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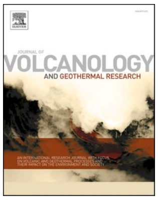

Invited review article

Volcanism in Antarctica: An assessment of the present state of research and future directions

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A R T I C L E I N F O

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A B S T R A C T

Over the past decades, significant efforts have been made to understand the nature, dynamics and evolution of volcanic systems. In parallel, the continuous demographic expansion and extensive urbanization of volcanic areas have increased the exposure of our society to these natural phenomena. This increases the need to improve our capacities to accurately assess projected volcanic hazards and their potential socioeconomic and environmental impact, and Antarctica and the sub-Antarctic islands are no exception. More than a hundred volcanoes have been identified in Antarctica, some of which are entirely buried beneath the ice sheet and others as submarine volcanoes. Of these, at least eight large (basal diameters > c. 20-30 km) volcanoes are known to be active and pose a considerable threat to scientific and ever-increasing tourism activities being carried out in the region. Despite the scientific and socioeconomic interest, many aspects of the past volcanic activity and magmatic processes in Antarctica, and current volcanic hazards and risks, remain unknown. Moreover, many of Antarctica's volcanoes preserve a remarkable history of the eruptive environment, from which multiple parameters of past configurations of the Antarctic ice sheet (AIS) can be deduced. Given the critical role that the AIS plays in regulating Earth's climate, Antarctica's volcanoes therefore can be regarded as the ground truth for current models of past climates derived from modelling and studies of marine sediments. Here, we provide a succinct overview of the evolution of volcanism and magmatism in Antarctica and the sub-Antarctic region over the past 200 million years. Then, we briefly review the current state of knowledge of the most crucial aspects regarding Antarctica's volcanic and magmatic processes, and the contributions volcanic studies have made to our understanding of ice sheet history and evolution, geothermal heat flow, as well as present-day and future volcanic hazard and risk. A principal objective is to highlight the problems and critical limitations of the current state of knowledge and to provide suggestions for future potential directions of volcanic-driven investigations in Antarctica. Finally, we also discuss and assess the importance and scope of education and outreach activities specifically relating to Antarctic volcanism, and within the context of broader polar sciences.

1. Introduction

Volcanic eruptions are among the most captivating, and yet most destructive, natural phenomena. The first volcano observatories were established at Vesuvius (Italy, 1847), Mont Pelée (Martinique Island, 1902), Kīlauea (Hawaii Islands, 1912), and Asama (Japan, 1933). The numerous volcanological studies carried out throughout the eighteenth and nineteenth centuries in these regions focused on observing,

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analysing, characterizing, and cataloguing volcanic phenomena to improve eruption forecasting and develop mitigation strategies (Lowenstern et al., 2022). During the past several decades, further efforts have been made to understand the nature, dynamics and evolution of volcanic systems, as well as to comprehend the role volcanism plays in the evolution of our planet, the origin of life, and past climate. Also, the continuous demographic expansion and the extensive urbanization of volcanic areas have increased the exposure of our society to phenomena connected to volcanic activity, raising the social concern for assessing and managing the occurrence and impact of volcanic hazards on populations, infrastructure, climate and the environment (Tilling, 2005; Erfurt-Cooper, 2010). In this sense, Antarctica (including the Antarctic islands) is no exception.

The earliest records relevant to volcanism in Antarctica include eyewitness accounts of active volcanoes in Bransfield Strait (northern Antarctic Peninsula) within a year of Antarctica being discovered and continuing throughout much of the 19th century (Adie, 1977; Smellie et al., 2023a) (Fig. 1). James Clark Ross, a British Royal Navy officer and polar explorer, also observed Mount Erebus volcano erupting on the opposite side of the continent in January 1841 (Ross, 1847). Thus began the exploration of Antarctica's volcanism, culminating in spectacular explosive activity at Deception Island between 1967 and 1970 and the discovery of a long-lasting lava lake on Mount Erebus (Figs. 1 and 2). Since then, the permanent settlement and seasonal presence of scientists, technicians, tourists, and logistical personnel close to active Antarctic volcanic areas have increased significantly (e.g., Bartolini et al., 2014; Geyer, 2021). This escalation in the amount of exposed infrastructure and population to a possible future eruption of a south-polar volcano increases the need to advance our knowledge of the volcanic and magmatic history, and future evolution of Antarctica and the sub-Antarctic region. In addition to this, volcanic studies in Antarctica have been – and will be – of relevance for understanding crucial aspects of the Earth's evolution, the interaction between ice and volcanic and magmatic activity, past environmental conditions, and the survival of life, among others.

Climate-induced sea-level rise is one of the most pressing societal

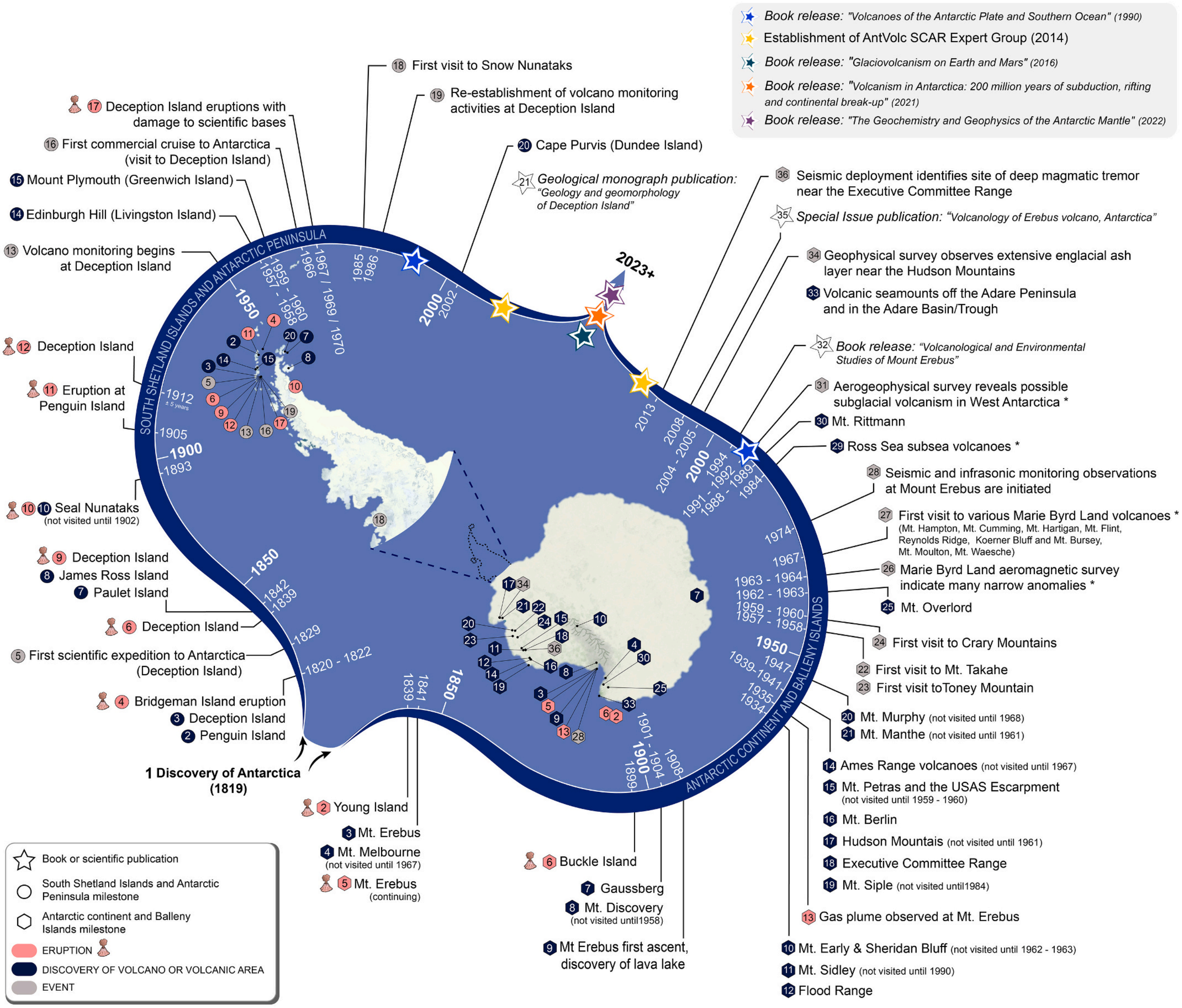


Fig. 1. Chronology of the discovery of Antarctic volcanoes and the sub-Antarctic islands, their eruptive activity and relevant scientific publications and events (see LeMasurier and Thomson, 1990; Kyle, 1994; Oppenheimer and Kyle, 2008;Smellie et al., 2021c; Martin and van der Wal, 2023 and references therein). For the sake of simplicity, the location for those events marked with an asterisk is not indicated in the map since they refer to too wide areas of the Antarctic continent (see Figure 3 for further details on the location of these areas).

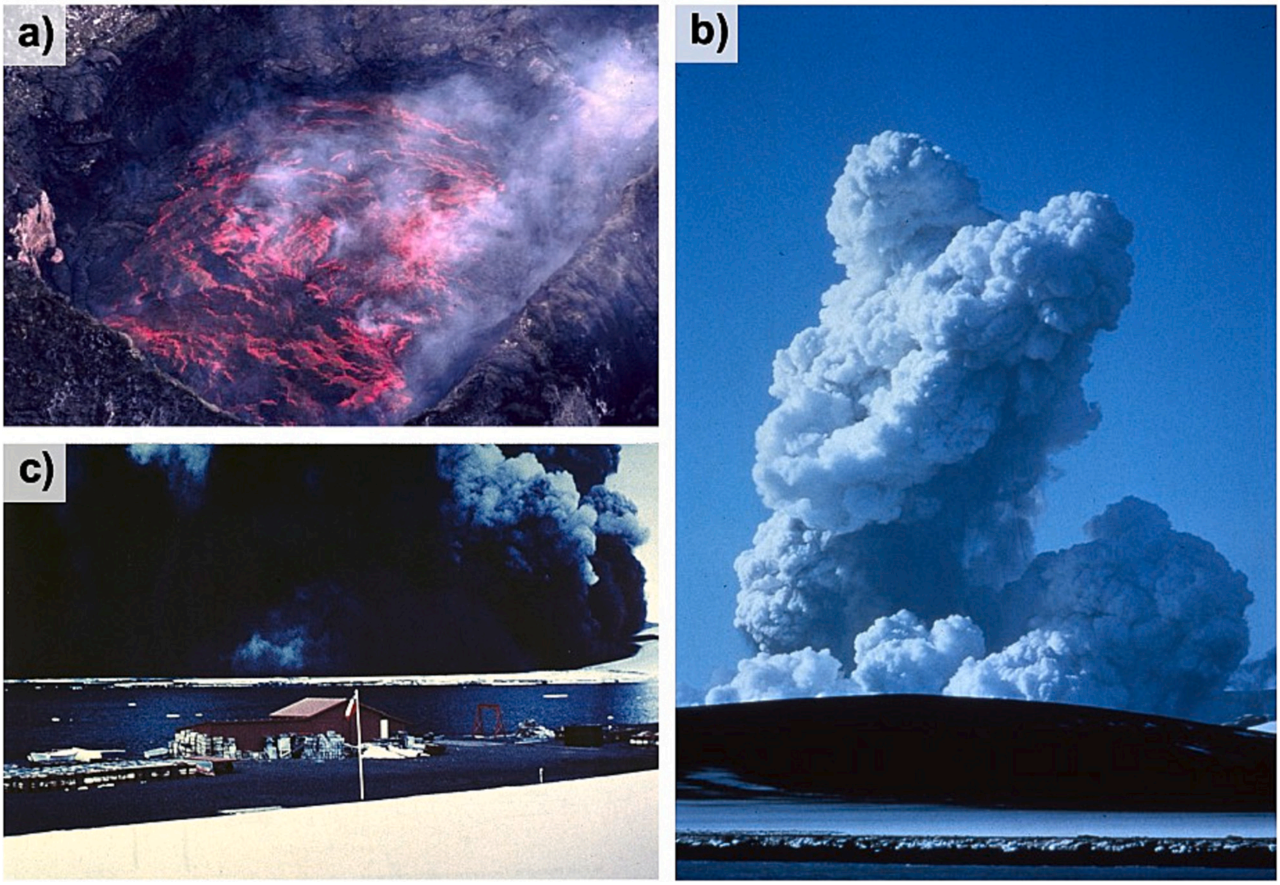


Fig. 2. (a) Image of Mount Erebus permanent lava lake in 1983 (Mount Erebus Volcano Observatory). (b) Eruptive column of Deception Island 1967 eruption (Author: British Antarctic Survey). (c) Eruptive column of Deception Island 1967 eruption observed from the Chilean Antarctic Base (Author: Chilean Navy, first published in González-Ferrán, 1995).

problems (IPCC, 2022). The rate at which Antarctic ice sheets will contribute to rising seas is a pending issue requiring immediate and ongoing research as findings inform global sea-level rise effects (DeConto et al., 2021; Kennicutt et al., 2015). Volcanological studies provide complementary and often unique insights to present and past ice sheet characteristics and drivers, such as wet versus dry basal melting via physical volcanology, geothermal heat flow via geochemistry, past-ice sheet thickness via glaciovolcanology, rates of change via tephra chronology, and lithospheric rheology and mantle evolution via petrology. These studies work in partnership with other investigative approaches such as geophysics, modelling and sedimentology such that they must be co-designed and undertaken with the same imperative driving all climate change research. To undertake this research requires people, infrastructure and transport in Antarctica, and travel to and from Antarctica. Science research stations, flight paths and research areas are, by necessity, exposed to volcanic hazard and risk from active volcanoes (Bartolini et al., 2014; Burbidge et al., 2020). Often, the only suitable building platform for an Antarctic base is on, or close to, an active volcano. Understanding and managing volcanic hazard and risk is a key imperative for volcanic research in Antarctica that is required for people to work safely on the continent. The third imperative is Antarctic-themed volcanic outreach so that the societal platform for volcanic research in Antarctica continues and flourishes.

In addition to the research described above, which can *only* be done in Antarctica, there are a number of key research areas that are *essential* components for global scientific inquiry. These encompass: (i) glaciovolcanology, including amongst the best exposures and only examples of their kind in the world; (ii) tectonism that records a diverse and dynamic history related to arc and intraplate volcanism and includes the development of one of the Earth's major trans-continental rift systems; (iii) petrogenesis of mantle and igneous rocks that supplies information on key secular changes in plate dynamics and mantle source domains for volcanism; (iv) tephra chronology that records intra-continental and globally significant events; and (v) physical volcanology that includes some of the best examples from which to elucidate explosive, effusive and depositional processes of volcanic activity.

Since Antarctica was formerly at the heart of the supercontinent Gondwana, which initiated the prolonged process of disintegration during Early Jurassic time (c. 200 Ma) (Veevers, 2012; Storey and Granot, 2021), volcanism has been particularly influential in its construction (Fig. 3). Volcanic studies have increased our understanding of how Gondwana foundered and broke up progressively, as well as how it subsequently developed with different eruptive styles and compositional types of volcanism associated with every stage in the process (e.g., Smellie et al., 2020). Regarding the interaction between ice and volcanic and magmatic activity, Antarctica also hosts the West Antarctic Rift System (WARS), the world's largest and longest-lived glaciovolcanic province (< 37 Ma; Wilch and McIntosh, 2002). The WARS formed in association with past varied configurations of the Antarctic Ice Sheet (AIS) and the nature of interactions between the AIS and the volcanism are superbly well displayed. The glaciovolcanic sequences contain a detailed record of the growth and development of the terrestrial AIS, which goes back to nearly 30 Ma. The detailed study of these sequences enables the deduction of critical parameters of past ice masses not available any other way (e.g., Smellie and Edwards, 2016; Wilch et al., 2021). Also, volcanoes active throughout the Quaternary have generated geographically widespread tephras, which are often preserved in pristine state in ice cores. Compositionally distinctive tephras offer

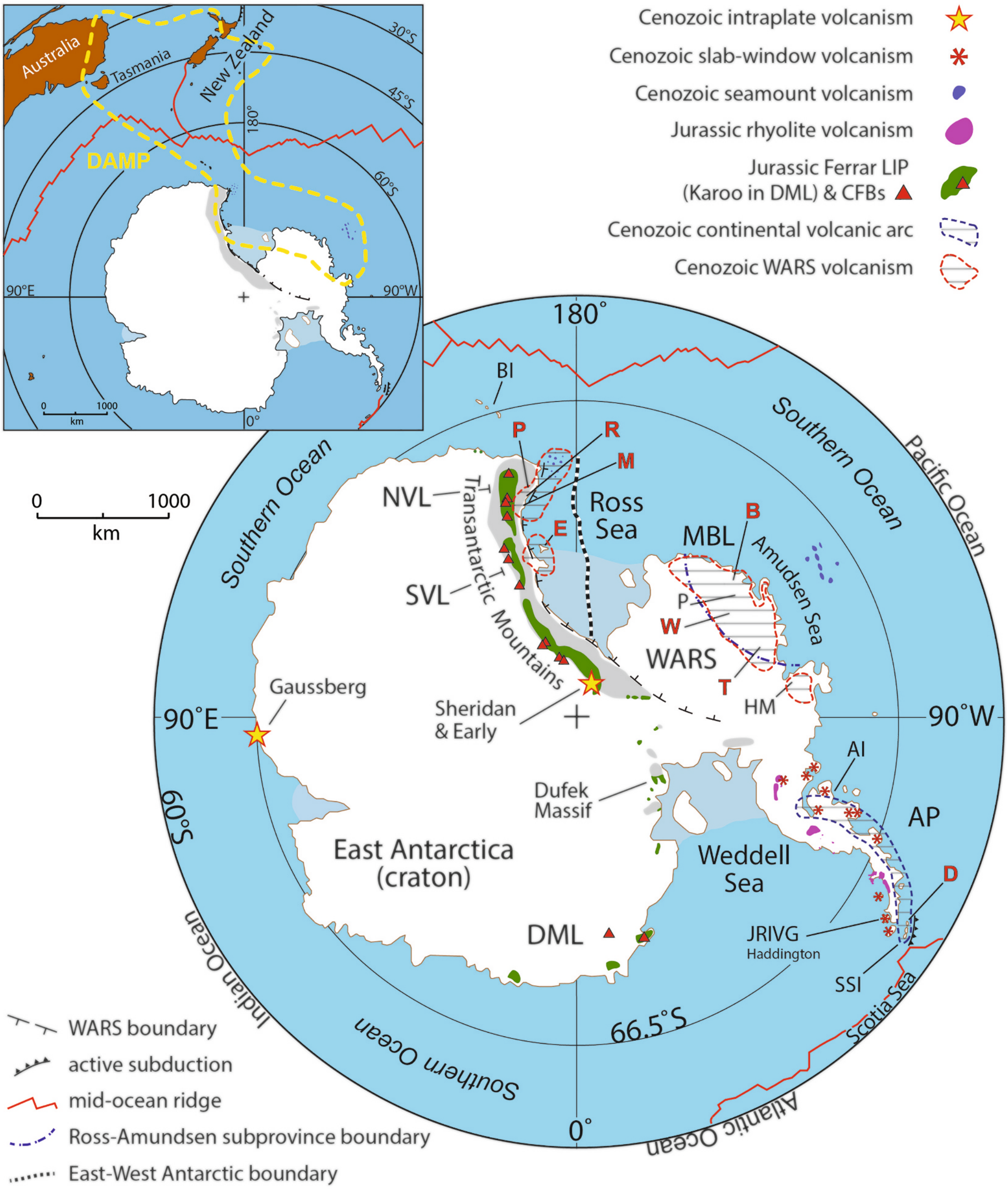


Fig. 3. Map of Antarctica showing the distribution of Mesozoic (Jurassic & Cretaceous) and Cenozoic tectonomagmatic provinces and volcanism (modified after Smellie et al., 2020). Distribution of Ferrar and Karoo Large Igneous Provinces (LIPs) and associated continental flood basalts (CFBs) after Elliot and Fleming (2021) and Luttinen (2018). Locations of Jurassic rhyolite volcanism are from Leat and Riley (2021a) The Ross-Amundsen geotectonic boundary of the West Antarctic Rift System (WARS) is after Jordan et al. (2020) and the geologic boundary between East and West Antarctica is after Tinto et al. (2019) and Jordan et al. (2020). The locations of active volcanoes indicated by bold red letters are B = Mount Berlin, D = Deception Island, E = Mount Erebus, M = Mount Melbourne, P = The Pleiades, R = Mount Rittmann, T = Mount Takahe, W = Mount Waesche. Other abbreviations are: AP = Antarctic Peninsula; Bi = Balleny Islands; DML = Dronning Maud Land; HM = Hudson Mountains; JRIVG = James Ross Island Volcanic Group (including Mount Haddington); MBL = Marie Byrd Land; NVL = north Victoria Land; P = Mount Petras; SSI = South Shetland Islands; SVL = south Victoria Land. Cenozoic WARS volcanism in MBL belongs to the Marie Byrd Land Volcanic Group (Wilch et al., 2021) and Cenozoic volcanism highlighted in NVL and SVL belongs to the McMurdo Volcanic Group (Smellie and Martin, 2021; Smellie and Rocchi, 2021). The latitude of 66.5°S is the Antarctic Circle. Inset: dashed yellow line delimits the distribution of intraplate magmatism belonging to the diffuse alkaline magmatic province (DAMP) after Finn et al. (2005).

essential stratigraphical time-lines, which are especially valuable for ice core-based environmental studies (Narcisi et al., 2005, 2010, 2012; Dunbar et al., 2008; Dunbar and Kurbatov, 2011; Narcisi and Petit, 2021). Indeed, tephra layers provide mappable datums that enable precise correlations between ice cores, as well as crucial links between marine and terrestrial environments (e.g., Hillenbrand et al., 2008, 2021; Del Carlo et al., 2015; Di Roberto et al., 2019, 2021a; Tesi et al., 2020). Petrological studies of Antarctic volcanism along with fragments of crust and mantle materials (i.e., xenoliths) that the magmas bring to the surface can provide information on geothermal heat flow and mantle rheology that are key properties in assessing past and present ice sheet stability (e.g., Whitehouse et al., 2019). The existence of active volcanoes in Antarctica throughout the Neogene and Quaternary may also have played a pivotal role in helping life to survive multiple glacial episodes during the past few tens of million years and also to undergo species diversification in spite of the dramatic climate variations (Convey et al., 2008; Fraser et al., 2014). Without volcanic activity, life in Antarctica would be considerably less rich today (Smellie, 2020).

Despite the unquestionable scientific – and social – interest, many aspects of the past volcanic and magmatic processes that occurred in Antarctica remain *terra incognita* to many Earth Scientists, probably in large part because of the remoteness, inaccessibility, and isolated and scattered nature of the available rock outcrops. Prior to c. 2000 CE (Common Era), Antarctica supported a large and diverse community of geologists and geophysicists interested in wide-ranging facets of Antarctica's volcanism. Publications were frequent, numerous and diverse, and the quadrennial Antarctic Earth Science Symposia organised by SCAR (Scientific Committee on Antarctic Research: https://www.scar.org/) always contained several volcanism-focused sessions (e.g., see papers in Adie, 1972; Craddock, 1982; Thomson et al., 1991; Yoshida et al., 1992; Ricci, 1997). However, as the geology of Antarctica became better known as a result of numerous investigations until the close of the 20th century, the numbers of volcanologists diminished and the community slowly became depauperate by comparison with earlier years, with far fewer new investigations initiated. To reverse this trend, a proposal was made to SCAR in 2014 by Massimo Pompilio and John Smellie, for the creation of an Expert Group on Antarctic Volcanism (AntVolc; https://www.scar.org/science/antvolc/home/). The objectives of AntVolc were: (i) to provide a new focus for Antarctic volcanic studies and an open forum for discussions; (ii) facilitate and increase the flow of volcanological ideas and information; (iii) sponsor workshops and symposia; and (iv) promote and mentor the next generation of scientists. Ultimately, the hope was that it would revivify interest in the subject. Important objectives of AntVolc included (1) a comprehensive volume reviewing all of Antarctica's varied volcanism over the past 200 million years (Smellie et al., 2021c), (2) a second volume doing the same for Antarctica's mantle (Martin and van der Wal, 2023), (3) the creation of a publicly accessible online Antarctic tephra database (Dunbar and Kurbatov; http://www.tephrochronology.org/AntT/about.html), and culminating in (4) the drafting of a document summarising the current state of knowledge of Antarctic volcanism, with an assessment of future research directions (this paper).

After an initial overview of the evolution of volcanism and magmatism in Antarctica and the sub-Antarctic region over the past 200 million years, this paper focuses on briefly reviewing the current state of knowledge of the most crucial aspects of Antarctica's volcanic and magmatic processes as we currently understand them. Additionally, we highlight the problems and critical limitations and provide suggestions for future potential directions for volcanic-driven investigations. In the last section, we evaluate the importance and scope of education and outreach activities specifically relating to Antarctic volcanism, and within the context of broader polar sciences. Prior to 200 Ma, the preservation of Antarctica's more ancient volcanism is patchy and substantially incomplete (e.g., see summary in Goodge, 2020) and, for practical reasons, that record is omitted from consideration here. For convenience of description, the paper is divided along disciplinary lines, whilst recognising that crossover exists between disciplines, and is encouraged.

2. Evolution of volcanism and magmatism in Antarctica: an overview

Since the Triassic, volcanism in Antarctica has been intimately linked to the dynamic tectonic history of the continent (Jordan et al., 2020; Storey and Granot, 2021). Over this period, igneous activity resulted from simultaneous tectonic processes of continental fragmentation and subduction as the Gondwana supercontinent drifted southward towards the South Pole. Variations in tectonic regime resulted in changes in magmatism associated with: (1) continental (Gondwana) breakup; (2) continent–ocean convergence and back-arc extension; (3) a transition from active to passive margin tectonics; and (4) trans-continental extension to form one of Earth's major rift systems (WARS; Smellie et al., 2020, 2021a). In addition, some widely dispersed volcanism, lacking any clear association with tectonic processes, occurs on both continental and oceanic portions of the Antarctic Plate (Kipf et al., 2014; Smellie and Collerson, 2021; Panter et al., 2021a, 2021b; Panter et al., 2022).

The initiation of Gondwana break-up volcanism at c. 190 Ma may have been aided by the effects of a large mantle plume (Storey and Kyle, 1997) and it is represented in Antarctica by two major voluminous volcanic provinces (Fig. 3): (i) the Ferrar - Karoo mafic large igneous province (LIP), with correlatives in South Africa, Tasmania, Australia and New Zealand (Luttinen, 2018; Elliot and Fleming, 2021; Elliot et al., 2021); and (ii) a series of felsic flare-ups that affected the entire Antarctic Peninsula and extended into southern South America (Chon Aike Province; Leat and Riley, 2021a,b). Contemporary with the break-up magmatism, the Pacific margin of Gondwana hosted a major long-lived continental magmatic arc, the products of which are preserved throughout the Antarctic Peninsula (Fig. 3) (Leat and Riley, 2021a,b). The magmatic activity ceased gradually in a clockwise direction, starting in Marie Byrd Land (MBL) in the mid-Cretaceous (Larter et al., 2002). Today, subduction is assumed to be active (at a very slow rate) only at the northern tip of the Antarctic Peninsula. There, a small ensialic marginal basin populated with numerous mainly submarine volcanic centres opened up in response to plate boundary forces, including slab roll-back and sinistral transtension (Haase and Beier, 2021; Smellie, 2021a). At the same time, from c. 12 Ma, a large back-arc mafic alkaline volcanic field developed outboard of Graham Land in the James Ross Island region (Fig. 3) (Haase and Beier, 2021; Smellie, 2021a). Subsequent to the gradual 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 result, numerous small monogenetic alkaline volcanic fields developed from c. 7.5 Ma, principally along the flanks of the Antarctic Peninsula (Fig. 3) (Hole et al., 1994; Smellie, 1999b; Hole, 2021).

The WARS, an extensive continental rift hosting abundant alkaline volcanoes of various sizes, developed due to renewed extension during the Cenozoic (Fig. 3) (Smellie and Martin, 2021; Smellie and Rocchi, 2021; Wilch et al., 2021). Additionally, abundant volcanic centres of uncertain origin (and largely unverified) may be widespread beneath the West Antarctic Ice Sheet (WAIS) as suggested by remote sensing studies (Behrendt et al., 1994; Van Wyk De Vries et al., 2018; Quartini et al., 2021). It has been hypothesized that their origin may be related to shallow thermal anomalies with associated edge flow or to deep mantle plumes (LeMasurier and Landis, 1996; Rocchi et al., 2005; Martin et al., 2021; Panter et al., 2021b; Rocchi and Smellie, 2021; Panter and Martin, 2022) and they are all linked geographically within the broad concept of a diffuse alkaline magmatic province (DAMP; Finn et al., 2005; Fig. 3 inset).

Finally, active volcanism in Antarctica can be grouped into: (i) hotspot-related oceanic islands (e.g., Balleny Islands: Lanyon et al., 1993; Tetzner et al., 2021); (ii) intraplate rift-related alkaline volcanism across the WARS in Marie Byrd Land (e.g., Mount Berlin, Mount Takahe; Dunbar et al., 2021), Ellsworth Land (e.g., Hudson Mountains; Dunbar et al., 2021), northern Victoria Land (e.g., Mount Melbourne, The Pleiades and Mount Rittmann; Gambino et al., 2021; Rocchi and Smellie, 2021; Smellie and Rocchi, 2021), southern Victoria Land (e.g., Mount Erebus: Martin et al., 2021; Sims et al., 2021; Smellie and Martin, 2021; Hill et al., 2022); (iii) volcanism associated with the closing stages of very slow subduction close to the north-eastern tip of the Antarctic Peninsula in the James Ross Island Group (e.g., Mount Haddington) and post-subduction volcanism further south on the Antarctic Peninsula (Hole, 2021; Smellie and Hole, 2021); and (iv) back-arc rifting volcanism related to the opening of the Bransfield Strait (e.g., Deception Island; Keller et al., 2002; Fretzdorff et al., 2004; Geyer et al., 2021). Moreover, there is evidence of subglacial volcanic activity in West Antarctica, mainly concentrated along crustal thickness gradients bounding the central WARS and in intra-rift sites with thinned, rifted crust, that has been tectonically reactivated during multiple stages of

WARS formation (Quartini et al., 2021).

3. Antarctic volcanism: a storehouse of past terrestrial environmental information

Volcanism in Antarctica occurred within geological periods characterized by contrasting climatic conditions, which changed during Earth's decline from a Hothouse World into the current Icehouse (in a 'Hothouse World', Earth's poles are ice-free and plants and animals that usually live in the tropics live near the poles; an 'Icehouse World' is one in which permanent thick ice caps cover either the North Pole, the South Pole or both). Therefore, the volcanic sequences have the potential to contain evidence for the changing environments. Although sedimentological and palaeontological techniques have thus far been the best way forward for extracting the environmental record, new volcanic-based proxies have the potential to shed further light on the eruptive environment(s). Although volcanology in general has not been applied to environmental issues of the geological past, glaciovolcanism has been developed into a sophisticated proxy for former ice (Smellie and Edwards, 2016; Smellie, 2018). As a result, deducing environmental criteria for the Icehouse World (see below) is becoming routine (e.g., Skilling, 1994; Wilch and McIntosh, 2002; Smellie, 2008, 2018; Barclay et al., 2009; Smellie et al., 2013, 2014, 2023c; Edwards et al., 2015). Volcanic investigations in Antarctica have been at the forefront of increasing our knowledge of glaciovolcanism.

Glaciovolcanic outcrops in Antarctica are characteristically very well-exposed due to a lack of obscuring effects of vegetation and chemical weathering. They are therefore prime targets for investigating glaciovolcanic eruption processes and depositional mechanisms, with access to details of the lithofacies and architecture that are often much more difficult to discern in other glaciovolcanic terrains of the world (e.g., Iceland, British Columbia; Smellie et al., 1993; Skilling, 1994; Smellie, 2008; Edwards et al., 2009). Indeed, significant advances in our understanding of glaciovolcanic eruptive and depositional processes have been made based on Antarctica's outcrops. For example, critical ice sheet parameters that are regularly obtained by glaciovolcanic investigations include: identifying localities where ice was formerly present, its age (by radioisotopic dating), thickness, surface elevation and thermal regime. Moreover, many criteria can be quantified. These data, integrated with results of palaeoclimatic interpretations using other non-volcanic proxies on same-age marine sediments, and with ice sheet and climate modelling have the potential to yield the most holistic assessment of environmental evolution in Antarctica (c.f., Smellie et al., 2009, 2023b, 2023c; Wilson et al., 2018, 2022).

Despite numerous glaciovolcanic outcrops having been documented at localities across Antarctica (e.g., Mount Petras, Marie Byrd Land (Wilch and McIntosh, 2000); James Ross Island Volcanic Group, Antarctic Peninsula (Smellie et al., 2008); Victoria Land (Smellie et al., 2011; Smellie, 2022), countless other outcrops remain unexamined or examined at a reconnaissance level only, and several issues concerning glaciovolcanism and Antarctica's paleoenvironments are unresolved. Despite recent publications (e.g., Smellie et al., 2018; Smellie et al., 2022a, 2022b; Smellie et al., 2023b; Smellie et al., 2023c; Wilch et al., 2021) many outcrops have not been visited within the last 20 years, the period in which glaciovolcanism became established as a distinctive branch of hydrovolcanism and an important palaeoenvironmental proxy (e.g., Hamilton, 1972; LeMasurier and Rex, 1989; LeMasurier and Thomson, 1990; Rowley et al., 1990; Rutford and McIntosh, 2007). Consequently, we are unaware if there are important glaciovolcanic discoveries yet to be made, what their characteristics and ages might be, and what new information they may reveal about the climatic and environmental evolution across the region. The numerous, often very well exposed and relatively accessible large volcanic centres in Victoria Land offer the highest potential for future study.

3.1. *Reconstructing the climate of terrestrial Antarctica: insights from volcanic sequences*

Non-glacial, including Hothouse conditions, are well-represented in Jurassic volcanism, mainly in the Transantarctic Mountains (East Antarctica), and in Cretaceous—Palaeogene volcanic arc sequences of the Antarctic Peninsula (Leat and Riley, 2021b; Elliot and Fleming, 2021; Elliot et al., 2021). Jurassic flood lavas in the Transantarctic Mountains are associated with lacustrine sequences that might hold crucial clues to polar non-glacial environments during the period (e.g., Elliot et al., 2021). By contrast, arc volcanic sequences are typically a very poor target for environmental studies in Antarctica due to their difficult access and pervasive hydrothermal alteration. A notable exception is the Palaeogene arc volcanic rocks in the South Shetland Islands, which represent a time period spanning the Palaeogene Hothouse — potentially including the Paleocene – Eocene thermal maximum (PETM) — and early Icehouse (e.g., Smellie et al., 2021a).

The Palaeogene Hothouse World of Antarctica has been a major target of expensive offshore drilling investigations for several decades, with limited and contested success (Hannah et al., 2001; Feakins et al., 2014). The South Shetland Palaeogene outcrops, despite the reasonably easy access and relatively little alteration compared to other arc sequences in the region, have not been included in volcanic-focussed environmental studies. However, they constitute very cost-effective targets for paleoenvironmental investigations of Antarctica's Hothouse conditions.

Currently, the few climatic indices available are derived from studies of fossil plants (e.g., Hunt and Poole, 2003; Cantrill and Poole, 2010; Fontes and Dutra, 2010) but environmental studies of the associated volcanic strata are absent. There is therefore a clear incentive to develop new volcanological and sedimentological climatic indices to create an improved understanding of the Palaeogene terrestrial environment and climate of the northern Antarctic Peninsula region. The information obtained can be used as an additional input to cross-verify climate and ice sheet models (e.g., Smellie et al., 2021d; c.f. Wilson et al., 2019; cf. Smellie et al., 2009). Despite the suggestion that the warm Eocene may have been a period with at least transient ice caps at both poles (Tripati et al., 2005), the evidence from Antarctica remains contentious (cf. Birkenmajer et al., 2005; Stickley et al., 2009; Carter et al., 2017; Smellie et al., 2021b; Smellie et al., 2021d). It is therefore an exciting opportunity to test for the presence of bipolar glaciation during the Eocene in Antarctica.

The arc-related sedimentary and volcanic sequences in the South Shetland Islands also preserve evidence for Oligocene—Miocene glacial and interglacial conditions. The thickest interglacial terrestrial records in Antarctica are preserved there and up to four glacial sequences have been identified (e.g., Troedson and Riding, 2002; Troedson and Smellie, 2002; Birkenmajer et al., 2005). However, the eruptive palaeoenvironments are currently poorly documented (e.g., Birkenmajer, 1987; Birkenmajer et al., 2002, 2005; Mozer, 2012; Mozer, 2013; Smellie et al., 2021d). For example, it has long been proposed that Oligocene volcanic strata sandwiched between glacial sedimentary sequences in the South Shetland Islands formed during interglacials (Birkenmajer, 1987, 1990; Birkenmajer et al., 2005). However, it is important to note that there is no published information on environmental factors other than an absence of evidence for contemporary glacial climates. Evidence for interglacial conditions also forms a minor but possibly widespread part of Neogene volcanic sequences interbedded with glaciovolcanic strata in Victoria Land and southern Transantarctic Mountains (Smellie and Panter, 2021; Smellie and Rocchi, 2021; Smellie et al., 2022a, 2022b; Smellie et al., 2023b, 2023c). The evidence consists of discrete volcanic units erupted under subaerial settings, which lack any evidence for coeval ice or show proof of an unconfined (i.e., non-glacial) eruptive setting (e.g., LeMasurier et al., 1994; Smellie, 2021b; Wilch et al., 2021). However, few outcrops are known so far and they have been examined only at a reconnaissance level, and little detailed information has been published (Smellie et al., 2021d; Smellie et al., 2022a, 2022b; Smellie et al., 2023b,c). It is thus unknown how common Neogene interglacial volcanic sequences are, the range of ages involved, and what the outcrops can tell us about the Antarctic interglacial climate. Interpreting them and extracting climatic indices will be challenging; new proxies shall be required to investigate the interglacial volcanic sequences. However, such studies will provide a uniquely valuable and independent counterbalance to the prevalent marine record (e.g., Levy et al., 2021), thus yielding a more holistic, coupled onshore—offshore assessment of Antarctic Neogene climatic conditions (Smellie et al., 2023c).

3.2. *Towards a fuller understanding of the evolution of the Antarctic Ice Sheet*

To this day, it is not fully known which glacial periods are recorded by glaciovolcanism in Antarctica, and what the volcanism may potentially tell us about the evolution of the Antarctic Ice Sheet in the past. With recent instrumental advances and using optimal datable material, 2-sigma errors in radioisotopic ages can be reduced to ± 5-10 ka and we can now position glaciovolcanic information much more accurately within Milankovitch glacial cycles, which will significantly increase the impact of its paleoenvironmental contribution. This has the potential to lead to much-improved assessments of ice volumes, which can in turn lead to better estimates of global sea level variations.

The possible presence of Eocene ice on Antarctica was raised by Birkenmajer et al. (2005) for outcrops in the South Shetland Islands and the studies have been cited by others in a global context (e.g., Miller et al., 2008; Tripati et al., 2005; Francis et al., 2008a, 2008b). Despite the presence of Eocene volcanic strata (e.g., Nawrocki et al., 2010), the evidence for Eocene ice is contested (Dingle and Lavelle, 1998; Smellie et al., 2021b). Numerous publications have demonstrated Eocene ice in the Arctic (e.g., Tripati et al., 2005, 2008) and proving the presence of Eocene ice in Antarctica is critically important for documenting Earth's climate evolution as well as its water inventory over time (see also Carter et al., 2017).

Glaciovolcanic studies may also provide proof that shall finally establish the evolution of basal thermal regime of the East Antarctic Ice Sheet (EAIS) during Miocene and Pliocene time. Until recently, it was postulated that a change in the thermal regime of the EAIS, from warm- to cold-based, took place in a single irreversible evolutionary step at either c. 14.5 or 2.5 Ma, based on geomorphological studies of the very ancient landscape in the McMurdo Dry Valleys, and the presence, seemingly in situ, of Pliocene diatoms in tillites in the Transantarctic Mountains laid down by wet-based ice (e.g., Lewis et al., 2007; Barrett, 2013). This paradigm is important because the thermal regime is a measure of the relative stability or dynamism of an ice mass and the ice in Antarctica exerts a controlling influence on Earth's climate system and global sea levels (Fyke et al., 2018; Zemp et al., 2019, 2020). However, the evidence derived from glaciovolcanic investigations in Victoria Land so far suggests that the ice sheet may have been *polythermal* during the Neogene and there was no single step change (i.e., the volcanic sequences erupted under spatially variable cold- and warm-based ice, without a single step-change evident; Smellie et al., 2011, 2014). Supplementary studies are urgently required to validate these results.

3.3. *Antarctic glaciovolcanic outcrops: key to understanding glaciovolcanic eruptive and depositional processes*

Few areas of the world outside of Antarctica can match the quality of exposure found in Antarctica because of its very cold and dry climate. Thus, where models for glaciovolcanic processes are constructed based on non-Antarctic outcrops, it may be possible to test and validate those models more robustly, or to create entirely new ones, based on the better Antarctic exposures. A wide range of glaciovolcanic centres and sequence types is present, more than in any other region on Earth, and sometimes several types of glaciovolcanism occur even within a single volcanic field (Smellie et al., 2023b; cf. Smellie, 2022). They include tuyas, megapillow complexes, pillow mounds, sheet-like sequences, glaciovolcanic tuff cones (tephra mounds) and large polygenetic volcanoes dominated by glaciovolcanic lava-fed deltas (fed by ʻaʻā- and pāhoehoe). In particular, glaciovolcanic ʻaʻā lava-fed deltas are currently only described from Antarctica (Smellie et al., 2013) and, because the way in which they are emplaced and how they interact with a glacial setting is not yet fully understood, could form a focus for future studies. Antarctica's pāhoehoe lava-fed deltas are also very well-exposed (Skilling, 2002; Smellie, 2006; Smellie et al., 2008) and worth further study focussed on emplacement mechanisms (e.g., Nehyba and Nývlt, 2015). Finally, Antarctica contains several very well-exposed mafic tuyas (a particularly distinctive type of flat-topped volcanic centre comprising a tuff cone and pillow lava core capped by a lava-fed delta), including the most comprehensively described example anywhere in the world (Brown Bluff: Skilling, 1994; see also Wörner and Viereck, 1987; Smellie and Hole, 1997; Giordano et al., 2012; Smellie and Rocchi, 2021; Wilch et al., 2021). The long-lived polygenetic Antarctic centres with lava-fed deltas, particularly those in Victoria Land and James Ross Island in the Antarctic Peninsula (Fig. 4), shall prove important in providing additional especially well-exposed examples with which to compare and contrast with others in more northerly latitudes (e.g., Smellie et al., 1993, 2011, 2013, 2023b; Smellie and Hole, 1997; Skilling, 1994; Smellie, 2006, 2008).

4. Petrology and geochemistry of Antarctic volcanic rocks

The petrological study of Antarctic volcanism is important in many ways including contributions to: (i) geophysical interpretations of the physical and chemical properties of the crust and upper mantle; (ii) constraining the age of the lower crust and uppermost mantle; (iii) understanding the stability of continental ice sheets and assessing volcanic hazards; and (iv) providing insight on the petrogenesis of igneous rocks worldwide.

The initial gathering and assembly of petrological information on volcanic rocks in Antarctica occurred between 1900 - 1960 and documented their occurrence, distribution, and variety (e.g., Prior, 1902, 1907; Knowles, 1945; Smith, 1954; Harrington, 1958; Gunn and Warren, 1962). In the 1970s and 1980s more detailed studies focused on the age and geochemistry of volcanism (e.g., Sun and Hanson, 1975; Armstrong, 1978; Kyle, 1981; Kyle et al., 1983; González-Ferrán, 1985; Smellie, 1987; LeMasurier and Rex, 1989), with most results collated in a seminal American Geophysical Union, Antarctic Research Series publication, "Volcanoes of the Antarctic Plate and Southern Oceans" (LeMasurier and Thomson, 1990). Since then, there have been significant advances in our understanding of the origin and evolution of magmas, facilitated in Antarctica by new exploration and more complete geochronological and geochemical data sets (e.g., Smellie et al., 2021b,c and references therein). However, despite the major improvements that have been made towards our understanding of the causes and petrogenesis of magmatic systems in Antarctica, there are still many critical issues left to be resolved. Moreover, addressing outstanding problems in Antarctica has application in the understanding of magma genesis in a diversity of tectonic environments globally. For example, rift-related Mount Erebus is one of the world's most active phonolitic volcanoes, with a permanent convecting lava lake in its summit crater, and further characterization of the petrology of this easily accessible open magmatic system may benefit numerous studies worldwide (Oppenheimer and Kyle, 2008; Moussallam et al., 2015); although not included in this review, the lava lake on Mount Michael, Saunders Island, in the sub-Antarctic South Sandwich Islands (Lachlan-Cope et al., 2001; Gray et al., 2019; Liu et al., 2021), is an alternative opportunity for magmatic open-vent studies, particularly insights gathered from combined geophysical and geochemical monitoring of observed activity (e.g., Edmonds et al., 2022).

Fig. 4. Beautifully exposed Pleistocene pāhoehoe lava-fed delta on James Ross Island, northern Antarctic Peninsula. The delta is glaciovolcanic and shows a well-exposed passage zone (planar junction separating lower orange stratified tuff breccias from upper grey lavas). The over-thickened capping pāhoehoe lavas contain several dark-coloured massive breccia zones formed during multiple stages of rise of the coeval meltwater lake surface, a diagnostic feature of glacially-emplaced lava-fed deltas (see Smellie, 2006, for further information).

4.1. Magmatism—tectonism relationships in Antarctica: current knowledge and open questions

Since the Triassic, the variety of tectonomagmatic settings represented in Antarctica has produced a diversity of erupted compositions ranging from basalt to rhyolite, encompassing both alkaline and sub-alkaline magma series and even including rare ultrapotassic series (e.g., lamproite; Smellie and Collerson, 2021) and a single occurrence of (Cambrian) carbonatite (Hall et al., 1995). The compositional diversity can ultimately be traced back to differences in the mantle source and the conditions that promoted melting (Panter et al., 2021a; Panter and Martin, 2022). This magmatism—tectonism relationship is deduced through the study of mafic igneous rocks (e.g., basalt with low SiO_2 and high MgO, Cr and Ni concentrations), with wide-ranging geochemical characteristics permitting discrimination by tectonic setting (Fig. 5).

The differentiation of mafic magmas in the Jurassic produced widespread rhyolite-rhyodacite volcanism on the Antarctic Peninsula, representing the southern extent of the voluminous Chon-Aike province of Patagonia (Leat and Riley, 2021a). It also produced the evolved hypabyssal intrusive complex of Butcher Ridge. These are the most voluminous silicic components of the overwhelmingly mafic Ferrar—Karoo large igneous province (LIP; Nelson et al., 2019; Elliot and Fleming, 2021). The Jurassic within-plate tholeiitic flood basalts that comprise the Ferrar–Karoo LIP were likely the result of melting facilitated by active subduction that was coincident with an active mantle plume (Luttinen, 2018; Choi et al., 2019; Elliot and Fleming, 2021). However, some aspects of their origin are still unclear. Petrological information integrated with detailed mapping, chronology, stratigraphy, and rock magnetics can elucidate the location of the eruptive centres and provide insight on processes of magma transport and emplacement mechanisms in a LIP in general and the Ferrar–Karoo LIP, in particular (Leat, 2008). Additionally, comprehensive geochemical and isotopic investigations of relatively unfractionated Ferrar-Karoo LIP rocks can document whether a single mantle source domain is responsible for the magmatism or if heterogeneities exist, and if they do, how they vary spatially.

Antarctic Peninsula Cretaceous–Miocene calc-alkaline volcanism was generated by the melting of subducted slab material and/or the melting of subduction-modified mantle wedge materials (Leat and Riley, 2021a). Later post-subduction (Miocene to present day) mafic alkaline volcanism along the Antarctic Peninsula was produced by the melting of upwelling asthenosphere enabled by slab-window tectonics (Hole et al., 1994; Haase and Beier, 2021;Anderson et al., 2023) or the melting of pyroxenite in the subducted lithosphere (Hole, 2021). In this sense, it is not fully clear how the tectonic conditions transitioned from an active arc to a passive margin and effected a complementary change in Antarctic Peninsula magmatism (Barker, 1982). Significant questions remain as to the timing and relationship between the end of subduction, slab-window formation, and alkaline magma genesis (Altunkaynak et al., 2022). The chronology of ridge-trench collisions is well established (Larter et al., 2002), but a comprehensive chronology of post-subduction volcanism is lacking (Hole, 2021), and further petrological investigations are needed to resolve conflicting hypotheses for melt sources (e.g., upwelling asthenosphere vs. mantle wedge vs. oceanic lithosphere) and the conditions of melting.

Intraplate alkaline magmatism associated with the WARS was initiated in the Middle Eocene (Tonarini et al., 1997; Rocchi et al., 2002), although most of the volcanism occurred since the Early Miocene

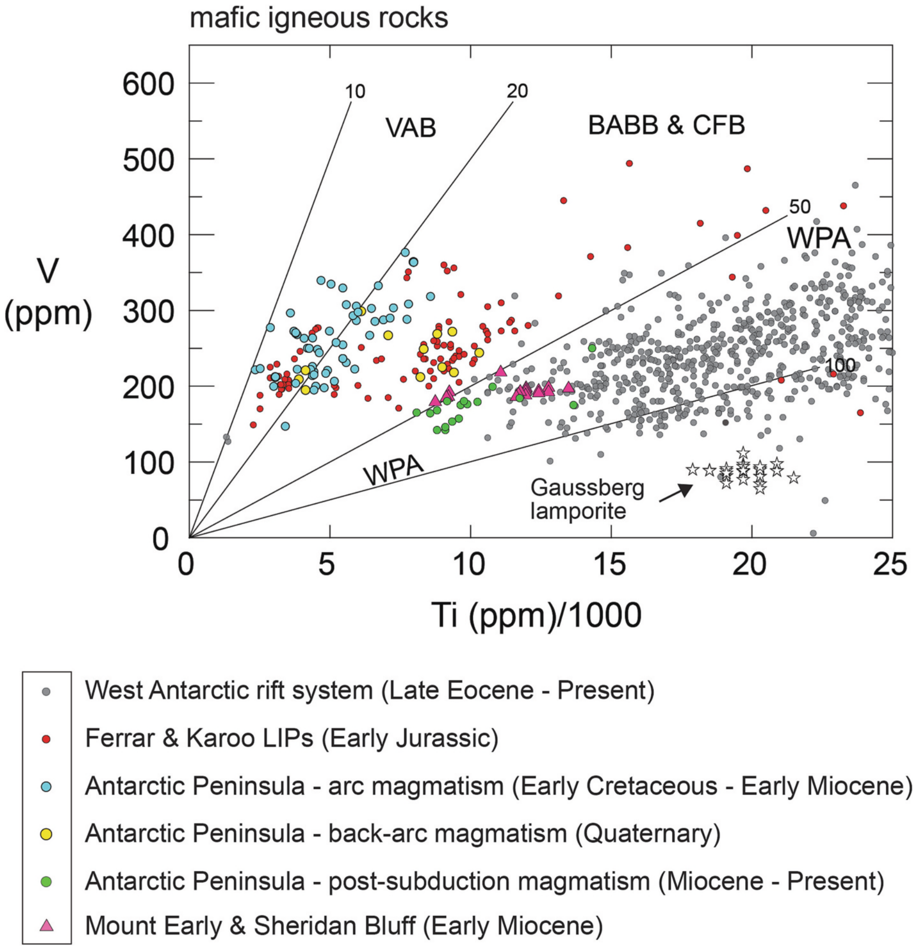


Fig. 5. Plot of mafic igneous rock compositions from Antarctica and their tectonomagmatic associations (modified from Panter and Martin, 2022). Mafic samples are restricted in SiO_2 between 40 and 54 percent by weight (wt.%) and MgO between 5 and 15 wt.%. All analyses are normalized to a 100% volatile-free basis. Mafic compositions plotted on a parts per million (ppm) Ti versus V diagram with tectonomagmatic associations from Shervais (1982). Field labels between lines of equal proportions are volcanic arc basalt (VAB), back-arc basin basalt (BABB), continental flood basalt (CFB) and within plate alkaline (WPA) basalt. Data sources for Antarctic mafic samples for the WARS are from Martin et al. (2021), Rocchi and Smellie (2021) and Panter et al. (2021a), which are compilations of previously published and unpublished data sets for the Ross Sea and Marie Byrd Land regions of the rift. Please refer to these publications for original data sources. Samples for the Ferrar and Karoo LIPs and arc magmatism from the Antarctic Peninsula are from the GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/), samples for back-arc magmatism from the Bransfield Strait, Antarctic Peninsula are from Keller et al. (2002) and the compositions for post-subduction magmatism on the Antarctic Peninsula are from Hole (2021) and the GEOROC database. The compositions of ultramafic lamprophyre dikes from the Ferrar LIP are from Riley et al. (2003) and lamproite pillow lava compositions from Gaussberg in East Antarctica provided by Murphy et al. (2002). Basaltic compositions from Sheridan Bluff and Mount Early are from Panter et al. (2021b).

(Martin et al., 2010; Panter, 2021; Wilch et al., 2021). Geochemical and isotopic signatures suggest that WARS volcanism is sourced from mantle domains that differ between the Victoria Land and Marie Byrd Land sectors of the rift. In Marie Byrd Land, magmatism results from plume materials variably mixed with subduction-modified mantle (LeMasurier et al., 2016; Panter et al., 2021a; Panter and Martin, 2022); whereas magmatism in Victoria Land is best explained by intraplate dynamics and melting of asthenospheric and metasomatised lithospheric sources (Martin et al., 2021; Rocchi and Smellie, 2021; Panter and Martin, 2022).

In the WARS, evolved compositions include silica-undersaturated phonolite and silica-saturated to oversaturated trachyte and alkali rhyolite, plus rare pantellerite and comendite (Panter, 2021). The divergence in silica-saturation with evolution is explained by a thermal barrier in Petrogeny's Residua System (Tuttle and Bowen, 1958; Hamilton and MacKenzie, 1965) that dictates whether basaltic melt will fractionate towards the thermal minimum of silica-oversaturation (rhyolite) or the thermal minimum of silica-undersaturation (phonolite). The coexistence of both undersaturated and oversaturated lineages at major volcanoes (e.g., Mounts Sidley and Morning) demonstrates that the thermal barrier was breached in these systems. High-pressure fractionation dominated by the removal of silica-deficient amphibole (LeMasurier et al., 2003, 2011, 2018) or crystal fractionation accompanied by the assimilation of silica-rich crust (Kyle et al., 1992; Panter et al., 1997; Sims et al., 2008; Martin et al., 2013; Kim et al., 2019) have been proposed to generate quartz-normative and quartz-bearing compositions in the WARS. Today, there are still many aspects regarding the WARS volcanism and magmatism that need to be clarified, including by comparison with other major continental rift systems, which will mutually benefit from petrological studies. For instance, alkaline volcanism in the northern Ross Sea is remarkable as it occurs contemporaneously across oceanic and continental crust (Panter et al., 2018(; Durkin et al., 2023) and this occurs only in two other locations in the world: east Africa to Indian Ocean (O'Connor et al., 2019) and the Cameroon Volcanic Line, west Africa to Atlantic Ocean (Ngwa et al., 2017).

The Early Miocene volcanoes of Mount Early and Sheridan Bluff, located in the upper Scott Glacier of the central Transantarctic Mountains, are isolated by more than 1000 km from all other exposed Cenozoic volcanic centres (e.g., Smellie et al., 2021e). The Quaternary

Gaussberg volcano is even more isolated; it is a small nunatak composed of lamproite pillow lavas located on the Wilhelm II Coast of East Antarctica (e.g., Smellie and Collerson, 2021). Although the cause of melting is unknown, the isotopic and geochemical signatures at Gaussberg indicate contributions from ancient sediments subducted and recycled from the mantle transition zone (Murphy et al., 2002; Zhang et al., 2019; Smellie and Collerson, 2021). In contrast, melting to produce alkaline and tholeiite compositions in the upper Scott Glacier may have been facilitated by the detachment, sinking and heating of metasomatized continental lithosphere (Shen et al., 2017; Licht et al., 2018; Panter et al., 2022).

4.2. *Towards a fuller understanding of the mantle beneath Antarctica*

Complementary to the above is the identification and characterization of possible Late Cretaceous and Late Cenozoic mantle plumes as well as the age, extent, character, and cause of metasomatism beneath West Antarctica. Addressing these questions requires a comprehensive geochemical and isotopic characterization of relatively undifferentiated volcanic rocks and mantle xenoliths, targeting key compositional criteria from which to identify the different source domains. Whether volcanism is caused by 'bottom-up' (deep mantle upwellings) or 'top down' (tectonic drivers) processes remains a subject of vigorous debate in Antarctica and for intraplate volcanism globally.

A further topic of interest that needs to be addressed to fully understand the mantle beneath Antarctica includes how its geophysical and geochemical character domain(s) compare with mantle found beneath the adjacent and once contiguous landmasses of Zealandia, Australia, South America, India, and South Africa. These comparisons along with that of mantle beneath the developed ocean basins, are critical for tectonic plate reconstruction and understanding of deep mantle dynamics.

4.3. *Understanding the response of volcanism and magmatism to glacial—interglacial cycles*

Although it has not yet been fully demonstrated in Antarctica, a connection between glacial loading/unloading and volcanic activity has been identified in other glaciated terrains such as Iceland (e.g., Hardarson and Fitton, 1991; Schmidt et al., 2013; Maclennan et al., 2002), Russia (e.g., Bigg et al., 2008) and Eastern California (e.g., Jellinek et al., 2004). Glacial Isostatic Adjustment (GIA) is by far the strongest short-term forcing function on the geometry of the lithosphere. Since at least 34 Ma ago, ice sheets in Antarctica have loaded and unloaded the crust repeatedly, in a sequence of events for which we only have indirect proxies and model constraints. The changing surface load associated with the ice sheet growth/decay (e.g., due to melting or ice-front disintegration) leads to modifications in the lithospheric stress state which can influence the degree of partial melting in the upper mantle and magma residence time in the crust (Albino et al., 2010; Sigmundsson et al., 2010; Lucas et al., 2022); both of which can be evaluated petrologically. In Antarctica, volcanic activity has been concurrent with dynamic changes in the AIS extent and thickness (e.g., Naish et al., 2009; Pollard and DeConto, 2020). Consequently, it is fundamental to advance our understanding of magmatic—cryospheric feedback by establishing greater numbers of higher-resolution and higher-precision age correlations between glacial cycles and volcanic activity in outcrop, in ice-proximal sediment cores (e.g., Nyland et al., 2013) and in ice cores (e.g., Iverson et al., 2017b). Explicitly, it is necessary to understand how ice sheet loading and unloading influenced melt productivity and eruptibility of Late Cenozoic volcanism within West Antarctica and the margins of East Antarctica.

5. Tephra and tephrochronology studies: a window into the past

Tephra (i.e., all clastic materials resulting from explosive volcanic eruptions) are products of volcanic events emplaced essentially instantaneously across vast areas and in all depositional environments. Even relatively low-energy eruptions are capable of injecting significant amounts of ash into the atmosphere, which can be dispersed by dominant winds and deposited over millions of square kilometres (e.g., Matthews et al., 2012; Dunbar et al., 2017).

Tephra can be characterized in very high detail (descriptions of the texture, morphology of ash particles, mineral assemblage, and single glass shard major and trace element geochemistry, isotopes) and their age determined with high precision using different methods (e.g., by ^{40}Ar-^{39}Ar or by indirect ^{14}C dating of the host sequences). These features make tephra perfect time-stratigraphic marker horizons and invaluable tools for the dating, correlation and synchronization of paleoclimate and environmental proxy records (Lowe, 2011; Freundt et al., 2021 and references therein). The results of tephrochronology studies allow the subsequent correlation and synchronization of individual tephra markers within different archives (e.g., marine, lacustrine, peat, ice) and across large distances (Lowe, 2011; Lowe and Alloway, 2015; Lane et al., 2017; Lowe et al., 2017). Additionally, in non-volcanic deposits (e.g., in marine or lacustrine biogenic sediment sequences), the study of tephra records helps to constrain the timing and rates of geological processes (e.g., Davies, 2015; Antoniades et al., 2018; Oliva et al., 2019).

In volcanology, tephrochronological studies are also fundamental in reconstructing the timing and tempo of past eruptions, their magnitude and dynamics, and the dispersal of erupted products (e.g., Shane, 2000; Lowe, 2011; Albert et al., 2012; Fontijn et al., 2014; Ponomareva et al., 2015). This information is complementary to that obtained from near-source volcanic sequences, and both contribute to the construction of a more complete record of explosive volcanic activity through time and help to trace the physical and petrochemical evolution of magmatic system(s) (e.g., Paterne et al., 1990; Allan et al., 2008). These two aspects are fundamental when deciphering possible relationships between large explosive volcanic eruptions and climate or, in turn, between glacial loading/unloading during glacial and interglacial periods and potentially enhanced volcanic activity.

5.1. *Tephra layers in the continental archives of Antarctica*

Tephrochronology has been widely used as a dating, synchronization and correlation tool between ice cores drilled in different locations of Antarctica in the framework of scientific projects aimed at providing information about past climatic and environmental changes. Many tephra and cryptotephra (i.e., layers of volcanic ash not visible to the naked eye) have been detected in deep ice sequences of East and West Antarctica, for example, at Dome Fuji, Vostok site, Taylor Dome, Siple Dome, Talos Dome and EPICA-Dome C, and in mid-depth to shallow ice cores such as Styx glacier, Roosevelt Island (RICE), and WDC05, WDC06A44 and GV7 sites (Narcisi and Petit, 2021 and references therein; Piva et al., 2023) (Fig. 6). Tephra layers have also been found in blue-ice in East Antarctica at Allan Hills (Borisova et al., 2020), Frontier Mountain, Brimstone Peak (Lee et al., 2019) and Mount DeWitt (Narcisi and Petit, 2021 and references therein), and as englacial tephras associated with Marie Byrd land volcanoes (Wilch et al., 1999; Hillenbrand et al., 2008). Similarly, tephra layers are common in lacustrine sequences of the South Shetland Islands and South Orkney Islands in Antarctica (Hodgson et al., 1998; Lee et al., 2007; Antoniades et al., 2018; Hopfenblatt et al., 2022 and references therein). Unfortunately, ice sequences of Antarctica cover a relatively limited period, typically only a few thousand years. However, the longest ice record (Epica-Dome C) covers the last c. 800 ka (Parrenin et al., 2007; Bazin et al., 2013) and the oldest age found in the blue-ice record goes back to c. 2.7 Ma at Allan Hills (Yan et al., 2019).

Besides their role as chronostratigraphic markers, englacial tephra layers have provided important datasets that complement the information obtained from proximal volcanic records and they may greatly improve our knowledge of the eruptive history of Antarctic volcanoes

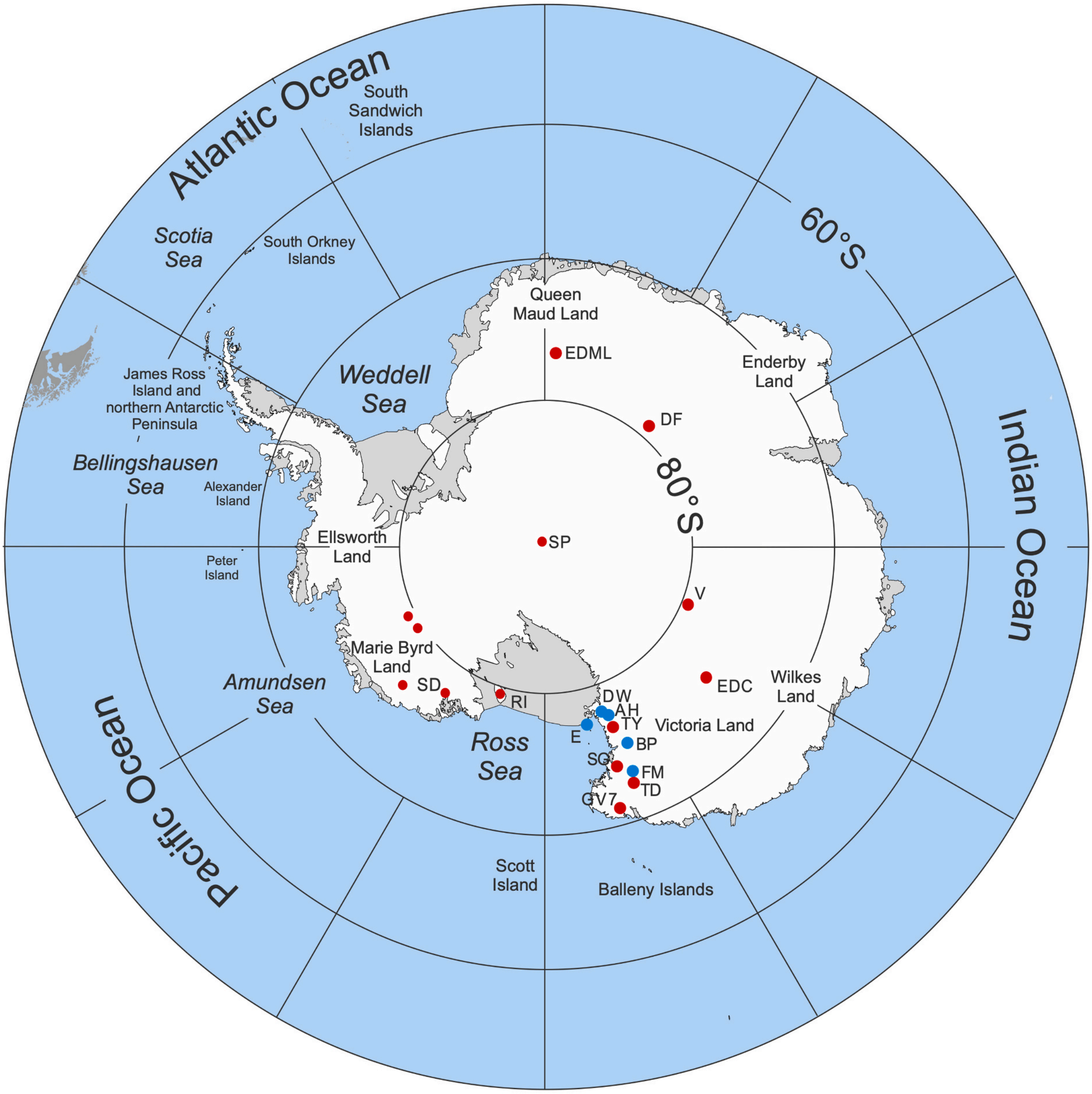


Fig. 6. Map of Antarctica with deep and shallow ice core, and other tephra records locations mentioned in the text. Ice cores (red dots): EPICA-Dome C (EDC), EPICA-Dronning Maud Land (EDML), Dome Fuji (DF), Roosevelt Island (RI), Siple Dome (SD), Talos Dome (TD), Taylor Dome (TY), Vostok (V), Styx Glacier (SG) and GV7. Other tephra occurrence (blue dots): Erebus flank (E), Mount DeWitt (DW), Allan Hills (AH), Brimstone Peak (BP), Frontiers Mountain (FM), Edisto Inlet (TR17-08) and Ross Sea (U1524).

(Smellie, 2002a; Harpel et al., 2008; Iverson et al., 2014; Lee et al., 2019; Hopfenblatt et al., 2022). The published tephrochronological studies of Antarctic ice records indicate that most of the observed tephra layers originated from Antarctic volcanoes, mainly from the South Atlantic region and, particularly, from the South Shetland and South Sandwich Islands (e.g., Smellie, 1999a; Del Carlo et al., 2018; Narcisi and Petit, 2021). Volcanoes in Marie Byrd Land and Northern Victoria Land are also very productive sources of englacial tephra (e.g., Del Carlo et al., 2018; Lee et al., 2019; Narcisi and Petit, 2021). By contrast, only a few englacial tephra layers appear to be derived from extra-Antarctic sources (e.g., South America and New Zealand). However, except for rare examples (Dunbar et al., 2017), attributing tephras to extra-Antarctic sources is difficult since the published analyses are generally based on low-quality data (e.g., major elements with very low total oxide weights), or they were obtained on extremely small particles (a few microns in diameter). They need much more extensive geochemical fingerprinting for their validation (e.g., trace element data).

5.2. *Tephra layers in the marine environment of the Southern Ocean*

In the last decade, the marine sediment sequences of the Southern Ocean have provided a very important archive of tephra complementary to the continental record. Besides their relevance for volcanological reconstructions, marine tephra represent a priceless chronological tool for establishing independent time-stratigraphic correlation and synchronization between continental ice-archives and marine sediments (Fig. 7). This, in turn, is crucial for a better understanding of the nature of connections and coupling processes between atmospheric conditions, ice sheets, ocean dynamics, marine sedimentary systems and climate change (Di Roberto et al., 2019).

Numerous tephra and cryptotephra layers have been found intercalated in marine sediment cores of the Southern Ocean surrounding

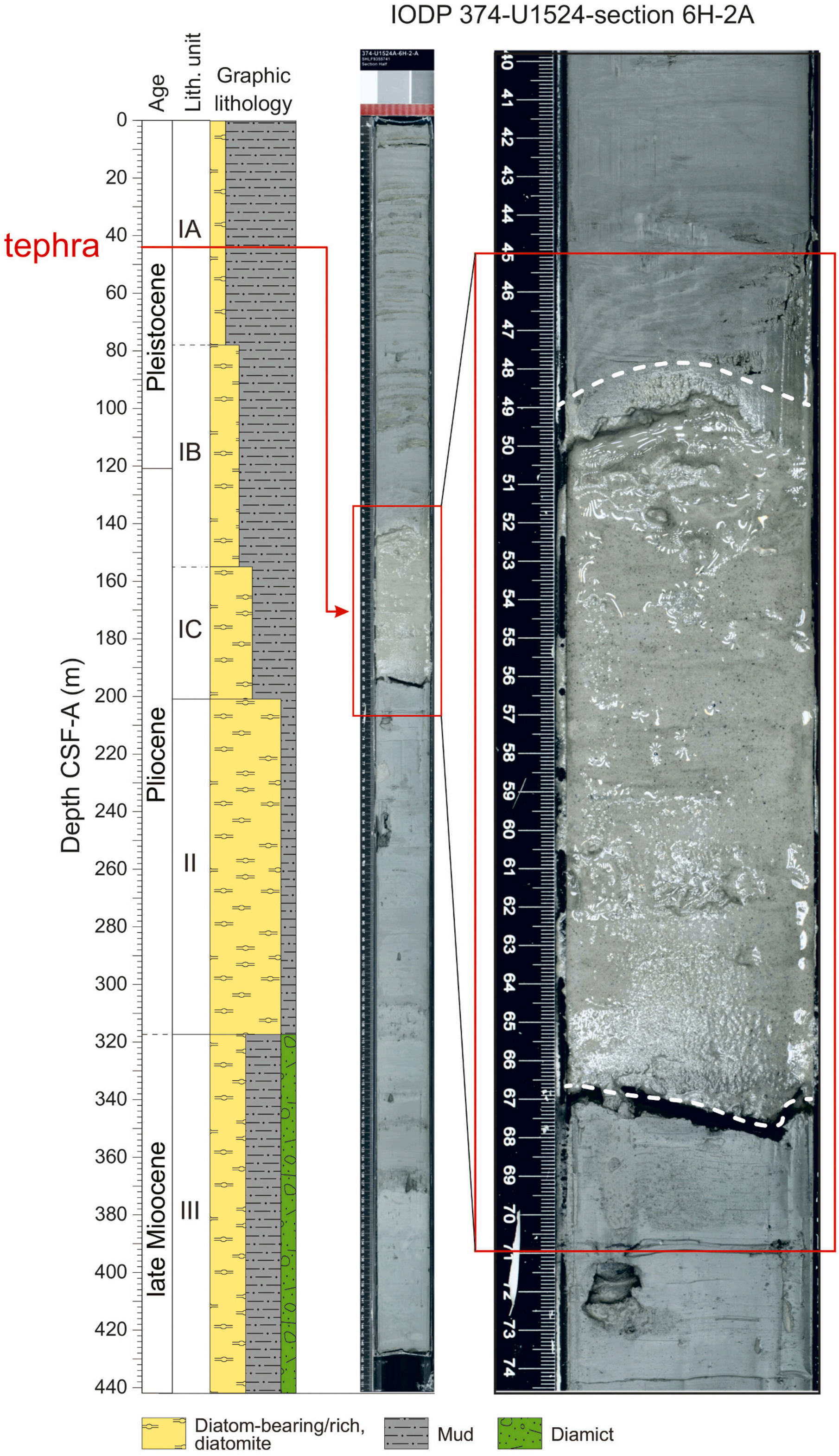


Fig. 7. Example of marine tephra layers. Photographs highlight a thick ash layer found in 6H-2A core section in IODP 374 drilling at site U1524A in the Ross Sea. The rhyolite tephra derives from a caldera-forming eruption of the Chang Peak volcano summit caldera, in the Marie Byrd Land, more than 1300 km from the site U1524. ^{40}Ar-^{39}Ar data gave a best age estimate of 1.282 ± 0.012 Ma (Di Roberto et al., 2021a, 2021b).

Antarctica (e.g., Licht et al., 1996; Colizza et al., 2003) and dedicated studies have been carried out for their characterization (e.g., Moreton and Smellie, 1998; Smellie, 1999a; Hillenbrand et al., 2008; Del Carlo et al., 2015; Oppedal et al., 2018; Di Roberto et al., 2019, 2020, 2021a, 2023). A comprehensive review was recently published by Di Roberto et al. (2021a) that highlights the importance of marine tephra for volcanological reconstructions and as chronological tools. Marine sediment sequences, in fact, often offer the opportunity to study very expanded and near-complete volcanological records tracing back to, at least, 26 Ma (Di Roberto et al., 2021a). These records are no longer present in the source volcanoes in Antarctica due to ice-covering or erosion by subsequent geological events. In recent years, many important chronological markers have been added to the sedimentary record of the Ross Sea (e.g., Del Carlo et al., 2015; Di Roberto et al., 2019, 2020, 2021b, 2023; Torricella et al., 2021). For example, tephra were discovered that were sourced from at least five previously unknown large Plinian eruptions at Mount Rittmann volcano (Northern Victoria Land) since the Late Pleistocene (Del Carlo et al., 2015; Di Roberto et al., 2019, 2023; Torricella et al., 2021). Recently, cryptotephra from three previously unknown explosive eruptions of Mount Melbourne volcano were also detected in marine sequences in Edisto Inlet (northern Victoria Land) and were dated to between the 3rd and 4th centuries CE (Di Roberto et al., 2023).

5.3. *Current challenges of Antarctic tephra and tephrochronology studies*

The most ambitious challenge for tephrochronology in Antarctica is to continue generating more cross-correlations between archives that integrate ice core, blue-ice, marine and terrestrial records, similar to what was done in the North Atlantic region by the INTIMATE network (Björck et al., 1998; Walker et al., 2001; Alloway et al., 2007), in order to correlate geological and climatic events in the various environments. To achieve this objective, it is necessary to construct a more comprehensive regional volcanic event stratigraphy with the highest possible resolution. This entails thorough profiling of a maximum number of tephra deposits, utilizing both major and trace element geochemical fingerprints, as well as exploiting textural and morphological characterisation as an independent correlation tool alongside geochemistry.

Furthermore, it will be highly beneficial that Antarctic tephra data (including textural, morphological, mineralogical and geochemical data – including the raw analyses –, and age) are collected into an open-access database to support subsequent multidisciplinary research projects. Currently, the AntT database (Dunbar and Kurbatov; http://www.tephrochronology.org/AntT/about.html) includes only a portion of the available data, including many of the tephra found in deep ice cores and blue-ice areas and a few from marine sequences of Antarctica. The establishment of such a database, which should also include data from proximal tephra exposures, would improve both the cross-correlations between archives and the correlation of tephra layers between sites located at great distances.

Concerning the correlation process itself, the nature of tephra layers – particularly distal ones – often poses limitations for their analysis due to quality issues with the data. Firstly, the frequent absence of minerals suitable for direct dating, particularly in cryptotephra, makes them useful as stratigraphic markers but not for dating. Fixing the precise age of these stratigraphic markers will establish the timing of the source eruption and help in using tephra and cryptotephra as a key tool for the high-precision dating of sequences and finally for the integration of different proxy archives. Secondly, the fine-grained nature of volcanic ash frequently makes electron microprobe (EPMA) and laser-ablation inductively-coupled plasma mass-spectrometry (LA-ICP-MS) analyses challenging. In recent years, the development of new instruments and procedures highlight the potential to acquire reliable major and trace element data even on small glassy fragments (<10 μm, under appropriate analytical conditions). In particular, improvements in trace element analysis are promising for discriminating tephra sources and determining reliable correlations when major element results alone are not sufficient. In the future, applying up-to-date and consistent analytical and data-treatment procedures (e.g., principal component analysis, Euclidean similarity coefficients, etc.) is highly recommended for unambiguously fingerprinting tephra, whether in Antarctica or elsewhere (e.g., Hayward, 2011; Riede and Thastrup, 2013; Hall and Hayward, 2014; Iverson et al., 2017a; Hopkins et al., 2021; Wallace et al., 2022).

In general, the timing of volcanic activity in Antarctica, the mineralogy and the glass geochemistry (single-shard major and trace element compositions) are, unfortunately, only available for a limited number of volcanoes. New geological surveys targeting pyroclastic deposits on Antarctic volcanoes, accompanied by radioisotopic dating and full analytical fingerprinting are strongly encouraged. In many cases, samples exist in national archive collections that might facilitate the process, at least as pilot studies to assess whether further investigation is required. The archived collections are an important and accessible resource open to the entire Antarctic scientific community (e.g., Polar Rock Repository, https://prr.osu.edu; NSF Ice Core Facility, https://icecores.org; Oregon State University Marine and Geology Repository, https://osu-mgr.org).

6. Geophysical studies in Antarctica

Most of Antarctica is covered by extensive ice or is under water, limiting direct access to much of the crust, and is likely obscuring substantial evidence of both active and past volcanism. In this sense, geophysical methods such as seismic and gravity studies or radar techniques, are a powerful tool to study areas covered by thick ice and derive information on both contemporary and past subglacial volcanism (e.g., Lough et al., 2013; Quartini et al., 2021), reveal Antarctica's lithospheric structure including potential magmatic sources (e.g., Behrendt, 1999; Tenzer et al., 2018; Almendros et al., 2020), and monitor active volcanic areas. Of particular relevance has been the detection of subsurface magma chambers (Lough et al., 2013), as well as the monitoring and geophysical imaging of Mount Erebus (e.g., Aster et al., 2004; Zandomeneghi et al., 2013; Grapenthin et al., 2022), Deception Island (e.g., Carmona et al., 2014; Rosado et al., 2019; Geyer et al., 2021) and Mount Melbourne (e.g., Bonaccorso et al., 1997; Gambino et al., 2021) (see section 8 for further details.)

Geophysical studies in Antarctica and the sub-Antarctic region commenced early in the 20th century and intensified after the International Geophysical Year (IGY, 1957-1958) onwards (e.g., Behrendt, 1962; Kristoffersen and Haugland, 1986; Blankenship et al., 1993). Extensive geophysical exploration (e.g., aerogeophysical surveys) has been undertaken by several international groups over the last few decades, and compilations of geophysical data have further enhanced their utility and availability for polar geosciences. One excellent example is the most recent magnetic anomaly map of Antarctica (Golynsky et al., 2018)(Fig. 8), compiled from more than 3.5 million line-km of aeromagnetic and marine magnetic data and which provides a complete and coherent view of the magnetic properties of the Antarctic crust. On the one hand, the map reveals a wide variation of magnetic anomalies reflecting crustal terranes of diverse lithologies and rock magnetic properties, ages, geothermal attributes, and tectonic affinities. On the other, it provides new constraints on major tectonic and magmatic processes that affected the Antarctic from Precambrian to Cenozoic times (Golynsky et al., 2018).

6.1. *Geophysical approaches relevant to the study of Antarctic volcanism: past, present and future*

After a start in the 1980s focusing mostly on West Antarctic ice streams, the International Polar Year (2007-2008) inspired the deployment of dedicated, long-lived and large-scale geodetic and seismic networks aimed at observing the polar regions in a changing world. An example of such a network is the Polar Earth Observing Network (POLENET; https://polenet.org), a project primarily focused on collecting GPS (Global Positioning System) and seismic data from autonomous systems deployed on Antarctic and Greenland ice sheets. Networks like POLENET placed constraints on the current tectonic state of Antarctica, and on the crust and mantle conditions underlying the Antarctic volcanic regions. Revealing the rheology and seismic structure of Antarctica's upper mantle (Ivins et al., 2021; Wiens et al., 2021) or the seismicity and Pn velocity structure of central West Antarctica (Lucas et al., 2021) are some of the most recent examples.

Additionally, many international research teams and institutions have aimed at improving the existing monitoring network on Antarctic volcanic systems and to extend the geophysical network also to other active Antarctic volcanoes, by deploying seismic, ground deformation and geochemical stations (e.g., Geyer et al., 2021, Larocca et al., 2023). Particularly challenging is the year-round real-time acquisition and reliable transmission of data. During the summer, technical staff and/or the scientific teams ensure the proper functioning of the deployed equipment. However, during the austral winter, the lack of sunlight, which compromises the performance of solar panels, and the extreme weather conditions (i.e., low temperatures, strong winds, and the almost constant presence of snow and ice) strongly constrain the power supply and, hence, the survival of the installed instruments. In this sense, important efforts are being made to solve the extreme influence of seasonality on the available energy and to guarantee the operation of the equipment through alternative power systems such as wind energy or hydrogen (e.g., Cabezas et al., 2017).

In addition to the long-lived networks, additional temporary ground-based, airborne, and marine geophysical surveys have provided valuable information during recent decades. There is a long history of geophysical studies performed from over-snow traverses, in particular, ground-based ice-penetrating radar and active seismic surveys, and magnetotellurics, gravity and geodetic surveys. Primarily motivated by glaciological problems, ground-based geophysics yield local, but very high resolution, data for understanding subglacial volcanic processes and are the only approach for obtaining active seismic data, which is critical for interpreting lithological context and constraining crustal structure below the ice-rock interface. However, because these methods are locally focused, they are unable to provide adequate hypothesis tests for the evolution of subcontinental-scale volcanic provinces. At the local scale (e.g., individual volcanic systems), ground-based geophysics has provided insightful information regarding the magma feeding system and internal structure of Mount Erebus (Zandomeneghi et al., 2013; Hill et al., 2022) and Deception Island (Zandomeneghi et al., 2009).

Airborne geophysical methods, carried out mainly using ice penetrating radar and frequently complemented by gravity and magnetic observations, are also well-established tools for studying both contemporary and past subglacial volcanic provinces and processes (e.g., Behrendt et al., 1995, 2002; Van Wyk De Vries et al., 2018; Dziadek et al., 2021). In the last few decades, a key task has been the integration of high-level data products (e.g., Fig. 8) such as ice thickness (Lythe and Vaughan, 2001; Fretwell et al., 2013), magnetic anomalies (Golynsky et al., 2018) and gravity anomalies (Scheinert et al., 2016), with the recognition that again the resolution of these products does not capture the necessary scale to understand subglacial processes well (see Quartini et al., 2021 for a summary). Although an extended archive of international airborne geophysical data is now available over Antarctica, given the size of the continent, resolution remains adequate only for identifying volcanic provinces but sparse on the scale of volcanic processes (outside of very local targets, the best line spacing is on the order of 5 to 20 km). Despite the potential resolution constraints, airborne geophysics has provided some of our best evidence for the existence of active subglacial volcanism in Antarctica (e.g., Blankenship et al., 1993), and has also been deployed effectively to better understand subaerial volcanic complexes, for example, at Mount Haddington (Antarctic Peninsula) (Jordan et al., 2009; Ghidella et al., 2013). In this sense, airborne ice-penetrating radar, which has evolved substantially over the decades and is actively being collected by a number of providers, has proven to be a strategic tool in providing a framework for understanding Antarctic volcanism. In addition to the fundamental parameter of ice thickness (in the context of a well-established ice sheet surface elevation), such studies can: (i) identify bed interface parameters to test hypotheses of associated lithological and hydrological properties (e.g., Young et al., 2016); and (ii) map the stratigraphy of the ice itself (Cavitte et al., 2016; Bodart et al., 2021), which can include exceptionally detailed records of tephra deposits through time over large regions (Corr and Vaughan, 2008).

Integration of these lower-level data products across organizations and time remains a challenge, but efforts are now underway (including the SCAR sponsored Antarchitecture effort, https://www.scar.org/science/antarchitecture/home/, and the new NSF-sponsored Open Polar Radar project, https://ops.cresis.ku.edu/). Moreover, complementing

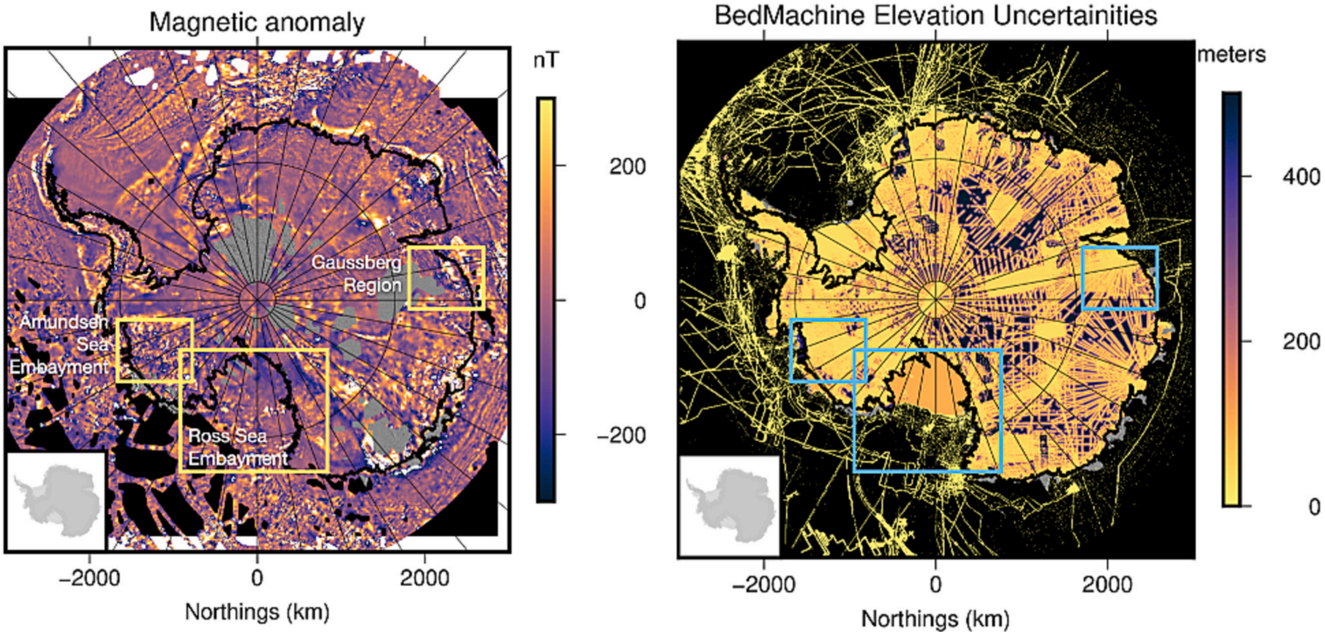


Fig. 8. Left: magnetic anomaly coverage from the ADMAP2 compilation (Golynsky et al., 2018), with key regions (boxes) for future investigation of subglacial and submarine volcanism. Right: BedMachine Antarctica (Morlighem et al., 2020) bedrock topography estimated uncertainties from radar data. Note that regions in yellow represent line spacings of 5 km or greater. BedMachine Antarctica is a self-consistent dataset of the Antarctic ice sheets. The bed elevation is calculated by subtracting the ice thickness from the surface elevation data.

ice-penetrating radar studies with airborne potential fields data can contribute to our understanding of Antarctic volcanism at two scales. On the one hand, magnetics can reveal the geological framework for a volcanic site, while gravity can be inverted for the reconstruction of density distribution and geometry of the feature. At larger scales, inversion of magnetic data for the depth of the Curie isotherm provides an indication of regional heat flow (although the method is highly dependent on geological assumptions, involving for instance the degree of magmatic intrusion), while the gravity field provides information on the large-scale elastic support of topography, which is also a function of geothermal heat flow.

In parallel, *s*hipborne geophysics allows the investigation of targets on the continental shelf, exposed by the post-glacial retreat of the AIS. For example, multibeam swath mapping, combined with acoustic profiling of the Ross Sea has revealed the remnants of locally fed subglacial hydrological systems, which would have required elevated geothermal heat flow (Simkins et al., 2017). In addition, complementary marine potential field studies have been essential for extending our interpretations of subglacial volcanic provinces to the continental shelf and associated plate boundaries (Dziadek et al., 2017).

6.2. Geophysical studies contribute to unravelling ice sheet and volcanism relationship in Antarctica

Much of the discussion in this paper is focused on the <0.2 % of the Antarctic continent that is exposed. However, the vast majority of the story of Antarctic volcanism lies buried beneath the ice sheet. Hence, our knowledge of the potential volcanic activity, and its extent, is quite restricted and scattered. Geophysical methods remain the most powerful way of accessing this record and providing insights on submarine and subglacial Antarctic volcanism. First, geophysics can play an important role in the site selection for subglacial volcanic targets, as it is already playing in a different context in the search for million-year-old stratigraphically intact ice in the interior of East Antarctica (Van Liefferinge et al., 2018; Cavitte et al., 2021). Second, the application of ice penetrating radar to map englacial tephra layers allows the extension of the three-dimensional age structure of the ice sheet from the ice core site (Fudge et al., 2023; Siegert et al., 2001; Steinhage et al., 2013), and thus is critical for calibrating ice sheet models. This creates a unique method for obtaining age constraints on specific intervals in time and in the interior of the ice sheet.

Additionally, volcanic activity can change and redistribute basal heat flow on time scales important for interpreting the history of ice sheet behaviour. In Antarctica, it is fundamental to understand whether enhanced geothermal heat fluxes and subglacial melting may contribute to the instability of the WAIS. Particularly in the interior, geothermal heat flow is critical in shaping the ice sheet. The reconstruction of the AIS over time and assessing the impact of crust-mantle processes and linkages with subglacial volcanism are vital for understanding the response of the ice sheet to climate forcing. For example, Gomez et al. (2010) found that, for a retreating WAIS, the resulting rapid uplift associated with the rheologically weak mantle acts to stabilize against a runaway collapse scenario. The change in bedrock elevation through time, however, will be required to calculate the hydraulic gradient that dictates the routing of volcanic-induced subglacial meltwaters, as well as hydrostatic pressure changes on West Antarctic magma chambers.

7. Satellite observations in Antarctic coverage

Satellite observations are demonstrably an excellent way in which to regularly collect data and monitor remote volcanoes that would otherwise be costly, difficult and/or highly dangerous to access in person (e.g., Dean et al., 2002; Patrick et al., 2005; Lu and Dzurisin, 2014; Gordeev et al., 2016). Space-based aerial views offer a unique and complementary perspective to other types of ground-based volcanic monitoring in the effort to understand the relationship between volcanic activity and changes in monitoring parameters (e.g., Patrick and Smellie, 2013). Observation capabilities span the electromagnetic spectrum (including optical, infrared, ultraviolet and radar), which can be resolved to analyse deformation, topographic changes, gas emissions, and thermal features (e.g., Pritchard and Simons, 2002; Jay et al., 2013; Carn et al., 2016; Coppola et al., 2020) (Fig. 9). Remote sensing observation techniques are increasingly useful tools for volcano monitoring with near real-time processing capabilities that can provide up-to-date status and changes of a volcanic region.

Many satellites have a sample rate, or time until the same scene on the Earth's surface is reimaged, typically on the order of days or weeks. This provides a consistent temporal timeline with which to study changes within the volcano and surrounding area (e.g., Chan et al., 2021; Coppola et al., 2021). Recent advancements in processing and storage even allow approximate real-time analysis of images from many satellites, providing valuable support for the study of volcanic systems and related phenomena. This is complemented by the coverage of large swaths of land – amounting to hundreds of square kilometres – that can completely image a volcanic region and the surrounding areas.

Up until the 21st century, satellite observations of isolated and inaccessible volcanoes in Antarctica have been limited due to technological challenges and focused primarily on the summit lava lake at Mount Erebus (Rothery and Oppenheimer, 1994; Harris et al., 1999). Additional satellite launches have recently provided paramount observations of isolated and inaccessible volcanoes that have established activity timelines. In one case, the LANDSAT thematic mapper observed a summit lava lake at Mount Erebus developed a heat and mass flux model of the lake to constrain circulate rates. Patrick and Smellie (2013) compared MODIS and ASTER imagery to conclude the constant presence of the summit lava lake from 2000 - 2010 (Fig. 10). At Mount Belinda (South Sandwich Islands), several lava flows were detected with LANDSAT, EO-1 in 2001 - 2003 (Patrick et al., 2005). The expansion of remote sensing to many Antarctic volcanoes has provided first time observations of activity or eruptions, which allows for a better understanding of Earth's processes on a global scale. In this sense, the remoteness and mostly scarce accessibility of Antarctic volcanoes imposes an important need to maximize the use of remote sensing techniques and to fully exploit their advantages compared to other ground-based monitoring data.

7.1. Remote sensing observations in Antarctica

In recent years, satellites have provided key information on Antarctic volcanoes, including: (i) thermal signatures; (ii) gas emissions; (iii) surface changes; and (iv) ground deformation processes. Here we provide a brief overview of the most relevant aspects and the reader is referred to complementary comprehensive reviews for further details and references therein (e.g., Mouginis-Mark et al., 2000; Joyce et al., 2009; Hooper et al., 2012; Dean and Dehn, 2015; Poland et al., 2020).

7.2. Temperature signatures and gas emissions

Features associated with elevated temperatures at volcanoes – typically observed in the infrared range of the electromagnetic spectrum – principally originate from exposed lava surfaces (lava lakes and flows) and high temperature gas emissions (fumaroles or explosive outgassing). Gas emissions, of which sulphur dioxide (SO_2) is most readily detectable, can be quantified using either infrared or ultraviolet remote sensing observations. In this sense, the primary instrument used for Antarctic coverage is the Moderate Resolution Imaging Spectroradiometer (MODIS, 375 m/pixel resolution), which is on both the Terra and Aqua polar-orbiting satellites and has full-Earth coverage approximately every 1 - 2 days. A NASA grant (NNX14AP37G) established the MODVOLC website and database (Wright et al., 2004; http://modis.higp.hawaii.edu/), which is a near real-time monitoring tool that utilizes data collected by MODIS to make it publicly available. Additionally, MIROVA

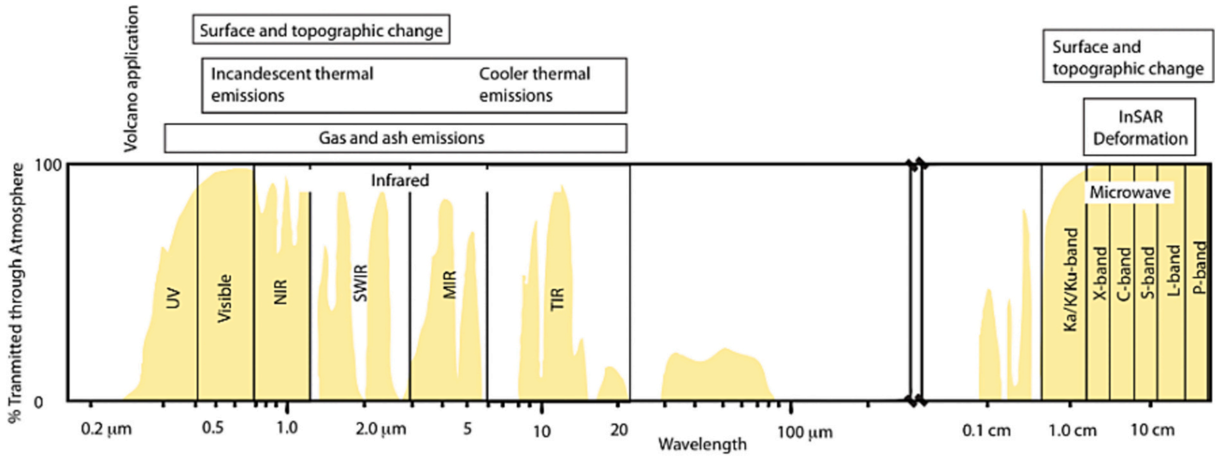


Fig. 9. The percent of radiation transmitted through the Earth's atmosphere as a function of wavelength from ultraviolet to microwave bands; note the break in scale between 200 - 300 um. The atmosphere is well suited at the micron and elevated microwave wavelengths to study thermal signatures and deformation, respectively (modified from Pritchard et al., 2022). InSAR: Interferometric Synthetic Aperture Radar; MIR: Mid-Infrared; NIR: Near-Infrared; SWIR: Short-Wave Infrared; TIR: Thermal Infrared; UV: Ultraviolet.

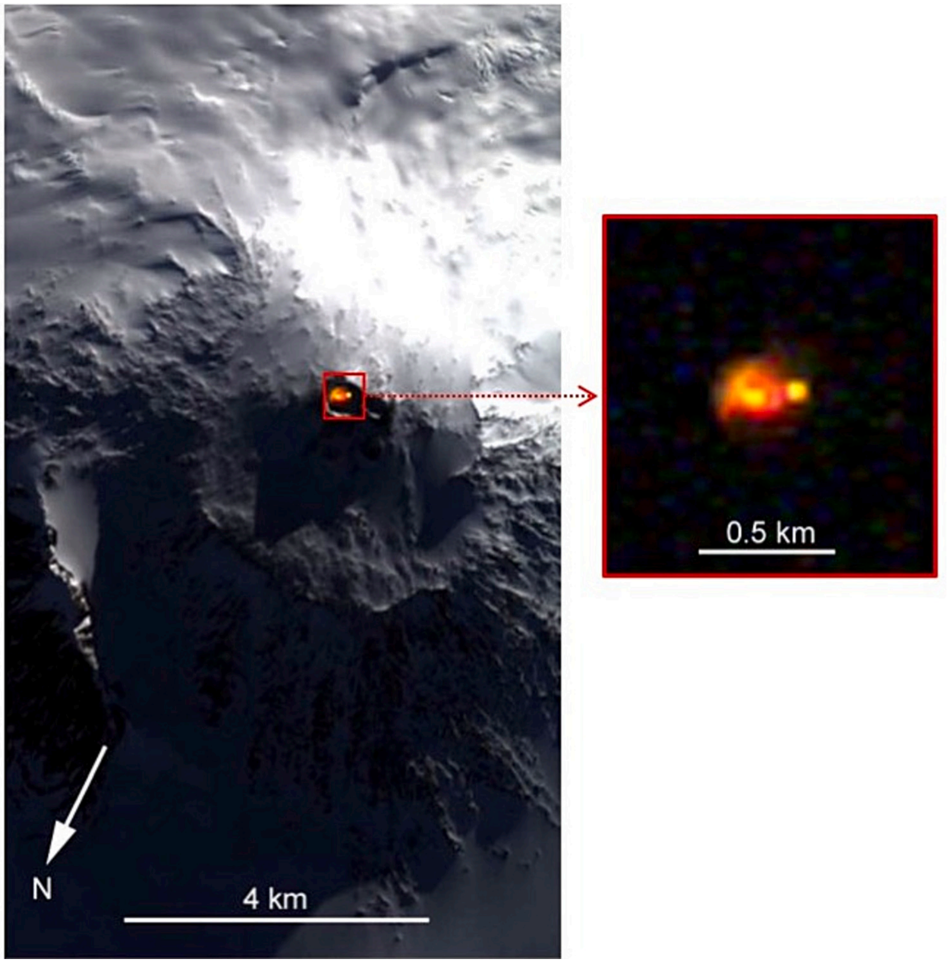


Fig. 10. Satellite picture of Mount Erebus showing its lava lake, on Ross Island, Antarctica (May 2004) with 10 m resolution. A zoomed in view of the crater lava lake is shown in the expanded image on the right. Image taken by NASA/EO-1 with the Advanced Land Imager.

(https://www.mirovaweb.it) also provides global real-time coverage of thermal anomalies (Coppola et al., 2020). Some volcanoes have a long-standing history of recent activity, such as the lava lake at Erebus. This was observed before the launch of MODIS with Thematic Mapper (TM) on LANDSAT starting in the mid-1980s to provide links to observed seismic activity and lake growth (Rothery et al., 1988; Rothery and Francis, 1990) and the Advanced Very High Resolution Radiometer to observe SO_2 (Harris et al., 1999).

7.3. Surface changes and ground deformation processes

The geomorphic and geological analysis of a volcano (or volcanic area), including its evolution throughout time, is commonly performed using high-resolution relief maps. These can be constructed from Digital Elevation Models (DEM), commonly made from both space and airborne craft. For example, recent LIDAR (Light Detection And Ranging) observations on the Airborne Topographic Mapper of the summit of Mount Erebus created a 2 × 2 m resolution DEM (Csatho et al., 2008). This improved the previous, and much coarser resolution DEM (200 × 200 m) obtained from aerial photographs from a survey by the United States Geological Survey (USGS) in 1970, followed by a 20 m DEM from the USGS in conjunction with the Land Information New Zealand (LINZ). Complementary, very-high-resolution (of centimetre-scale) DEMs or Digital Surface Models (DSMs) can be composed from data commonly obtained with ground- or UAS (Unoccupied Aircraft System)-borne LIDAR or photogrammetry, mostly with more limited spatial coverage (Vieira et al., 2021; Civico et al., 2022).

Surface changes – for example, caused by erosion or mass wasting processes, as well as ground deformation phenomena caused by the movement of magma, active tectonics, or fluids in the subsurface, can be studied via optical and radar instruments. These provide surface-level information that can be used to assess changes in topography on metre-scale resolutions, with radar having the possibility to observe through a cloud layer and at any time of the day (see Ajadi et al., 2016; Pritchard and Yun, 2018 for further detail). Surface changes or ground deformation processes can be very subtle, but interferometric synthetic aperture radar (InSAR) is a remote sensing technique utilizing microwave wavelengths that is capable of detecting these changes on sub-cm scales (Massonnet and Sigmundsson, 2000; Fournier et al., 2010). It involves repeated observations of the same scene in the radar wavelength, which are compared to one another to create a displacement image called an interferogram.

Unfortunately, data acquisition from both optical and radar instruments is still limited by the presence of snow and ice, which can cause decorrelation between successive scene acquisitions. Consequently, viable interferograms of polar and high-altitude areas are not coherently produced (Zebker et al., 2000; see also Massonnet and Sigmundsson, 2000; Dzurisin, 2006). While data coverage of Antarctic volcanoes from numerous SAR satellites exists, the aforementioned problems with snow and ice mean that the information is rarely published. Interferograms were made from ALOS collections for Deception Island, Hudson Mountains, Mount Melbourne, Mount Erebus, and Mount Takahe and from ENVISAT for Mount Erebus with various temporal baselines ranging from a few weeks to years from 2006 to 2010 (Table 1) (Cooper, 2014). However, The Pleiades, Hodson, Peter 1st, and Young islands had coverage but could not make a baseline due to excessive ground baseline distance.

7.4. Towards maximizing the use of remote techniques to monitor and study Antarctic volcanoes

The instruments previously discussed in Section 7.1 were not intentionally designed for volcanic monitoring and the number of operational satellites was limited before the emergence of numerous commercial satellites in recent years. For example, the forward push from various industries such as resources, transportation, and land management may drive the SAR industry to new capabilities and open up new opportunities for volcanic remote sensing, particularly with InSAR.

Regardless of location, satellite observations are also limited by detection thresholds of various sensors observing through the atmosphere (e.g., clouds, turbulence, water vapour), insufficient ground sample distance, and the lifetime of the sensor, which is typically on the order of a decade. In combination with the struggle to identify the relation between volcanic unrest and satellite observations, this makes it a challenge to fully monitor and analyse volcanoes, even those that are nearby to civilization as it requires a significant set of resources to maintain. Thus, both the capabilities and observing strategies are not optimized for global volcanic monitoring, and Antarctica is disproportionately affected due to being located far out of the geosynchronous orbit path and not within other popular observing features. Additionally, some data are not freely available and the incurred costs are not feasible for all researchers, thus hindering access to datasets and potential discoveries. Limited budgets may push the data acquisition to areas with a higher chance of successful observations and impact on the community.

Remote sensing is a field with an immense amount of potential, but it requires considerable and consistent effort to become a reality. Many of the pieces of this puzzle are individually established, and it can develop into a highly useful and important tool on a global scale for active volcano monitoring.

Table 1
Instrument and observation baseline dates used to create an interferogram for Deception Island, Erebus, Hudson Mountains, Melbourne, and Takahe volcanoes. Coverage of Antarctic volcanoes is limited for several reasons mainly including the lack of orbit paths around the poles. Dates provided as dd/mm/yy.

Volcano	Instrument & Track	Temporal range
Deception Island	ALOS-1 PALSAR 127	05/01/07 - 13/10/09
Mount Erebus	ALOS-1 PALSAR 484	05/01/08 - 12/04/10
		07/10/07 - 22/11/08
	Envisat 70	16/01/10 - 27/03/10
	Envisat 299	06/08/07 - 15/10/07
		26/07/10 - 30/08/10
	Envisat 415	23/06/11 - 23/07/11
	Envisat 485	16/04/06 - 08/10/06
		21/05/06 - 25/06/06
		21/05/06 - 08/08/10
		17/12/06 - 19/08/07
		06/05/07 - 10/06/07
		23/09/07 - 10/02/08
		03/08/08 - 01/03/09
		06/12/09 - 25/04/10
Hudson Mountains	ALOS-PALSAR 247	08/09/07 - 14/12/09
Mount Melbourne	ALOS-PALSAR 427	01/04/07 - 22/11/09
Mount Takahe	ALOS-PALSAR 295	12/10/07 - 17/01/10

8. Volcano monitoring, volcanic hazard assessment and early-warning systems: outstanding issues

As mentioned in previous sections, Antarctica hosts several active volcanoes, with Mount Erebus and Deception Island being the ones considered to be more active, each with numerous eruptive events in the last two centuries (Sims et al., 2021; Geyer et al., 2021). At Mount Erebus, historical eruptive activity has been characterized by the existence of an active lava lake within the innermost crater in the summit caldera, from which rare phreatic and daily Strombolian eruptions of diverse styles, magnitude, and frequency have occurred (Kyle, 1994; Sims et al., 2021). Recent analysis of over 20 years of continuous GPS observations shows that Erebus is inflating which could herald a new episode of larger and more frequent eruptions (Grapenthin et al., 2022). Deception Island experienced several periods of high activity during the 19th to the 20th century (e.g., 1818-1828, 1906-1912, 1967-1970), including numerous phreatomagmatic and magmatic eruptions closely spaced in time (e.g., Roobol, 1980; Smellie, 2002a). Despite a lack of eruptions since 1970, it has continued to be designated as volcanically restless (Cooper et al., 1998). Since the last eruption (August 1970) there have been several periods of intense, but non-eruptive, activity (e.g., 1991-1992, 1995-1996, 1999-2000, 2014-2015, and 2020-2021) with significant increases in seismicity, localized ground deformation and raised ground temperatures (see Rosado et al., 2019; Moreno-Vacas and Almendros, 2021 and references therein; Geyer et al., 2021). Recent evidence of volcanic activity on Deception Island consists of soil gas emissions reaching 100°C locally (e.g., Cerro Caliente) and temperatures of 45° and 65°C in hot springs at Pendulum Cove and Whalers Bay, respectively (Fig. 11). Since December 2019, regional seismic activity in Bransfield Strait has been very intense at times, with earthquakes up to 6.9 magnitude and frequent seismic swarms (Loureiro Olivet et al., 2021; Cesca et al., 2022; Poli et al., 2022).

8.1. Monitoring networks on Antarctic volcanoes: current state and future challenges

In Antarctica, the deployment (and maintenance) of volcano monitoring networks relies on national research programs funded by a few of the participating countries in the Antarctic Treaty. For economic reasons, monitored networks have only been deployed at those active volcanic centres situated close to scientific bases, namely: Mount Melbourne, Mount Erebus, and Deception Island. Additionally, some ad hoc seismic measurements were collected at Mount Rittmann volcano in January 2017 as part of the ICE-VOLC project (Gambino et al., 2021).

Monitoring activities at Mount Melbourne began in the late 1980s with the Italian National Antarctic Program setting up a volcanological observatory and the installation of GPS-tilt and seismic networks (Gambino et al., 2021). From 2010-2011, broadband seismic stations were installed there by the Korean Polar Research Institute. More recently, new seismological, geochemical, and volcanological research was carried out in the framework of the ICE-VOLC project between 2016 and 2018 (Gambino et al., 2021). Currently, a multiparametric monitoring system is installed in Mount Melbourne with data acquired, transmitted, and analysed in real time (Larocca et al., 2023). This monitoring system, designed and run by researchers at the Istituto Nazionale di Geofisica e Vulcanologia (INGV-Catania division) and the University of Catania, is composed of seismic, geochemical, and thermal stations deployed in two different fumarolic ice caves at the volcano summit (Fig. 12) (Larocca et al., 2023).

The Mount Erebus main vent is 38 km from McMurdo Station (United States) and Scott Base (New Zealand), capable of supporting up to 1,200 and 86 residents, respectively. Regular monitoring commenced in 1972 (Giggenbach et al., 1973) and included measuring gas compositions and fluxes, and infrasonic monitoring from 1974 by New Mexico Tech (United States) and Victoria University (New Zealand) (e.g., Kyle, 1994; Oppenheimer and Kyle, 2008; Sims et al., 2021). In the early 2000s, the New Mexico Tech Mount Erebus Volcano Observatory (MEVO) project reinforced the network by installing a digital data acquisition system, which incorporated short-period sensors together with infrasound and intermediate-period (30 s natural period) seismometers in a continuous recording system. The MEVO seismic system functioned until late 2016 (Sims et al., 2021). Currently, the volcano's summit activity is recorded by a temporary seismic network maintained by the Incorporated Research Institutions for Seismology (IRIS) Consortium. A network of GPS sensors initially also installed in the early 2000s by MEVO continues to operate and recently has shown evidence of inflation consistent with increased storage of magma and/or gas at shallow depths in the crust, with the potential for elevated explosive activity in the future (Grapenthin et al., 2022). Additionally, the United States Antarctic Program (USAP) is contemplating installing a multi-year network of five IRIS-supported seismographs and infrasonic sensors to continue monitoring activities at Mount Erebus (Sims et al., 2021).

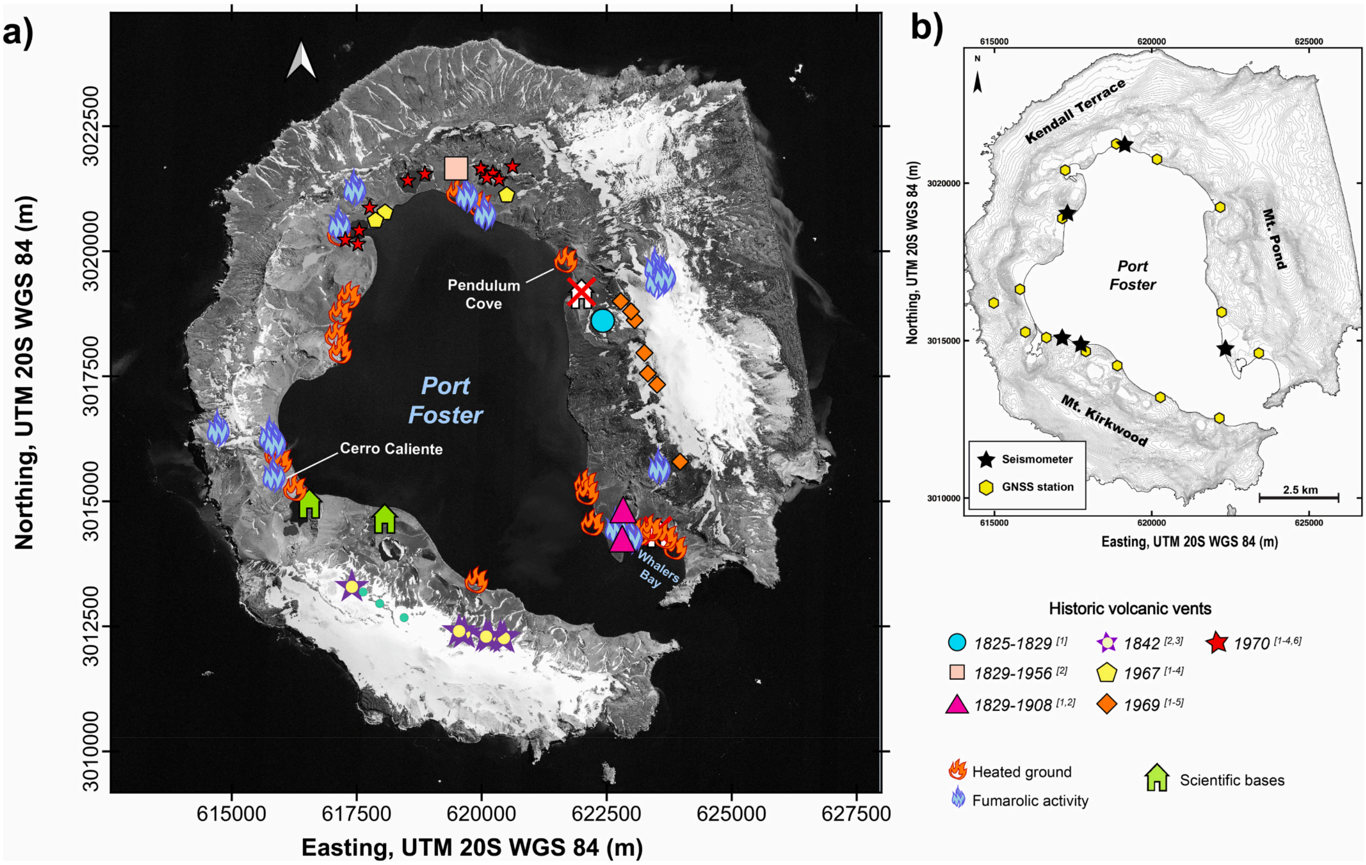


Fig. 11. a) Orthophotomap of Deception Island showing the location of the historical volcanic vents and the areas of fumarolic activity and heated ground. [1] Roobol (1980); [2] Roobol (1982); [3] Roobol (1973); [4] Baker et al. (1975); [5] Smellie (2002b); [6] Baker and McReath (1971). B) Simplified topographic map of Deception Island showing the position of the seismic network (black stars)(source: https://www.ign.es/web/ign/portal/vlc-area-volcanologia) and the GNSS stations (yellow hexagons) of the REGID network (Spanish acronym: Red Geodinámica Isla Decepción –Deception Island Geodynamic Network–) and the DIESID system (Spanish acronym: Dilatómetro e Inclinómetro Espacial Isla Decepción –Deception Island Spatial Dilatometer and Inclinometer–).

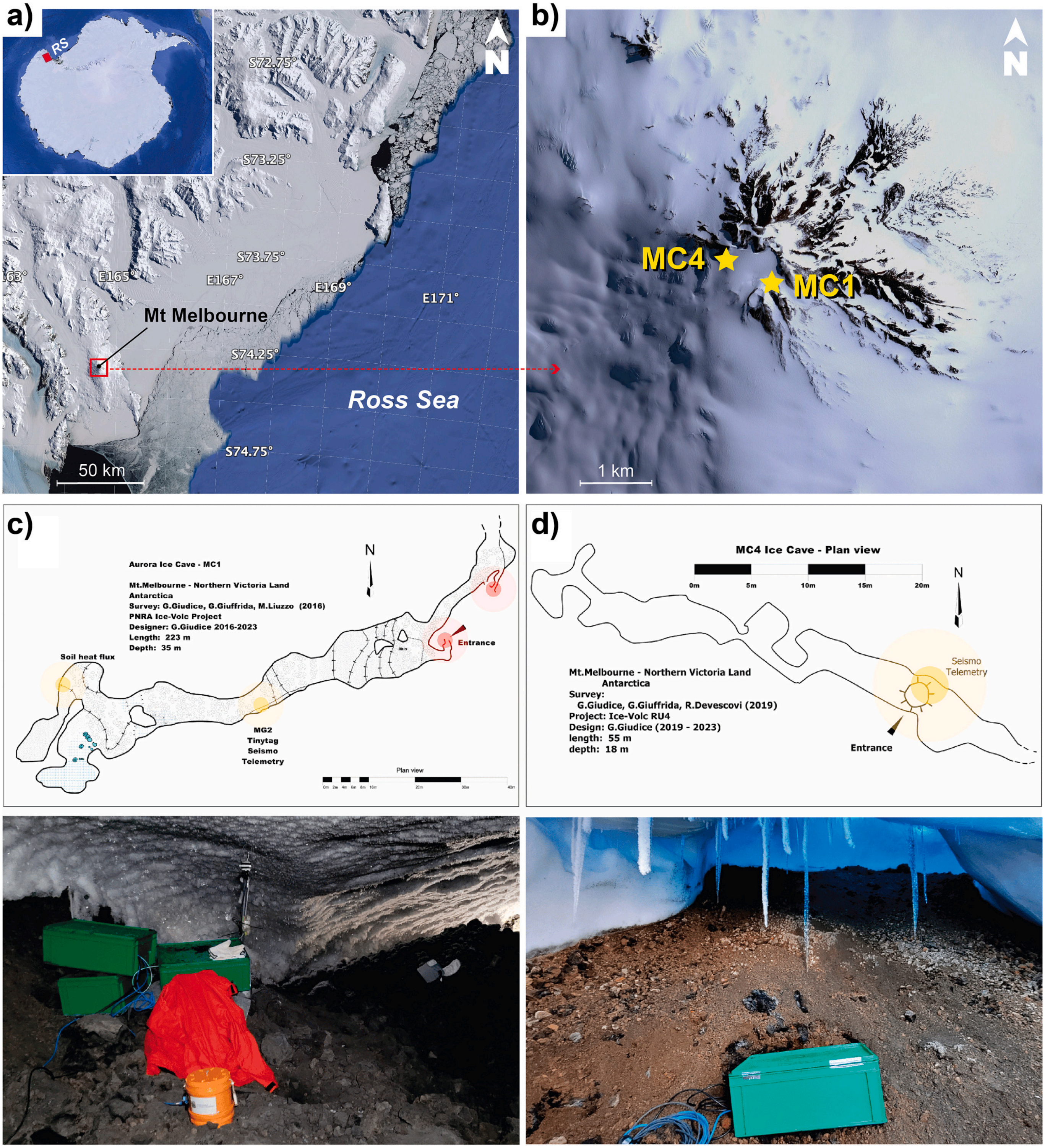


Fig. 12. a) Aerial image of Mount Melbourne Volcanic Province indicating the location of Mount Melbourne volcano. Image obtained from Google Earth Pro. Source: US Geological Survey. b) Aerial image of Mount Melbourne volcano with the location of the two fumarolic ice caves used for the monitoring station installations (yellow stars) according to Larocca et al. (2023). Image obtained from Google Earth Pro. Source: US Geological Survey.c,d) Maps of MC1 and MC4 ice caves (top) and pictures showing the installed instrumentation within the caves (bottom) (modified from Larocca et al., 2023).

Volcano monitoring activities at Deception Island began with the deployment of seismometers at the Argentinian, Chilean and British stations, in the 1950's, 1965 and 1969, respectively; all of which were abandoned or destroyed during the 1967 and/or 1969 eruptions. Monitoring activities were resumed in 1986 (Geyer et al., 2021). Since then, the island's seismicity and ground deformation (since 1991-1992) have been regularly monitored by Spanish and Argentinean scientists during the austral summers. Additional data from gravity and magnetic surveys, and measurements of water and ground temperatures, compositions of fumaroles and other gas emissions complement the seismic and geodetic data collected. The Argentinian monitoring team, belonging to the Observatorio Argentino de Vigilancia Volcánica from the Argentinian Geological Mining Survey (Servicio Geológico Minero de Argentina – SEGEMAR, https://www.argentina.gob.ar/economia/segemar), has four stations that include seismometers, GNSS instruments and an IP camera (https://oavv.segemar.gob.ar/monitoreo-volcanico/isla-decepcion/, last accessed 16/10/2023). From the Spanish side, the universities of Cádiz and Granada (Spain) have deployed seismic and GNSS instrumentation, maintaining continuous data series that monitor the activity during Antarctic summer campaign periods during the last 20 years. Since 2020, the National Geographic Institute (Instituto Geográfico Nacional - IGN, Spain, https://www.ign.es) has had the responsibility for volcanic surveillance on Deception Island and has begun to deploy a multidisciplinary surveillance network with continuous registration and data transmission throughout the year, which will allow the constant evaluation of activity. To date, the IGN has installed a network of 3C broadband seismic stations with real-time and continuous transmissions. In future campaigns, IGN will densify the GNSS network and install an appropriate geochemical network.

Finally, in the past few decades, volcanism in the Bransfield Strait rift has been a focus of attention and several research groups have deployed seismic stations and Ocean-Bottom Seismometers (OBS) in the South Shetland Islands region (Robertson Maurice et al., 2003; Almendros et al., 2020; Loureiro Olivet et al., 2021; Cesca et al., 2022; Poli et al., 2022). This has allowed the detection and location of tectonic earthquakes related to regional extension and subduction processes, strike-slip faulting and magmatic processes. Some of these events were large enough to be detected by global catalogues (e.g., NEIC, USGS). This seismic information, frequently combined with high-resolution marine geophysics, has allowed detailed seismological and geophysical studies of the Bransfield Strait region to be performed (e.g., Almendros et al., 2020).

Antarctica has no legislation that identifies which countries or institutions are responsible for monitoring the active Antarctic volcanoes. This hinders the acquisition of continuous funding and, hence, in ensuring long-term data collection with consistent standards. Longer monitoring periods prior to episodes of volcanic unrest allow a more accurate definition of the volcano's baseline state and permit the earlier and more accurate detection of any measurable departure from the volcano's "normal" behaviour (Tilling, 2005, 2022). Only continuous volcano-monitoring can reliably diagnose episodes of unrest and, in turn, provides the most reliable scientific basis for short-term forecasts (hours to months in advance) of an impending eruption, or of mid-course changes to an active eruption (e.g., Sparks, 2003).

From the technical point of view, it is necessary to work towards monitoring systems that allow year-round near real-time telemetered data acquisition. Advances in low-maintenance, low-power and high-capability instrumentation have the potential to enhance monitoring in remote areas of Antarctica. Additionally, volcano-monitoring systems shall benefit from incorporating the newest techniques that acquire, process, and display data in real-time or near real-time. These techniques are likely to increasingly complement and, in some cases supplant, conventional ground-based techniques.

8.2. Volcanic hazard, risk management and early warning systems in Antarctic volcanoes

Potential hazards related to Antarctic volcanic eruptions range from pyroclastic density currents to lava flows. However, tephra fallout is often considered the most serious hazard because of the wide geographical area it may affect and the speed with which it is deposited. Indeed, tephra generated during a moderately to highly explosive Antarctic eruption has the potential to affect proximal, regional and even global aviation safety, infrastructures or sea traffic (Geyer et al., 2017). In Antarctica, the abundance of water as snow, ice, seawater, or freshwater can: (i) lead to efficient magma–water interaction and hence, to highly explosive ash-forming hydrovolcanic eruptions (e.g., 1970 Deception Island eruption; Pedrazzi et al., 2014, 2018); (ii) generate phreatic events (e.g., 1993 Mount Erebus eruption); and (iii) trigger highly destructive lahars or *jökulhlaups* (e.g., 1969 Deception Island eruption; Smellie, 2002b).

Past eruptions in Antarctica with a direct impact on infrastructure were only documented for Deception Island volcano during the 1967, 1969, and 1970 events, which severely damaged or destroyed the scientific bases on the volcano but also had a lesser impact on neighbouring South Shetland islands (e.g., King George Island; Baker et al., 1975; Roobol, 1982). However, an eruption occurring today could have a much larger impact, due to the escalation in the number of people in the region (including tourists) and the amount of associated infrastructure. Despite the seriousness of these consequences, comprehensive hazard assessments (including event-tree, hazard level maps and eruptive scenarios) have been conducted only for Deception Island volcano (Bartolini et al., 2014). Preliminary assessments also exist for Mount Erebus (Poirot, 2002; Asher, 2014; Magil et al., 2023).

In the same way, only Deception Island has an established early warning system and alert protocol, which is regularly revised and updated and included as part of its Management Plan: Antarctic Specially Managed Area (ASMA) No. 4 (Management Plan for ASMA No. 4, https://documents.ats.aq/recatt/att656_e.pdf, last accessed 05/10/2023). The possibility of a Mount Erebus volcanic hazard monitoring system is being actively explored.

The current alert system at Deception Island is based on the continuous record of volcanic activity on the island during the approximately four months of the austral summer field season, coincident with the maximum human presence there. Ship Captains entering Port Foster, and pilots of aircraft or helicopters overflying the island, must request information on VHF Channel 16 Marine about the state of the island's volcanic activity monitored by the Gabriel de Castilla (Spain) and Decepción (Argentina) bases (Management Plan for ASMA No. 4, https://documents.ats.aq/recatt/att656_e.pdf, last accessed 05/10/2023). To communicate this information, and similar to other active volcanoes worldwide, a traffic light system is used as recommended by the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) (Table 2). The responsible monitoring teams must update the state of the traffic lights system, according to the variability of the recorded volcanic parameters. If an orange state of alert is declared: (i) Ships should be advised not to access Port Foster in order to reduce future evacuation problems; (ii) all ships should leave Port Foster immediately after taking on board all crew and passengers that are ashore; and (if) it is recommended to take some other precautionary actions by every ship (i.e., breathing masks, abandon the main deck).

Volcanic hazard assessment in most Antarctic volcanoes is limited by the incomplete geological record, scarcity of outcrops, and the challenging conditions for mapping volcanic deposits. Often it is difficult to reconstruct the eruptive history of these active volcanic systems and to quantify the magnitude and extent of past eruptions—two fundamental aspects necessary to carry out a proper volcanic hazard assessment and to evaluate their potential future eruptive activity. It is fundamental to work towards a complete geological record, including more geochronological data for the reconstruction of the past eruptive histories of the different active volcanoes. Only in this way will it be possible to produce hazard assessments, hazard-zonation maps, and long-term probability forecasts. Of special interest is quantifying the volcanic hazard (particularly to air traffic) from ash clouds. Volcanoes at lower latitudes such as Deception Island have the additional hazard that ash plumes can escape the polar atmospheric gyre and extend to more tropical latitudes (Geyer et al., 2017). This highlights the need for detailed, multi-year wind data around the most active volcanoes and the incorporation of these data into dispersion models.

An efficient early warning system allows more time for decision-makers to implement volcanic hazard response plans. This applies not only to those volcanoes situated close to scientific stations but also to the more remote volcanoes, whose past highly explosive eruptions may have the power to significantly influence regional climate and promote

Table 2
Traffic light system used in Deception Island as recommended by IAVCEI (International Association of Volcanology and Chemistry of the Earth's Interior) (Management Plan for Antarctic Specially Managed Area (ASMA) No.4, Deception Island).

Colour code	Alert state	Description	Operative actions
Green	No eruption expected	Normal volcanic parameters recorded. This is the normal island status.	Control.
Yellow	Some anomalies in the volcanic system. A volcanic crisis could arise at some point in the future.	There are small but significant anomalies in the volcanic parameters recorded.	Control. Increase volcanic parameters recordings. Verify the parameters.
Orange	Increased probability of a volcanic eruption in the near future.	Significant increase in volcanic parameters anomalies recorded. New changes in volcanic parameters appears.	Increase readiness to respond. Start preparing the evacuation plan. Recommend restricting access to the island. Recommend temporary evacuation of the island including ships and helicopters.
Red	High probability of an imminent volcanic eruption or ongoing volcanic event.	High probability of volcanic eruption confirmed with a significant change in the number of volcanic parameters anomalies.	Personnel on the island to move to emergency camps or evacuate the island entirely depending on the location of the eruption. Prohibit ships and helicopters from entering the island, unless for rescue purposes.

environmental change (Iverson et al., 2017b). A unified early-warning system for all Antarctic volcanoes is not possible due to their different nature, dynamics and activity levels. However, there is an urgent need to establish or improve early warning systems for each active Antarctic volcano and clearly define responsibilities. Alert and communication protocols should be implemented to ensure that those scientific bases, vessels and aircrafts potentially in danger receive timely and relevant information.

9. Outreach and education on Antarctic volcanism

Antarctica may be located far from any permanent inhabitants, but its changes impact people all around the world. As such, knowledge about the Antarctic continent is important for a wide segment of the general public, including schoolchildren, decision-makers, and scientists from other disciplines. Conversely, ensuring adequate public knowledge of Antarctic issues is also important for scientists working in the region, as the funding and logistical support for research are derived from public support.

Recent studies on geoscience education have clearly highlighted that the current knowledge of polar knowledge is, in general, low among key audiences. A national survey on polar knowledge in the USA reported that less than half of respondents understand that land-based ice most affects sea level rise or even the location of the South Pole (Hamilton, 2016). Similar results were obtained from a game-based quiz of 25,000 schoolchildren, which highlighted a comparable low overall understanding of polar issues, with response accuracy in some regions no better than guessing (Pfirman et al., 2021). In a similar way, it has been demonstrated that the teachers' knowledge of polar topics exceeds that of the general public (Schloesser and Gold, 2021); however, about 35% of the teachers surveyed could not list a single educational resource about polar topics. To date, no study has explicitly investigated public knowledge of Antarctic volcanism but surveys of other cryosphere science topics (Hamilton et al., 2012; Arrhenius et al., 2021; Gold et al., 2021; Hamilton, 2021; Pfirman et al., 2021) suggest that it will be low.

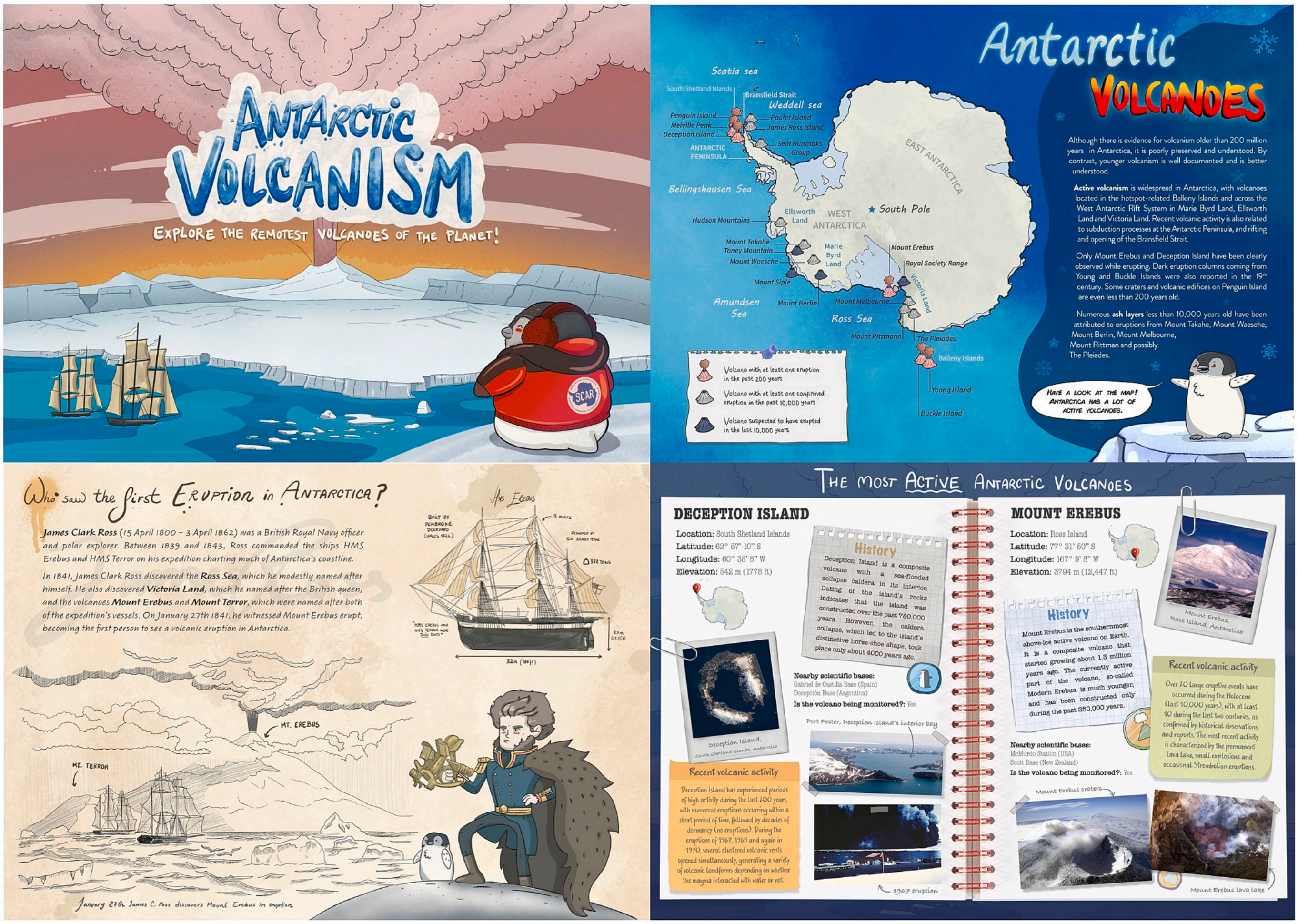
These results clearly indicate the need for increasing the knowledge of these topics among the general public and provides a strong motivation for scientists to build outreach and education as an integrative part of their research programs. In this sense, existing literature and outreach activities (e.g., Sweitzer et al., 1996; Gold et al., 2021; St. John et al., 2021) reveal four primary (not mutually exclusive) motivations for carrying on with such a highly-relevant task: (i) educate on the underlying science or societal issues associated with polar science; (ii) communicate scientific results of direct societal relevance, for instance, with decision-makers or risk managers; (iii) raise the profile of polar science among under-represented groups, with a view to increasing present and future diversity; and (iv) disseminate scientific results to scientists from different fields, in order to promote multidisciplinary work. These outreach and dissemination activities may be conducted in a wide range of formats (e.g., books, quizzes, talks) and platforms (e.g., video games, YouTube video channels, etc.). It has long been recognized that scientific knowledge and relevant actions or societal responses are associated, and even argued that this association is one of the key arguments for scientific education (e.g., Jenkins, 1994). Recent systematic reviews of scientific education literature relating to climate change (Rousell and Cutter-Mackenzie-Knowles, 2020) and conservation (Ardoin et al., 2020 and references therein) further underline the need for better public understanding of key issues and more creative outreach and education activities to promote wider action.

Since its creation in 2015, the AntVolc Expert group and its individual members, have been involved in a range of activities including numerous talks in educational centres, the creation of the AntVolc website and social media pages, and the organization and convening of sessions on relevant topics at the American Geophysical Union (AGU), European Geophysical Union (EGU), IAVCEI and SCAR Open Science and Earth Science conferences. Of high relevance is the publication of the illustrated children book "Antarctic Volcanism – Explore the remotest volcanoes of the planet" (Geyer et al., 2022)(Fig. 13). This book is available at the open-access repository Zenodo.org and has registered over 3,300 downloads since its publication. Currently, the book has been published online in English (Geyer et al., 2022), Spanish (Geyer et al., 2023a) and Italian (Geyer et al., 2023b) and has been distributed as hard-copy among representative libraries and educational centres.

Today, complementing the more traditional outreach activities (e.g., talks), recent technologies are increasingly providing new avenues to communicate Antarctic science. In particular, phone and video communication are now possible directly from many Antarctic bases and field camps. Social media provides a wide reach and possibilities to reach communities less involved in more conventional outreach. Museums and media companies already have a framework in place to reach a wide audience. Collaboration with such organizations, for instance for science exhibits or documentaries, is an efficient means of sharing research with a wide audience. Finally, we note that effective outreach requires careful planning, time commitment and, in many cases, exclusively allocated funding. Rather than auxiliary or peripheral objectives, education and outreach activities should be considered, and planned, as integral parts of research programs – and doing so will benefit both scientists and the general public.

10. Research on Antarctic Volcanism: key global societal challenges to be addressed

Sea-level rise from melting ice will affect millions of people over the coming decades (Kopp et al., 2014). The AIS contains 90% of the world's fresh water and holds the potential to contribute tens of centimetres of sea-level rise by 2100 (DeConto and Pollard, 2016; DeConto et al.,



Although there is evidence for volcanism older than 200 million years in Antarctica, it is poorly preserved and understood. By contrast, younger volcanism is well documented and is better understood.

Active volcanism is widespread in Antarctica, with volcanoes located in the hotspot-related Balleny Islands and across the West Antarctic Rift System in Marie Byrd Land, Ellsworth Land and Victoria Land. Recent volcanic activity is also related to subduction processes at the Antarctic Peninsula, and rifting and opening of the Bransfield Strait.

Only Mount Erebus and Deception Island have been clearly observed while erupting. Dark eruption columns coming from Young and Buckle Islands were also reported in the 19th century. Some craters and volcanic edifices on Penguin Island are even less than 200 years old.

Numerous **ash layers** less than 10,000 years old have been attributed to eruptions from Mount Takahe, Mount Waesche, Mount Berlin, Mount Melbourne, Mount Rittman and possibly The Pleiades.

Who saw the first ERUPTION in ANTARCTICA?

__James Clark Ross__ (15 April 1800 – 3 April 1862) was a British Royal Navy officer and polar explorer. Between 1839 and 1843, Ross commanded the ships HMS Erebus and HMS Terror on his expedition charting much of Antarctica's coastline.

In 1841, James Clark Ross discovered the __Ross Sea__, which he modestly named after himself. He also discovered __Victoria Land__, which he named after the British queen, and the volcanoes __Mount Erebus__ and __Mount Terror__, which were named after both of the expedition's vessels. On January 27th 1841, he witnessed Mount Erebus erupt, becoming the first person to see a volcanic eruption in Antarctica.

DECEPTION ISLAND

Location: South Shetland Islands
Latitude: 62° 57' 10" S
Longitude: 60° 38' 8" W
Elevation: 542 m (1778 ft)

History

Deception Island is a composite volcano with a sea-flooded collapse caldera in its interior. Dating of the island's rocks indicates that the island was constructed over the past 780,000 years. However, the caldera collapse, which led to the island's distinctive horse-shoe shape, took place only about 4000 years ago.

Nearby scientific bases:
Gabriel de Castilla Base (Spain)
Decepción Base (Argentina)
Is the volcano being monitored?: Yes

Recent volcanic activity

Deception Island has experienced periods of high activity during the last 200 years, with numerous eruptions occurring within a short period of time, followed by decades of dormancy (no eruptions). During the eruptions of 1967, 1969 and again in 1970, several clustered volcanic vents opened simultaneously, generating a variety of volcanic landforms depending on whether the magma interacted with water or not.

MOUNT EREBUS

Location: Ross Island
Latitude: 77° 31' 50" S
Longitude: 167° 9' 8" W
Elevation: 3794 m (12,447 ft)

History

Mount Erebus is the southernmost above-ice active volcano on Earth. It is a composite volcano that started growing about 1.3 million years ago. The currently active part of the volcano, so-called Modern Erebus, is much younger, and has been constructed only during the past 250,000 years.

Nearby scientific bases:
McMurdo Station (USA)
Scott Base (New Zealand)
Is the volcano being monitored?: Yes

Recent volcanic activity

Over 20 large eruptive events have occurred during the Holocene (Last 10,000 years), with at least 10 during the last two centuries, as confirmed by historical observations and reports. The most recent activity is characterized by the permanent lava lake, small explosions and occasional Strombolian eruptions.

Fig. 13. Example of cover (top left) and three pages from the AntVolc outreach book "Antarctic Volcanism – Explore the remotest volcanoes of the planet" (Geyer et al., 2022), designed for communicating key information about Antarctic volcanism.

2021). Predicting how Antarctica will continue to contribute to sea-level rise is enabled by studying AIS behaviour in the present and the past, to both of which volcanic research has a unique, and uniquely important, contribution.

Present AIS studies are enhanced in major part through volcanological research focussed on geothermal heat flow and GIA. Geothermal heat flow determines how the present-day AIS deforms internally and slides basally but, despite its importance, the property remains poorly known (Burton-Johnson et al., 2020a, 2020b). Geothermal heat flow promotes ice flow via basal melting, affecting basal ice temperature, changing the mechanical properties of ice, modifying hydrological systems and subglacial lakes and -saturating basal sediments (e.g., Llubes et al., 2006; Winsborrow et al., 2010; Larour et al., 2012). Geothermal heat flow can be measured from heat production in rocks, with plutonic felsic rocks typically having significantly higher heat flow than mafic igneous rocks or sedimentary rocks (Carson et al., 2014; Norden et al., 2020). Accurately understanding the geothermal heat flow from Antarctic crust, including from volcanic rocks, is critical as it is currently the least constrained parameter affecting ice sheet dynamics (Larour et al., 2012; Burton-Johnson et al., 2020b). Additionally, active sub-ice volcanism has the potential to further destabilise the AIS and speed up the rate of ice loss (Iverson et al., 2017b; Van Wyk De Vries et al., 2018). Together, volcanic and plutonic rocks and active volcanism contribute to present-day AIS instability and must be studied in order to provide much-needed geological constraints for AIS models.

GIA describes the ongoing viscoelastic response of Antarctica to ice and water loading and de-loading (Whitehouse et al., 2012). GIA is essential to constrain sea-level changes going forward (Wan et al., 2022) which is affected via GIA-induced bedrock uplift and accompanying migration of AIS grounding-lines (Gomez et al., 2010; Martin et al., 2023). One of the least constrained parameters of GIA is mantle composition which affects rheology and heat flow (Sutter et al., 2019; Martin and van der Wal, 2023). Mantle composition can be studied remotely through geophysical methods, or it can be studied directly via xenoliths, which are fragments of the lithospheric mantle entrained and brought to the surface during volcanic eruptions. Geochemical and petrological studies of the mantle thus contribute in a dual way to parameterising present-day geothermal heat flow and informing GIA models.

Secondly, past AIS studies are enhanced more specifically through paleoenvironmental studies of glaciovolcanic outcrops, from which critical parameters of former ice can be derived. These include ice sheet thickness (Davies et al., 2012; Smellie et al., 2009), ice sheet stability (Smellie et al., 2011; Smellie et al., 2023c) and chronologically well-constrained timing of events, including through tephra-chronology (Narcisi et al., 2005; Ross et al., 2012). Such parameters are vital ground-truth for validating results of climate modelling. The effect of climate change on the world is intimately linked to AIS mass wasting, amongst other factors (Foster et al., 2012; Hall, 2009). Computer model simulations of how Antarctic ice sheets will react in a warmer world can be tested using geological evidence for past climate variations and ice sheet characteristics and dynamics (Hill et al., 2007; Smellie et al., 2009; Seroussi et al., 2020). The terrestrial volcanic rock record is the only source of information on ice thickness and thickness variations over time, as well as a reliable source of information on the temporal evolution of ice sheet thermal regime, a crucial measure of ice sheet dynamism. Although glacial sedimentary rocks can also provide information on thermal regime, it is often difficult or impossible (Hambrey and Glasser, 2012). By contrast, volcanic rocks can be dated precisely (a major advantage over terrestrial glacial sedimentary rocks) and, uniquely, they preserve records of ice thickness that are typically unobtainable by other methods but routinely determined for glaciovolcanic rocks. Compared with offshore studies by drilling (e.g., ANDRILL, Cape Roberts Project), glaciovolcanic studies are inexpensive and results are thus delivered at a comparatively low cost. Furthermore, increasingly precise and accurate determination of radiometric ages on primary volcanic rocks (e.g., tephra units and lava flows) are starting to routinely determine ages with errors much less than the duration of glacial cycles, thus making direct comparisons with the marine isotope record feasible and providing a means to estimate the rates of change of past environmental conditions important for numerical modelling. Thus together, glaciovolcanology and chronology on volcanic sequences provide critical and often unique geological boundary conditions for numerical models on past AIS behaviour. Addressing these societal challenges will require further focussed research in the fields of glaciovolcanology, chronology, petrology, and geochemistry.

11. Recommendations for future research on Antarctic volcanism

Despite the many initiatives and scientific activities carried out during the past several decades, there is still an urgent need to: (i) progress current scientific knowledge about the petrological functioning of Antarctic volcanic systems and related magmatic processes; (ii) increase our knowledge of past terrestrial environmental conditions (mainly Icehouse but potentially Hothouse) via studies of the volcanic successions and synthesize those data in a pan-Antarctic sense to complement and integrate with the better-known but still incomplete tephra and marine sedimentary records; (iii) increase our preparedness for possible forthcoming eruptions (e.g., by developing accurate volcanic hazard assessments and creating new assessments for volcanoes currently lacking them, improving monitoring networks, and establishing early-warning systems); and (iv) further educate the general public and policymakers about these remote but ecologically, environmentally, and climatically important areas of the planet. Here, we present a simplified list of initiatives and activities that could be carried out in the near future that will contribute to addressing some of these issues. They focus on those activities that have been particularly neglected until now; specific scientific research foci are identified in the earlier sections of this paper. However, we also encourage and advocate proposals for volcanological—petrological—paleoenvironmental field campaigns, potentially including drilling and dredging, designed not only to include targeted areas that have a strong potential for high-profile research outcomes but also to promote the exploration of understudied areas, such as subglacial and seafloor environments.

11.1. Towards more complete and accessible databases

Since the first scientific expeditions in Antarctica (Fig. 1), the amount of available data regarding Antarctic volcanoes has continuously increased. However, there are still specific aspects that have been poorly studied. In particular, we strongly highlight the need for more uniform and complete geochemical (major and trace element compositions) and isotopic (e.g., Sr, Nd, Pb, Hf, Os, He, O, etc.) datasets on volcanic products in order to facilitate comparison across Antarctica and beyond. This would allow us, for example, to define the petrological conditions characteristic of large to very-large volcanic eruptions and whether any currently active or dormant volcanoes possess similar petrological characteristics. It would also permit the comparison of the WARS with other major continental rift systems (e.g., Basin and Range and East Africa rift systems). Furthermore, we encourage the application of novel and cutting-edge petrologic tools such as high-precision microanalytical techniques and the study of halogen, noble gas and other volatiles from minerals and melt inclusions. These may contribute to petrologically defining a Moho depth, better constraining mantle rheology to improve GIA and heat flow models, and a better understanding of magmatic degassing processes (which are critical to driving explosive volcanic behaviours).

All these data should be compiled and curated in a comprehensive Antarctic petrological database building on those already implemented (e.g., GNS Science Petlab https://pet.gns.cri.nz/#/). Such a database should integrate, or be linked to, physical repositories of intrusive and extrusive rock samples, sediment, tephra, drill core, dredge materials, xenoliths, etc., several of which have already been established (e.g., GNS Science National Petrology Reference Collection https://pet.gns.cri.nz/#/nprc and the U.S. Polar Rock Repository http://research.bpcrc.osu.edu/rr/).

As far as tephras are concerned, the creation of new comprehensive databases (including data that are already available; e.g., http://www.tephrochronology.org/AntT/about.html) with high-quality geochemical data would facilitate the dating, synchronization and correlation of Antarctic archives as well as advance our knowledge of volcanism, through the study of products no longer available or inaccessible/unexposed in the source centres.

11.2. Preparing for a future eruption in Antarctica

The occurrence of an eruptive event in one of Antarctica's large active volcanoes (e.g., Deception Island, Mount Erebus, Mount Melbourne, The Pleiades, and Mount Rittmann) is highly probable, possibly in the near future. Therefore, it is mandatory to carry out mitigation in the form of hazard maps and risk assessments to be properly prepared and limit the potential impact, as well as to carry out informed land use planning or develop tourism protocols. It is crucial to advance the knowledge of the volcanic and magmatic history of those Antarctic volcanoes with confirmed or suspected Holocene activity (Geyer, 2021). More fieldwork campaigns are fundamentally important in defining volcanic hazards, with special emphasis on chronology, chemistry, and physical volcanology studies. Information obtained as a result of fieldwork should also be combined with probabilistic hazard models (e.g., for lava flow inundation areas, tephra dispersal) initiated for a range of realistic scenarios. Tephra layers found in glaciers and marine/lacustrine sediment cores are also highly important for reconstructing patterns of past volcanic activity.

A much clearer picture of the recurrence and size of past eruptions, and the spatial extent of the associated hazards, is fundamental for a proper assessment, to accurately quantify the potential impact of a future volcanic event, and to provide support to the monitoring teams interpreting the geophysical and geochemical signals during unrest episodes. There is also an urgent need to significantly improve monitoring networks on most of these volcanoes by expanding the recording-station coverage and ensuring real-time transmission of geophysical and geochemical monitoring equipment. The volcanic remote sensing community (e.g., Pritchard et al., 2022) is working to establish a global observatory within the next decade where relevant researchers, stakeholders, governments, civil protection groups, institutes and others will come together to advance the coordination and development of remote sensing. This should aid response-scenarios designed to mitigate the impacts of imminent eruptions, by improving forecasting and designing bespoke safety precautions. Additionally, this would pave the way for increased data access, particularly in areas with little to no scientific research funding. The remote sensing community may also greatly benefit from the proliferation of commercial satellite companies in providing relevant data, and help to push technology to achieve improved resolution, processing, sensor limits, and overall capabilities.

Finally, an important pillar of any volcanic risk preparedness plan is the early education of the people working, living close to or visiting a hazardous area. For example, educating about the natural warning signs that may precede a hazardous event can help improve the response. We consider that education campaigns need to be carried out to increase risk perception of the scientists (including those Earth Scientists who are not experts on volcanology), tourists and technical staff exposed to active Antarctic volcanoes. Such campaigns should focus on: (i) increasing knowledge of the types of volcanic hazards most likely to happen; (ii) raising awareness of the early warning signs, alert levels and information systems available; and (iii) indicating the preparedness measures and actions that should be adopted in order to mitigate personal risk if a warning is subsequently issued (e.g., Bird et al., 2010). These campaigns should ultimately aim to increase the perception of risk in order to ensure that personal preparedness measures are implemented (e.g., Johnston et al., 2005), and the vulnerability is reduced. Evidently, this should be accompanied by an increase in the knowledge of emergency procedures and participation in emergency training and evacuation exercises. Hazard, risk and emergency response information must also be distributed using several sources and channels according to the target audience (i.e., scientists, tourists, etc.). Such sources may include, for example, the preparation of pamphlets to be distributed among visitors, short videos, informative talks, accessible and easily understandable hazard maps, etc. Because an internationally accepted system for publicly disseminating information on the current state of activity of Antarctica's volcanoes does not yet exist and given the considerably increased numbers of scientists and tourists now visiting the region, creating such a system is highlighted here as a priority.

11.3. *Promote scientific collaboration and multidisciplinary research*

Based on the experience of SCAR and other international initiatives, the AntVolc Expert Group strongly encourages the fostering of scientific collaboration among different disciplines, promoting multidisciplinary research not only in the field of the Earth Sciences but also with Glaciology, Climate Change, and Biodiversity, among others. For example, close collaboration between petrological investigations and geophysical programs should aim to integrate physical and geochemical models for magmatic systems, thus linking the source to the surface. This would permit, for example, the definition and testing of rigorous criteria to verify the presence or absence of currently contested deep mantle plumes (e.g., under West Antarctica and the margin of East Antarctica) and explore scientific explanations for any genetic linkages between the geophysical and petrological data that become evident.

Finally, because of the high cost and risks associated with working in Antarctica, which make it financially prohibitive for many nations, we strongly encourage the creation of a permanent focussed Expert Group, under the aegis of SCAR to: (i) report on the threat level and current state of monitoring of active Antarctic volcanoes; (ii) provide practical support for assessing any volcanic hazard (including training in the use and interpretation of hazard maps, event trees, eruptive scenarios, etc.) and risk assessment tailored to the anticipated end-use (including the involvement of decision makers, media, etc.); (iii) contribute to the establishment or improvement of early-warning systems; (iv) improve or implement alert systems and communication protocols including a better coordination with existing Volcanic Ash Advisory Centers (VAAC) especially those in Wellington and Buenos Aires; and (v) increase the preparedness and awareness of exposed populations by proposing mitigation strategies (e.g., fortifying buildings, implementing educational programs addressed at enhancing public awareness).

Finally, we propose the creation of a virtual Volcano Hazard Observatory governed by SCAR and populated by experts, which should encourage the establishment of new monitoring networks and provide support to the ones already established (e.g., Deception Island, Mount Erebus, Mount Melbourne).

These proposals and initiatives, even if partially realized, would provide new light and lifeblood for volcanological research on active volcanism in Antarctica. Science in Antarctica has relevance for the future of multiple Earth systems and volcanological studies conducted there shall significantly improve our understanding of global issues.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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