did not develop offshore of northern Victoria Land, although there is evidence for continental rupture that may predate much of the onshore volcanism (Davey *et al.* 2016). Thus, the volcanism remains in a subaerial position and did not subside below sea-level.

Inland volcanoes within the WARS are largely uneroded and they typically show only the subaerial products of the latest eruptions (Hamilton 1972; Smellie and Rocchi 2021; Wilch *et al.* 2021). By contrast, the coastal volcanoes are often deeply eroded and contain very detailed environmental histories, which are the focus of recent and ongoing investigations (Wilch and McIntosh 2002; Smellie *et al.* 2011*a*, *b*, 2014; Smellie and Rocchi 2021; Smellie and Martin 2021; Wilch *et al.* 2021). The volcanism coincided with the inception and development of the Antarctic Ice Sheet and glaciovolcanic sequences are prominent. The information the outcrops contain provides important environmental data for a period well beyond instrumental records, including the growth, decay and critical parameters of the ice sheets in Antarctica; interglacial environments are much less documented. It may be that the impingement of a mantle plume below Marie Byrd Land from *c.* 37 Ma (at least), causing uplift that raised large areas a few hundred metres above sea-level, facilitated the initiation and growth of the West Antarctic Ice Sheet (Smellie 2020*b*; cf. Wilson *et al.* 2013). Moreover, geothermal heat currently associated with the volcanism in Marie Byrd Land may be having an influence on drawdown of the West Antarctic Ice Sheet (Schroeder *et al.* 2014; Seroussi *et al.* 2017; Loose *et al.* 2018; Quartini *et al.* 2021). Some eruptions from Antarctic volcanoes (overwhelmingly found within the WARS) may also influence regional climate and have the potential to accelerate Antarctica out of glacials (McConnell *et al.* 2017).

The large polygenetic centres in the WARS are overwhelmingly effusive and exposed sections are dominated by multiple superimposed glaciovolcanic ʻaʻā lava-fed deltas, which gives them their shield-like profiles (Smellie *et al.* 2011*a*, *b*, 2013*b*). Although mainly mafic (basanite), they include rare evolved examples (tephriphonolite and trachyte: Wilch *et al.* 2021; and unpublished information of the author and Sergio Rocchi). Other glaciovolcanic sequence types are rare but they include sheet-like sequences, including the first plausible felsic sheet-like sequences to be described (Smellie *et al.* 2011*a*). The volcanic sequences in the WARS were the first to demonstrate the existence of an extensive pre-Quaternary ice sheet in Antarctica (Craddock *et al.* 1964; Rutford *et al.* 1968, 1972; Hamilton 1972; LeMasurier 1972), well ahead of the earliest drilling discoveries by DSDP (Hayes *et al.* 1975). Despite papers describing the glacial setting in Marie Byrd Land (LeMasurier 1972; LeMasurier and Rex 1982; LeMasurier *et al.* 1994), the investigations were too early to benefit from a fully modern understanding of glaciovolcanism (i.e. post-2000; see the summary of palaeoenvironmental applications by Smellie 2018), and the environmental history of the region remains generally poorly described and understood (but see Smellie 2001; Wilch and McIntosh 2000, 2002, 2007; Haywood *et al.* 2009; Wilch *et al.* 2021). In part, this reflects the often very poor exposure available, particularly inland. By contrast, critical parameters and the evolution of the terrestrial East Antarctic Ice Sheet (EAIS) in northern Victoria Land are better known due to the often excellent exposure on the coast. Between *c.* 12 Ma and present, the ice cover in Victoria Land comprised relatively thin ice (mostly <200 m) and the region would have resembled an ice field rather than drowned by a much thicker ice sheet (Smellie *et al.* 2011*a*, *b*; Smellie and Rocchi 2021). However, because of the high errors characteristic of the published $^{40}Ar/^{39}Ar$ isotopic ages (typically 40–80 ka, i.e. much more than a glacial cycle), the calculated thicknesses cannot be assigned to either glacial maxima or minima. They are regarded as ‘*typical thicknesses*’ for glacial conditions during the period since more persistent thicker ice would have left a prominent and unmistakable glaciovolcanic record. Much thicker (and wet-based) ice must have existed at times: for example, to deposit abraded basement erratics on top of volcanic deposits at Harrow Peaks (400 m asl: Smellie *et al.* 2018); up to an elevation of 500 m asl on northern Adare Peninsula (Hamilton 1972; Johnson *et al.* 2008); and up to *c.* 900 m asl on Minna Hook (unpublished information of the author). Moreover, the distribution and variable ages of localities showing evidence for warm- and cold-based ice coeval with eruptions during the late Miocene and Pliocene suggest that the thermal regime of the EAIS was polythermal overall: that is, a patchwork mosaic of wet-based ice and ice frozen to its bed (Smellie *et al.* 2014). The prevailing paradigm for EAIS evolution that has existed since the early 1980s states that the thermal regime underwent a change from wet-based dynamic ice to cold-based and stable in a single unidirectional step either at 14.5 Ma or *c.* 2.5–3 Ma (Webb and Harwood 1991; Wilson 1995; Lewis *et al.* 2007; Barrett 2013). However, judging ice thermal regime from sedimentary records is extremely challenging (Hambrey and Glasser 2012), and only drill-core material is available since appropriate-age outcrops are absent onshore in Victoria Land. By contrast, thermal regime is often straightforward to determine from glaciovolcanic sequences (Smellie 2018). Thus, the new paradigm involving polythermal ice, based on the volcanic evidence, is a significant change.

Pyroclastic products are uncommon in the WARS, probably because most eruptions coincided with an ice cover. Any tephra would therefore be distributed on the ice surface and subsequently advected to the ocean, leaving behind little or no onshore geological record apart from in ice cores (see Dunbar *et al.* 2021; Narcisi and Petit 2021). In most cases, their presence in rock outcrop probably signifies eruptions during ice-poor or ice-free conditions, presumably during interglacial periods. Known examples in Marie Byrd Land include Plinian fall deposits at Chang Peak (close to Mount Waesche) and Mount Sidley; ignimbrites on Mount Sidley and Mount Berlin; and welded fall deposits at several volcanoes (LeMasurier and Rex 1989; LeMasurier and Kawachi 1990; Panter *et al.* 1994; Dunbar *et al.* 2021; Wilch *et al.* 2021). In Victoria Land, ignimbrites occur on Mount Overlord and, uniquely in Antarctica, form an extensive plateau-like outcrop at Deception Plateau and possibly at Malta Plateau (localities close to Mount Overlord and The Pleiades, respectively: Fig. 1) (Noll 1985; Kyle 1990; Schmidt-Thomé *et al.* 1990; Smellie and Rocchi 2021). Polymict lithic breccias are also present on the summits of Mount Rittmann (northern Victoria Land) and Mount Waesche (Marie Byrd Land), and were probably erupted during caldera collapses at both volcanoes (Smellie and Rocchi 2021; Dunbar *et al.* 2021). In addition, the presence of numerous loose trachyte pumice lapilli and large broken bombs scattered on several of the scoria cones in The Pleiades attests to a relatively recent felsic pyroclastic eruption (Kyle 1982; Smellie and Rocchi 2021). The mid-Miocene (*c.* 12 Ma) Mason Spur volcano (near Mount Discovery, southern Victoria Land) contains the thickest deposits of ignimbrites and related breccias (*c.* 800 m thick), which fill a large caldera and represent the products of the largest Neogene eruption known in Antarctica (Martin *et al.* 2010, 2018; Smellie and Martin 2021). A block and ash deposit is also present on the northern Hallett Peninsula (Smellie *et al.* 2011*a*). Englacial pyroclastic layers (cryotephras) erupted in the WARS during the last few hundreds of thousand years are described by Dunbar *et al.* (2021) and Narcisi and Petit (2021).

There are also numerous small mafic monogenetic centres (i.e. small volcanoes, *sensu* White and Ross 2011). About 130 are known in Victoria Land, and are grouped within the Northern and Southern Local Suite volcanic fields (Fig. 10) (Smellie and Rocchi 2021; Smellie and Martin 2021). They are also common in Marie Byrd Land where they are parasitic or flank vents on the numerous large central volcanoes (LeMasurier 1972). They overwhelmingly comprise small scoria cones but rare tuff cones have been described at Mount Petras, Mount Murphy, Mount Siple and on the Hobbs Coast (Marie Byrd Land: LeMasurier *et al.* 1994; Wilch and McIntosh 2000, 2007; Smellie 2001; Wilch *et al.* 2021), and a few examples are present in the Mount Melbourne Volcanic Field (northern Victoria Land: Wörner and Viereck 1989; Giordano *et al.* 2012). The latter includes a small tuff cone north of Mount Melbourne, which erupted during the Marine Isotope Stage 16 (MIS) glacial (*c.* 640 ka) and was interpreted as glaciovolcanic. It erupted under relatively thin, cold-based ice (Smellie *et al.* 2018). In addition, a few tuyas have been postulated near Mount Murphy, Mount Takahe, Mount Berlin and the Hobbs Coast (Marie Byrd Land); in the Hudson Mountains (Ellsworth Land); and at Shield Nunatak (southern flank of Mount Melbourne, northern Victoria Land), but they are rare generally in the WARS (Wörner and Viereck 1989; Smellie 2001; Giordano *et al.* 2012; Wilch *et al.* 2021). The rarity of tuyas in the WARS contrasts with their abundance in the Antarctic Peninsula (cf. Skilling 1994; Smellie and Hole 1997).

Finally, the radiating age trends of magmatism in the WARS together with the reconstructed morphology of the subvolcanic West Antarctic erosion surface have been used to infer domical uplift of the central WARS in Marie Byrd Land, usually attributed to the influence of an underlying large mantle plume during the Neogene (LeMasurier and Rex 1989; LeMasurier and Landis 1996; LeMasurier 2008; but see Paulsen and Wilson 2010 for an alternative view involving transmitted far-field plate-tectonic effects). It is less well known, however, that the magmatism can also be used to broadly constrain vertical movements of the WARS rift margin in the Transantarctic Mountains of Victoria Land. For example, using reasoning similar to Rocchi *et al.* (2006) for the Dorrel Rock gabbro in Marie Byrd Land, it is inferred that, for plutons in the Meander Intrusive Group to be exposed at the surface in northern Victoria Land, at least 3 km of overburden has to be removed since Eocene–Oligocene time, presumably with accompanying uplift of similar magnitude. Possible support for this is provided by thermochronological studies in northern Victoria Land. For example, Prenzel *et al.* (2018) suggested uplift and exhumation of *c.* 3.5 km (ranging from <2 to *c.* 4.8 km) caused by erosion since Oligocene time (≤*c.* 35 Ma), possibly within a period of just 5 myr, and Olivetti *et al.* (2016) identified an episode of rapid uplift at 26 Ma. The additional presence of younger subaerially erupted volcanic rocks (i.e. scoria cones and glaciovolcanic ʻaʻā lava-fed deltas) at sea-level throughout the coastal volcanic belt, both in northern Victoria Land and in the Erebus Volcanic Province of southern Victoria Land, implies that no uplift or possibly some currently unquantified collapse of the rift shoulder has occurred during the last *c.* 12 myr, at least (Smellie *et al.* 2011*b*; Rocchi and Smellie 2021; Smellie and Martin 2021). However, whilst the observation is consistent with an absence of a plume below northern Victoria Land, it is apparently at odds with the supposed presence of a plume (and associated doming effects) below the Erebus Volcanic Province. However, Ross Island has a 'root' extending to *c.* 2.2 km caused by gravitational subsidence of the volcanic pile into weak Mio-Pliocene strata of the Victoria Land Basin (Aitken *et al.* 2012), which may have compensated for plume-related uplift. Similar reasoning may apply to other volcanoes in the Erebus Volcanic Province. Gravitational settling is unlikely to have occurred below the northern Victoria Land volcanoes as they are founded on strong Paleozoic basement rocks (Hamilton 1972).

Isolated within-plate volcanism of enigmatic origin

Small, Early Miocene (*c.* 25–19 Ma) mafic volcanic centres with tholeiitic and alkali basalt compositions are present inboard of the WARS and high on its southern flank, at Mount Early, Sheridan Bluff and a subglacial site 200 km from the South Pole (Fig. 1) (Licht *et al.* 2018; Panter *et al.* 2021*a*; Smellie *et al.* 2021). They are the most southerly volcanic occurrences on Earth. Mount Early is a small glaciovolcanic tuff cone and pillow mound, whereas Sheridan Bluff is a small shield volcano with an original basal diameter of *c.* 6 km (Smellie *et al.* 2021). Studies underway are providing significant palaeoenvironmental information for the Early Miocene. These isolated volcanoes may have an origin related to extensional stresses caused by the WARS, or to flexural bending linked to motion between East and West Antarctica (Granot and Dyment 2018). However, formation of the magmas is probably distinct from those in the WARS, and may be a result of the detachment and sinking of lithosphere into the convecting mantle beneath the East Antarctic Craton (Panter *et al.* 2021*a*).

Elsewhere, volcanism with an enigmatic origin is also present at Gaussberg, a small isolated outcrop 370 m high on the coast of East Antarctica at 66° 47′ S, 89° 18′ E (Fig. 1) (Tingey *et al.* 1983; Smellie and Collerson 2021). The nearest exposed rock is *c.* 150 km away and consists of Precambrian basement, but aeromagnetic investigations suggest that Gaussberg may be one of a cluster of several similar-sized subglacial volcanic edifices present within a 30 km radius. Gaussberg is a pile of ultrapotassic lamproite pillow lava *c.* 1200 m high with a possible original diameter of *c.* 10 km (identified magnetically). Other lithofacies are minor. The nunatak represents a relatively small pillow volcano, which erupted subglacially 56 kyr ago, during the last glacial when the local ice cover was much thicker than present (*c.* 1300 m). Because of the confining effects of ice, glaciovolcanic pillow mounds might be expected to have higher aspect ratios than analogous mounds emplaced subaqueously. Published data on glaciovolcanic pillow mounds seem to contradict this but are too few to be definitive (Smellie 2013). Gaussberg was probably constructed by multiple overlapping vents, which created a broad, low-profile shield-like edifice under the ice. As in Victoria Land, the presence of erratics and striations on Gaussberg indicate that it was overridden by wet-based ice at LGM, similar to several localities known in Victoria Land. Because of its isolated location and unusual lamproite composition, the importance of Gaussberg environmentally and petrologically is out of all proportion to its small size. The genesis of the Gaussberg lamproites has been ascribed to melting of a sediment-contaminated deep mantle source followed by entrainment in a plume, although not the plume responsible for volcanism in the Kerguelen Plateau nearby (Smellie and Collerson 2021).

Summary

Antarctica has been affected by volcanic processes on a range of scales and under variable tectonic conditions (i.e. Gondwana-break-up, subducting continental margin, and slab-window and continental rifting). They differ widely in the duration, volume and geographical distribution of the erupted products. Jurassic volcanism associated with Gondwana break-up was short lived but is represented by widely dispersed, astonishingly high-volume, mafic and felsic flare-ups that included the longest interpreted lateral flow of (mafic) magma on Earth, and had a major environmental impact on Life on Earth that potentially triggered several mass extinctions.

Long-lived subduction, including during the period prior to that considered in this Memoir, created a continental margin arc. It was formerly a major physiographical feature that dominated the Pacific margin of Antarctica, from Marie Byrd Land to the Antarctic Peninsula. Subduction now persists only at the northern tip, at the South Shetland Trench. It was an extensional arc, with transitional arc characteristics in the South Shetland Islands due to the relatively thin crustal thicknesses there (*c.* 25–30 km). Its early (pre-200 Ma) history is very poorly known but from the Jurassic onwards it was probably characterized by alternating episodes of high magma-flux flare-ups and magmatic lulls, which have been identified in the South Shetland Islands and Alexander Island, and for plutons in southern Palmer Land. The reasons for the episodic nature of the magmatism are uncertain. Like other continental margin arcs, they probably relate to fluctuations in subduction parameters caused by transient regional stresses or far-field changes in plate motions (i.e. plate 'jostling'), which triggered extension-related flare-ups and compression-related lulls. The arc volcanism migrated trenchwards from the Late Cretaceous in the Antarctic Peninsula, probably because of enhanced growth of the coeval accretionary complex caused by an orthogonal subduction trajectory and the cuspate (concave to the west) shape of the peninsula helping to trap and preferentially accumulate subducted sediments. This caused the subducted slab to migrate trenchwards, taking the volcanic axis with it. By contrast, subduction was much more oblique opposite the northern Antarctic Peninsula, in the South Shetland Islands, which probably elicited tectonic erosion of the forearc. As a result, the volcanic axis there migrated *away* from the trench. Associated important features of the Antarctic continental margin arc include voluminous (flood lava) alkaline back-arc volcanism in the James Ross Island region, which includes Antarctica's largest volcano (Mount Haddington). A small intra-arc marginal basin also opened up in Bransfield Strait, where the largest Holocene eruption took place during caldera formation on Deception Island. The progressive stepwise cessation of subduction in a northerly direction created a series of slab windows that triggered small-degree alkaline mafic melts, which were erupted as numerous small-volume monogenetic volcanoes mainly on the flanks of the peninsula. The relative alkalinity and erupted volumes of the slab-window magmas show a clear correlation with crustal thickness. The back-arc and slab-window basalts also interacted with the Antarctic Peninsula Ice Sheet, and its critical parameters and history are now relatively well known as a result of several focused volcanological–palaeoenvironmental investigations since the 1980s.

Neogene alkaline rift-related volcanism in Antarctica in the West Antarctic Rift System (WARS: and also, to a large extent, alkaline back-arc- and slab-window-related volcanism in the Antarctic Peninsula) is overwhelmingly effusive. As a consequence, prior to year 2000, most published maps were based on geochemical investigations of the lavas, and fragmental rocks were poorly represented. The absence of substantial pyroclastic deposits is probably because the WARS volcanism coincided with the inception and development of the Antarctic Ice Sheet. Tephra produced by any pyroclastic eruptions during glacials would have fallen on the surrounding ice and was advected to the Southern Ocean, thus removing any onshore evidence. However, several caldera rim exposures preserve pyroclastic deposits, mainly in Marie Byrd Land. Their presence confirms that explosive eruptions also occurred, and may have been relatively common (cf. the Pleistocene–Holocene ice-core record). Pyroclastic deposits are possibly only preserved on the cratered summits of volcanoes in the WARS because, when they were active, the focused high heat flow may have prevented significant thicknesses of ice from accumulating. This is the case for Mount Erebus and Mount Melbourne today. Because of the volcanothermal effects, the crater regions of large volcanoes in the WARS are thus unlikely locations in which to derive unambiguous information on the prevailing climate. However, because of their broad (up to 12 km) basin-like shape and more dispersed heat flow, volcano calderas will permit the widespread build-up of ice, not only during glacials but probably also in interglacials. This is demonstrated by some caldera volcanoes considered to be active in the WARS today (e.g. Mount Berlin, Mount Takahe and Mount Rittmann), which have an extensive ice cover. It is also true of active caldera volcanoes in Iceland (e.g. Grimsvötn, Eyjafjallajökull and Katla), which support prominent summit ice caps. Thus, evidence for the prevailing climatic regime may be preserved in the summit regions of caldera volcanoes, although not for the thermal regime of any ice (as explained earlier for the James Ross Island Volcanic Group (JRIVG)). In general, during periods of much reduced ice cover in prominent interglacials, tephra can be preserved more widely on ice-poor or ice-free volcano flanks unless removed subsequently by glacial erosion (e.g. tephras preserved on Mount Sidley (Marie Byrd Land) and possibly Deception Plateau (northern Victoria Land)).

There is a conspicuous volcanological difference between the alkaline volcanism in the West Antarctic Rift region and the Antarctic Peninsula. The WARS is an ‘a‘ā province dominated by multistorey ‘a‘ā lava-fed deltas in numerous central volcanoes. It is the only ‘a‘ā-dominated glaciovolcanic province currently known. This is probably the reason why Marie Byrd Land (and the WARS generally) has very few examples of pillow lavas and all are small outcrops. By contrast, the Antarctic Peninsula (comprising back-arc and slab-window volcanism) is a pāhoehoe province characterized by numerous glaciovolcanic tuyas in monogenetic volcanic fields, and pāhoehoe lava-fed deltas that largely constructed the Mount Haddington shield volcano and associated satellite centres. Thus, pāhoehoe lava-fed deltas are the predominant eruptive unit in the Antarctic Peninsula. Iceland and British Columbia, the other large glaciovolcanic regions on Earth are also dominated by pāhoehoe. The overall differences between the two Antarctic regional provinces are probably related to compositional and possibly tectonic contrasts, the latter influencing magma volumes and thus discharge rates. The Antarctic Peninsula volcanism is typically more weakly alkaline and includes tholeiites. In the WARS, the volcanism is generally more alkaline, plume-related and much greater volumes were erupted.

A single occurrence of ultrapotassic lamproite magma is also present at Gaussberg, a small isolated outcrop on the otherwise almost rock-free coast of East Antarctica. The outcrop is a compositionally unusual volcanic centre, constructed of subglacially-erupted pillow lava. It is also unusually important for petrological studies and for palaeoenvironmental information linked to the last glacial in an onshore region largely devoid of other environmental evidence.

Following several investigations of volcanism in the WARS in recent years, the East Antarctic Ice Sheet in Victoria Land is becoming increasingly well documented and understood. The characteristics and evolution of the West Antarctic Ice Sheet are less well known, however, due to the remoteness of the outcrops and (especially) the frequent lack of suitable exposures. Characteristics of the interglacial periods are infrequently described in any area. With the exception of scoria cones, which require subaerial conditions, and lapilli tuffs, which can form in a variety of eruptive settings (subaerial and glaciovolcanic), the presence of pyroclastic deposits in the WARS generally requires non-glacial conditions for their preservation since they otherwise get removed quickly by ice advection. Their occurrence, therefore, is broadly diagnostic of interglacial periods and they are a focus of several current volcanological–palaeoenvironmental investigations in the region.

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