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 Gondwanaland, 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 Antarctic 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 glacio-volcanic province. The glacio-volcanic 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 mapped (Smellie et al. 2008; Smellie and Edwards 2016; Wilec 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; Goode 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 correlates in South Africa, Tasmania, Australia and New Zealand (Elliot et al. 2021; Elliot and Fleming 2021; Luttin 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 2012a, 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 2021a). 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 $0.5 \times 10^6$ 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 2021a, 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 widespread beneath the West Antarctic Ice Sheet, 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. 2021b; 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. 2021b; 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 volcanic centres 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 metamorphosed, 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 Gausenberg, 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. 2021a). 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 relic heat (Mount Berlin, Mount Melbourne and Mount Rittmann) and abundant englacial and marine tephra sourced in Mount Takahe, Mount Berlin, Mount Waesche, and Mount Rittmann and, possibly, The Pleiades indicate that many of those were active in recent geological time (<10 ka: Lec 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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References
Antoniades, D., Giralt, S. et al. 2018. The timing and widespread effects of the largest Holocene volcanic eruption in Antarctica. Scientific Reports, 8, 17279, https://doi.org/10.1038/s41598-018-35406-x.
Bartolini, S., Geyer, A., Martí, J., Pedrazzi, D. and Aguirre-Díaz, G. 2014. Volcanic hazard on Deception Island (South Shetland Islands, Antarctica). Journal of Volcanology and Geothermal Research, 285, 150–168, https://doi.org/10.1016/j.jvolgeores.2014.08.009.
Bay, R.C., Bramall, N.E., Price, P.B., Clow, G.D., Hawley, R.L., Udisti, R. and Castellano, E. 2006. Globally synchronous ice core volcanic tracers and abrupt cooling during the last glacial period. Journal of Geophysical Research: Atmospheres, 111, D11108, https://doi.org/10.1029/2005JD006306.
Behrendt, J.C., Blankenship, D.D., Finn, C.A., Bell, R.E., Sweeney, R.E., Hodge, S.R. and Brozena, J.M. 1994. CASERTZ aeromagnetic data reveal late Cenozoic flood basalts(?) in the West Antarctic rift system. Geology, 22, 527–530, https://doi.org/10.1130/0091-7613(1994)022<0527:CAECBC>2.0.CO;2.
Boichu, M., Oppenheimer, C., Roberts, T.J., Tsaney, V. and Kyle, P. 2011. On bromine, nitrogen oxides and ozone depletion in the tropospheric plume of Erebus volcano (Antarctica). Atmospheric Environment, 45, 3856–3866, https://doi.org/10.1016/j.atmosenv.2011.03.027.
Burgess, S.D., Bowring, S.A., Fleming, T.H. and Elliott, D.H. 2015. High precision geochronology links the Ferrar Large Igneous Province with early Jurassic ocean anoxia and biotic crisis. Earth and Planetary Science Letters, 415, 90–99, https://doi.org/10.1016/j.epsl.2015.01.037.
Choi, S.H., Mukasa, S.B., Ravizza, G., Fleming, T.H., Marsh, B.D. and Bépard, J.H.J. 2019. Fossil subduction zone origin for magmas in the Ferrar Large Igneous Province, Antarctica: evidence from PGE and Os isotope systematics in the Basement Sill of the McMurdo Dry Valleys. Earth and Planetary Science Letters, 506, 507–519, https://doi.org/10.1016/j.epsl.2018.11.027.
Di Roberto, A., del Carlo, P. and Pompilio, M. 2021. Marine record of Antarctic volcanism from drill cores. Geological Society, London, Memoirs, 55, https://doi.org/10.1144/M55-2019-29.
Dunbar, N.W., Iverson, N.A., Smellie, J.L., McIntosh, W.C., Zimmerer, M.J. and Kyle, P.R. 2021. Active volcanoes in Marie Byrd Land. Geological Society, London, Memoirs, 55, https://doi.org/10.1144/M55-2019-29.
Elliott, D.H. and Fleming, T.H. 2021. Ferrar Large Igneous Province: petrology. Geological Society, London, Memoirs, 55, https://doi.org/10.1144/M55-2018-39.
Elliott, D.H., Fleming, T.W., Kyle, P.R. and Foland, K.A. 1999. Long-distance transport of magmatism from the Jurassic Ferrar Large Igneous Province, Antarctica. Earth and Planetary Science Letters, 167, 89–104, https://doi.org/10.1016/S0012-821X(99)00043-0.
Elliott, D.H., White, J.D.L. and Fleming, T.H. 2021. Ferrar Large Igneous Province: volcanology. Geological Society, London, Memoirs, 55, https://doi.org/10.1144/M55-2018-44.
Ernst, R.E. and Youbi, N. 2017. How large igneous provinces affect global climate, sometimes cause mass extinctions, and represent natural markers in the geological record. Palaeogeography, Palaeoclimatology, Palaeoecology, 478, 30–52, https://doi.org/10.1016/j.palaeo.2017.03.014.
Finn, C.A., Müller, R.D. and Panter, K.S. 2005. A Cenozoic diffuse alkaline magmatic province (DAMP) in the southwest Pacific without rift or plume origin. Geochemistry, Geophysics, Geosystems, 6, Q02005, https://doi.org/10.1029/2004GC000723.
Fraser, C.I., Terauds, A., Smellie, J., Convey, P. and Chown, S. 2014. Geothermal activity helps life survive glacial cycles. Proceedings of the National Academy of Sciences of the United States of America, 111, 5634–5639, https://doi.org/10.1073/pnas.1321437111.
Gambino, S., Armienti, P. et al. 2021. Mount Melbourne and Mount Rittmann. Geological Society, London, Memoirs, 55, https://doi.org/10.1144/M55-2018-43.
Geyer, A. 2021. Antarctic volcanism: active volcanism overview. Geological Society, London, Memoirs, 55, https://doi.org/10.1144/M55-2020-12.
Geyer, A., Marti, A., Giralt, S. and Folch, A. 2017. Potential ash component derived from ancient subducted sediment (Murphy et al. 2002).
Geyer, A. 2021. Antarctic volcanism: active volcanism overview. Geological Society, London, Memoirs, 55, https://doi.org/10.1144/M55-2018-39.
Geyer, A., Marti, A., Giralt, S. and Folch, A. 2017. Potential ash component derived from ancient subducted sediment (Murphy et al. 2002).
Geyer, A., Marti, A., Giralt, S. and Folch, A. 2017. Potential ash component derived from ancient subducted sediment (Murphy et al. 2002).
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