Introduction to volcanism in Antarctica: 200 million years of subduction, rifting and continental break-up

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Antarctica has undergone several important phases of volcanism throughout its long history. It was formerly at the heart of Gondwana but, from early Jurassic time (*c.* 200 Ma), it commenced the prolonged process of disintegration, which resulted in the dispersal and final disposition of the southern hemisphere continents that we are familiar with today (Veevers 2012; **Storey and Granot 2021**). As a consequence, volcanism has been particularly important in its construction and it is geographically widespread, although mainly located within West Antarctica (Fig. 1). Its effects have frequently been felt far outside of the continent. For example, it has been a driver of global mass extinctions (Burgess *et al.* 2015; Ernst and Youbi 2017) and it has potentially driven Antarctica climatically, and by implication the world, both into and out of glacials (Bay *et al.* 2006; McConnell *et al.* 2017). Conversely, Antarctica's volcanoes may have played a pivotal role in helping Life not only to survive multiple glacial episodes during the past few tens of millions of years but to undergo species diversification on the continent in spite of the dramatic climate variations (Fraser *et al.* 2014). Eruptions from Mount Erebus also represent a significant point source of gases and aerosols to the Austral polar troposphere, including affecting the ozone layer (Boichu *et al.* 2011; Zuev *et al.* 2015). Some of Antarctica's active volcanoes also have the potential to have a significant impact on southern hemisphere aviation (Geyer *et al.* 2017). Finally, Antarctica contains the world's largest and longest-lived glaciovolcanic province. The glaciovolcanic sequences contain a detailed record of the terrestrial Antarctic ice sheet going back to nearly 30 Ma and that record is now beginning to be tapped (e.g. Smellie *et al.* 2009; Smellie and Edwards 2016; **Wilch *et al.* 2021**). Despite these attributes, however, volcanism in Antarctica remains terra incognita to many Earth scientists, probably in large part because of its remoteness and inaccessibility.

The only previous volume to be devoted solely to Antarctic volcanism was published 30 years ago (i.e. LeMasurier and Thomson 1990). The scope of that volume was also considerably more restricted than in this Memoir: that is, to volcanoes <*c.* 30 myr old. That necessitated a main focus on the generally well-preserved volcanoes erupted into the West Antarctic Rift System (WARS), one of the world's major continental rift zones. The young remnants of formerly much more widespread arc-related volcanism, and intraplate volcanism in the sub-Antarctic region, were also included. Nevertheless, nothing else existed at the time and it was, and remains, a landmark publication that inspired a generation of Earth scientists to work in Antarctica, particularly volcanologists and petrologists. As a result, numerous new investigations rapidly followed and our knowledge of Antarctica's volcanism increased profoundly, with the generation of abundant new observations and many large datasets. However, as is always the case, much of the new knowledge has remained unpublished. A major intention of this volume is to capture that information and review it in a modern context after three decades of scientific advancement and enlightenment.

The Proterozoic and Paleozoic record of Antarctica's volcanism is patchy and comparatively poorly known (Riley *et al.* 2012; Goodge 2019). However, from the Early Jurassic (*c.* 200 Ma) onward, the record is much more complete and the multiple compositionally and tectonically diverse episodes of Antarctic volcanism have been intensively investigated. The volcanism can be divided into five categories (Smellie 2020): (1) Gondwana break-up volcanism (flood lavas and sills); (2) subduction-related continental margin arc, back-arc and marginal basin volcanism; (3) post-subduction slab-window basalts; (4) continental rift volcanism; and (5) intraplate volcanism of enigmatic origin. In this Memoir, the focus is on the better-preserved and much better-known record from *c.* 200 Ma, and each category is reviewed and assessed on a geographical basis in terms of its volcanology and eruptive palaeoenvironments; and petrology. Reviews of Antarctica's widely dispersed active volcanism, including tephrochronology (both onshore and offshore) and active subglacial volcanism, are also included. Overall, the objective of this Memoir is to review and assess the present state of knowledge of volcanism younger than *c.* 200 Ma right across Antarctica in all its aspects, and in the context of the interplay between the volcanism and the prevailing tectonic setting. Together with numerous geological maps, comprehensive tables of geochemical data and isotopic ages, and geophysical information, the intention is that this volume shall be the go-to resource for information on Antarctica's volcanism, *the* reference text for the coming decades. Our hope is that it shall act as a springboard for new proposals which, like the LeMasurier and Thomson volume, will revivify volcanic research in the region.

Volcanism in Antarctica: a brief overview

Gondwana break-up volcanism commencing at *c.* 190 Ma may have been driven by the effects of a large mantle plume (Storey 1995) and it is represented in Antarctica by two major voluminous volcanic provinces (Fig. 1a). One is a mafic large igneous province (LIP) that crops out throughout the Transantarctic Mountains and in Dronning Maud Land, with correlatives in South Africa, Tasmania, Australia and New Zealand (**Elliot *et al.* 2021**; **Elliot and Fleming 2021**; **Luttinen 2021**). The other consists of a series of felsic flare-ups that affected the entire Antarctic Peninsula and extended into southern South America (Chon Aike province: **Riley and Leat 2021*a*, *b***). The mafic volcanism in Antarctica is

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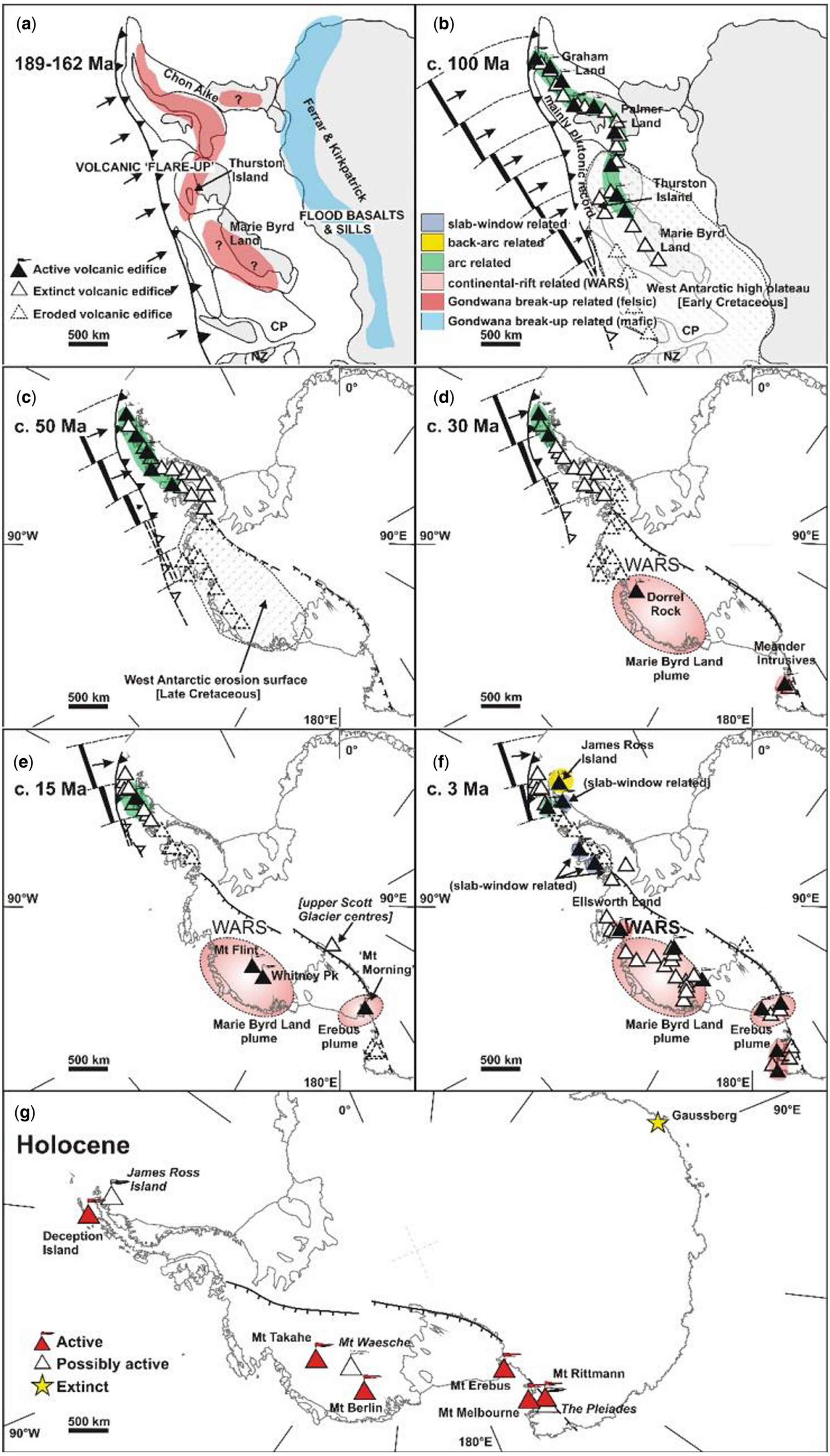

Fig. 1. Schematic time slices illustrating the different stages of volcanism that have affected Antarctica during the past 200 myr (modified after Smellie 2021*a*). The legends in diagrams (**a**) and (**b**) apply to diagrams (**a**)–(**f**), inclusive. In the Holocene depiction (**g**), only large volcanoes (≥*c.* 10 km basal diameter) are shown. The diagram also includes Gaussberg, a small, extinct, ultrapotassic volcanic centre 56 ka in age, to show its remarkable isolation from all other volcanic outcrops in Antarctica. NZ, New Zealand; CP, Campbell Plateau.

known as the Ferrar Supergroup but representatives in Dronning Maud Land show greater compositional affinities to coeval mafic lavas and sills in the Karoo of South Africa. The mafic LIP comprises voluminous flood lavas and thick dolerite sills. The event probably had a total volume of more than 0.5 × 10^6 km^3 but it may have been emplaced in a very short time, perhaps as little as 400 kyr (Marsh 2007; Burgess *et al.* 2015). Magma in the sills is estimated to have travelled *c.* 4000 km laterally, making it the longest interpreted magma flow on Earth (Elliot *et al.* 1999; Leat 2008). The earliest eruptive phase was characterized by phreatomagmatic pyroclastic eruptions from nested maar–diatreme vent complexes collectively called phreatocauldrons (White and McClintock 2001).

By contrast, the felsic Chon Aike province was erupted in three major pulses, individually *c.* 6–10 myr in duration, between 189 and 153 Ma (Pankhurst *et al.* 2000; Riley *et al.* 2001; **Riley and Leat 2021*a*, *b***). Each corresponds to a predominantly explosive volcanic flare-up (*sensu* Paterson and Ducea 2015) resulting mainly in the eruption of rhyolite ignimbrites. A prominent Pacific-ward progression observed in the ages of the volcanism has been linked to the impact and sublithospheric melting effects of the large spreading head of the same plume responsible for the Ferrar–Karoo LIP. An arc-like (subduction-influenced) mantle source, rather than a plume, has also been postulated for the mafic LIP (Choi *et al.* 2019; **Elliot and Fleming 2021**; **Panter 2021**).

Coincident with the break-up magmatism, the Pacific margin of Gondwana was already the locus of a major long-lived continental magmatic arc, the products of which are today widely preserved throughout the Antarctic Peninsula (Fig. 1b–e) (**Leat and Riley 2021*a*, *b***). The volcanism in the arc, and its plutonic equivalents, have been extensively dated, revealing that the activity probably took place as a series of magmatic flare-ups and lulls (Riley *et al.* 2018). This is particularly evident in the South Shetland Islands, which is the most intensively dated arc-related region (Haase *et al.* 2012; **Leat and Riley 2021*a***). The locus of active arc volcanism in Palmer Land and much of Graham Land moved into the forearc region during the Late Cretaceous, probably due to orthogonal subduction coupled with enhanced time-integrated growth of an extensive accretionary complex. By contrast, the volcanism migrated obliquely away from the trench in the South Shetland Islands possibly due to a highly oblique subduction vector causing much more limited accretion and possibly forearc erosion (**Smellie 2021*a***). The magmatic activity shut down progressively in a clockwise direction, commencing in Marie Byrd Land in the mid-Cretaceous (Larter *et al.* 2002). Subduction is active today (at a very slow rate) only at the northern tip of the Antarctic Peninsula, where a small ensialic marginal basin populated with numerous submarine volcanic centres opened up in response to plate boundary forces, including slab rollback (**Haase and Beier 2021**; **Smellie 2021*b***). The marginal basin includes Deception Island, one of Antarctica's most active volcanoes (**Geyer *et al.* 2021**), which underwent a major caldera collapse eruption *c.* 4 kyr ago that dispersed ash more than 4000 km in an arcuate swathe across the Scotia Sea and much of East Antarctica (Antoniades *et al.* 2018). Coincidentally, from *c.* 12 Ma an extensive back-arc mafic alkaline volcanic field developed to the rear of Graham Land in the James Ross Island region (Fig. 1f) (**Haase and Beier 2021**; **Smellie 2021*b***). It is dominated by the very large shield volcano of Mount Haddington, which is predominantly glaciovolcanic and contains an unrivalled record of the Antarctic Peninsula Ice Sheet (Smellie *et al.* 2008).

Following the progressive shut down of subduction, 'windows' opened up in the downgoing oceanic slab, allowing ingress and decompression melting of mantle unaffected by subduction metasomatism. As a consequence, several small monogenetic alkaline volcanic fields were constructed from *c.* 7.5 Ma, mainly along the flanks of the Antarctic Peninsula (Fig. 1f) (Hole *et al.* 1995). The outcrops are overwhelmingly glaciovolcanic and, like Mount Haddington, they also preserve a uniquely valuable record of the Antarctic Peninsula Ice Sheet, as well as influencing our understanding of glaciovolcanism (Smellie and Edwards 2016; **Smellie and Hole 2021**). New research suggests that melting of the downgoing slab may be involved in the generation of the slab-window basalts (**Hole 2021**).

Over a period of a few million years in the Cretaceous, Antarctica's magmatism shifted from arc-related to rift-related during the latest stage of Gondwana break-up that separated Zealandia from Antarctica (*c.* 90–83 Ma). Rare Late Cretaceous alkaline intraplate magmatism is found in southern Zealandia (Weaver and Smith 1989), including HIMU-like ocean island basalt (OIB) (Panter *et al.* 2006; Hoernle *et al.* 2020), and mafic dykes are present along the Ruppert and Hobbs coasts of Marie Byrd Land (Storey *et al.* 1999). However, the episode was largely amagmatic. The extension also probably caused widespread topographical lowering until much of the region in Marie Byrd Land (and coeval terrain in New Zealand) subsided down to, or close to, sea level (LeMasurier and Landis 1996).

Renewed extension during the Cenozoic resulted in the creation of the WARS, a very large continental rift characterized by widespread alkaline volcanism (Fig. 1d–f) (Siddoway 2008; **Smellie and Martin 2021**; **Smellie and Rocchi 2021**; **Wilch *et al.* 2021**). The rift contains numerous large and small volcanoes with basalt–trachyte, phonolite and rhyolite compositions (**Martin *et al.* 2021**; **Panter *et al.* 2021*b***; **Rocchi and Smellie 2021**). Remote sensing studies have also suggested that numerous additional volcanic centres may be widespread beneath the West Antarctic Ice Sheet, including several that may be active (Behrendt *et al.* 1994; van Wyk de Vries *et al.* 2018; **Quartini *et al.* 2021**). The origins of the volcanism are disputed, and variable roles have been inferred for deep mantle plumes and shallow thermal anomalies with associated edge flow (LeMasurier and Landis 1996; Rocchi *et al.* 2005; **Martin *et al.* 2021**; **Panter *et al.* 2021*b***; **Rocchi and Smellie 2021**). They are all linked within the broad concept of a diffuse alkaline magmatic province (DAMP), which also includes Late Cretaceous and Cenozoic volcanism in eastern Australia, Tasmania and Zealandia (Finn *et al.* 2005). The striking compositional commonality throughout the DAMP region has been explained by melting of a mantle source component inferred to underlie the entire region, with the characteristics of HIMU-like OIB. The mantle reservoir may have been emplaced as a large plume head, of late Cretaceous age or older, or lithosphere that has been metasomatized, or both sources exist (**Panter 2021**). Like alkaline volcanism in the Antarctic Peninsula, the volcanism in the WARS is also predominantly glaciovolcanic, and it has also provided uniquely important information on the development of the West and East Antarctic ice sheets (**Smellie and Rocchi 2021**; **Wilch *et al.* 2021**).

The tectonic setting of some of Antarctica's volcanoes is enigmatic, however. They include at least three small monogenetic phreatomagmatic edifices in the southern Transantarctic Mountains (upper Scott Glacier) and beneath the East Antarctic Ice Sheet, less than 300 km from the South Pole (Fig. 1e) (**Smellie *et al.* 2021**), and Gaussberg, which is an isolated pillow volcano on the East Antarctic coast far from any other expression of volcanism on the continent (Fig. 1g) (**Smellie and Collerson 2021**). The upper Scott Glacier and nearby subglacial centres are outside of the WARS and they are believed to have formed in response to the detachment and sinking of lithosphere into the convecting mantle beneath the East Antarctic Craton (**Panter *et al.* 2021*a***). The composition of Gaussberg is unique in Antarctica and very rare worldwide, being formed of ultrapotassic lamproite. Its origin is probably linked to a small deep-sourced mantle plume, distinct from the large Kerguelen plume, that incorporated a component derived from ancient subducted sediment (Murphy *et al.* 2002).

Antarctica also contains several large active volcanoes (**Geyer 2021**) (Fig. 1g). Only two have been observed in eruption (Mount Erebus and Deception Island); both have been intensively investigated (Oppenheimer and Kyle 2008; **Geyer *et al.* 2021**; **Sims *et al.* 2021**). Mount Erebus also hosts the world's only semi-permanent phonolite lava lake. The presence of relict heat (Mount Berlin, Mount Melbourne and Mount Rittmann) and abundant englacial and marine tephras sourced in Mount Takahe, Mount Berlin, Mount Waesche, Mount Rittmann and, possibly, The Pleiades indicate that many others were active in recent geological time (<10 ka: Lee *et al.* 2019; **Dunbar *et al.* 2021**; **Gambino *et al.* 2021**; **Narcisi and Petit 2021**; **Di Roberto *et al.* 2021**). Three of the volcanoes are, or have been, monitored (Deception Island, Mount Erebus and Mount Melbourne) but only one has published hazard and risk assessments (Deception Island: Bartolini *et al.* 2014; Pedrazzi *et al.* 2018; **Geyer *et al.* 2021**).

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