Magmatism in Antarctica and its relation to Zealandia

Smellie, J.L.[a], Martin, A.P.[b]; Panter, K.S.[c], Kyle, P.R.[d] and Geyer, A.[e]

[a]School of Geography, Geology & the Environment, University of Leicester, LE1 7RH, UK; [b]GNS Science, Dunedin, New Zealand; [c]School of Earth, Environment & Society, Bowling Green State University, Ohio 43403, USA; [d]Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, USA; [e]Institute of Earth Sciences Jaume Almera, ICTJA, CSIC, 08028 Barcelona, Spain

Abstract

Antarctica and Zealandia were once adjacent blocks of Gondwana with a shared magmatic history during the Mesozoic and earlier. This is preserved in (a) shared Palaeozoic and Mesozoic Gondwana plutonism; (b) magmatism associated with syn-Gondwana breakup, including Jurassic-aged dolerite rocks of the Ferrar large igneous province, and igneous intrusions of similar isotopic affinity occurring on both continents coeval with Late Cretaceous rifting of Antarctica from Zealandia. The shared magmatic history continued post-Gondwana breakup through (c) the generation of oceanic crust and (d) eruption of diffuse alkaline magmatic province (DAMP) rocks. The DAMP encompasses magmatism from the Late Cretaceous to present day that shares isotopic and trace element characteristics over a (now) widely dispersed area of the southwest Pacific. This has been ascribed to either a previously contiguous mantle lithosphere with a shared, syn-Gondwana breakup history contributing to volcanic melts or to an isotopically distinct Antarctica—Zealandia asthenospheric mantle domain. The development of the Antarctic ice sheet after 34 Ma resulted in many volcanoes recording ice interactions that reveal many new details of Antarctica's palaeoenvironmental history. Study of the volcanic history of Antarctica helps to advance understanding of the geological history of the region, including once-conjugate continents like Zealandia.

Keywords: Gondwana, large igneous province, West Antarctic rift system, New Zealand volcanic geology, alkaline volcanism, pluton

Introduction

Magmatism has played an important role in the geological evolution of Antarctica with many similarities to Zealandia. However, today, an ice sheet covers most of the Antarctic landmass in stark contrast to New Zealand. Prior to c. 90 Ma, Antarctica and Zealandia were part of Gondwana. Zealandia is the almost wholly submerged continental landmass that subsided and fragmented after breaking away from Gondwana, leaving New Zealand as its largest fragment exposed above sea level (Mortimer et al. 2017; Fig. 1). Magmatism in Antarctica has occurred in a variety of tectonic settings that have resulted in diverse magma types and eruptive styles (Fig. 2). Some of the volcanism mirrors that occurring in New Zealand, but there are differences. Moreover, the presence of an extensive ice cover in Antarctica, and its interaction with the volcanism, has given rare opportunities to use the volcanic record to understand past environmental conditions. This paper examines the relationship between Antarctic—Zealandia magmatism, which by the nature of past plate reconstruction focuses on Marie Byrd Land and Victoria Land, and the ocean floor between Antarctica and Zealandia.

Geological Setting

Antarctica and Zealandia were once-conjugate blocks bounding the Pacific margin of Gondwana. Antarctica consists of ancient cratons and orogens with overlying strata in East Antarctica and; continental blocks, magmatic arc rocks and immature sedimentary rocks in West Antarctica (Siddoway 2008; Goodge & Finn 2010; Veevers 2012). The suture between East and West Antarctica is proposed to approximately intersect beneath the middle of the Ross Sea (Tinto et al. 2019; Fig. 2), so that Victoria Land is underlain by crust with East Antarctic affinities and Marie Byrd Land by West Antarctic crust. Antarctica and Zealandia share a Mesozoic batholithic history with age distribution patterns of West Antarctic plutons comparable to Median Batholith rocks in Zealandia (Weaver et al. 1994; Siddoway 2008; Siddoway et al. 2004; Tulloch et al. 2019).

Trans-continental rifting of Gondwana started in the Early Jurassic (c. 183 Ma) with a mantle plume that drove the Ferrar and Karoo large igneous provinces (Weaver et al. 1994; Storey & Kyle 1997). The rapid and short-lived emplacement of large volumes of mafic magma took place as intrusions and lava flows in East Antarctica and small volume dolerite intrusions in New Zealand (Mortimer et al. 1995; Figs 1, 2). Major, mainly rhyolitic explosive activity, which took place on the Antarctic Peninsula (Fig. 2), is unrepresented in New Zealand at that time. Simultaneously with the rhyolitic explosive activity, subduction and related magmatism formed a prominent long-lived continental magmatic arc along the Pacific margin. Subduction in Antarctica ended in the Cretaceous in Marie Byrd Land (Weaver et al.

1994) and parts of New Zealand (Tulloch and Kimbrough 2003) but continued along the Antarctic Peninsula as a consequence of plate reorganisation (Weaver et al. 1994).

A second episode of rifting took place in the mid-Cretaceous, culminating in the separation of Zealandia from Antarctica (Kula et al. 2007, 2009; Fig. 1). Rare, Late Cretaceous magmatism continued in Marie Byrd Land and southern Zealandia (Dennison and Coombs 1977; Weaver et al. 1992; Scott et al. 2015; Tulloch et al. 2019), but this period is usually regarded as amagmatic in Victoria Land (Jordan et al. 2020). Further rifting between East and West Antarctica became focused in the West Antarctic rift system (WARS). The WARS is a major pan-Antarctic continental rift 3000 km in length and 750-1000 km wide (Behrendt et al. 1991; Behrendt 1999; Jordan et al. 2020; Fig. 2). From Eocene time, alkaline magmatism became widespread throughout the WARS, including early plutonism in northern Victoria Land and eastern Marie Byrd Land but switched dominantly to volcanism, which has continued to the present-day. Temporally equivalent alkaline volcanism occurred in New Zealand in large polygenetic volcanoes at Dunedin, Banks Peninsula and various volcanic fields (e.g. Auckland, Waiareka Volcanics), seamounts and volcanic islands (Hoernle et al. 2006; Coombs et al. 2008; Timm et al., 2009, 2010; Mortimer, this volume; Scott et al. this volume). The WARS volcanism is characterised by numerous large volcanoes (LeMasurier 1990; Smellie et al. in press) that are related to a mantle plume in Marie Byrd Land and either mantle-edge flow, a mantle plume(s) or lithospheric delamination with asthenospheric decompression melting in Victoria Land and Zealandia (Hole and LeMasurier 1994; Hart et al. 1995, 1997; Timm et al. 2010; Gamble et al. 2018; Panter et al. 2018). Several volcanoes in Antarctica (Fig. 2) are considered to be active. Of these, at least eight (Mt Erebus, Mt Berlin, Mt Takahe, Mt Waesche, Mt Melbourne, Mt Rittmann, The Pleiades, possibly Hudson Mountains) are considered to be active mainly on the basis of dated Holocene eruptions, and three of them (Mt Erebus, Deception Island, Mt Melbourne) even have reported frequent volcanic activity in historical times.

Gondwana magmatism

Ross Orogen-associated magmatism in Victoria Land has occurred at least between c. 650 Ma and 492 Ma. In southern Victoria Land, rhyolite rocks have been dated at c. 650 Ma (Cooper et al. 2011), calc-alkaline plutons were emplaced during overlapping, but geographically separate, events at c. 550 to 525 Ma (south) and 515-492 Ma (north), which also coincided with alkalic and carbonatitic intrusions in southern Victoria land between c. 550 and 509 Ma (Hagen-Peter and Cottle 2016). In the Central Transantarctic Mountains plutonism is thought to occur in three phases (Goodge et al. 2012). The earliest phase between c. 590 and 555 Ma represents arc development, the middle phase (c. 555 to 515 Ma) is syn-tectonic and the youngest phase is mostly post-tectonic between c. 515 and 480 Ma (Goodge et al. 2012).

The Ross Orogen plutonism is known collectively as the Granite Harbour Intrusive Complex (Cox et al. 2012; Fig. 1) and rocks thought to be equivalent to this have been mapped in New Zealand (Gibson & Ireland 1996; Allibone et al. 2009a). At least four examples of Cambrian plutonism in New Zealand are thought to equate to Ross Orogen related rocks. One example of granitoid orthogneiss at Kellard Point in Doubtful Sound (Fig. 1) has been dated at 481 ± 8 Ma (Gibson & Ireland 1996), the Jaquiery granitoid gneiss (Fig. 1) has been dated at 492 ± 9 Ma (Allibone et al. 2009a), the Pandora Orthogneiss (tonalite) is c. 500 Ma (Allibone et al. 2009b) and the Dead Goat Conglomerate contains a metagranitic clast with a radiometric date of 496 ± 9 Ma (Gutjahr et al. 2006). The Ross Orogen-related rocks in New Zealand are chronologically equivalent to the latest, post-tectonic phase of plutonism recognised in the Granite Harbour Intrusive Complex. The major element, whole rock chemistry of the New Zealand Jaquiery granitoid gneiss is described as distinctly different from Antarctic Ross Orogen lithologies, with relatively high Ca and exceptionally low K for such a siliceous rock (e.g. Allibone et al. 2009a). Comparison with more recently acquired geochemistry, however, shows a high degree of overlap of whole rock trace element concentrations (Martin et al. 2015 and references therein; Fig. 3). In summary, Ross Orogen-related plutonism does form part of the New Zealand basement, with studied New Zealand examples overlapping chronologically and geochemically (trace elements) with rocks in Victoria Land, Antarctica.

In Marie Byrd Land, the basement has been divided into the Amundsen Province and Ross Province (Pankhurst et al. 1998; Fig. 1). Granitoids in the Amundsen Province chronologically and geochemically correlate with rocks in the Zealandia Median Batholith (Fig. 1). Ross Province granitoids are better correlated with Devonian—Carboniferous terranes and suites in Zealandia (Pankhurst et al. 1998; Tulloch et al. 2019; Fig. 1). This is exemplified by a pulse of coeval granitoid magmatism in both the Antarctic Fosdick Mountains and Zealandia Karamea Suite at 370 ± 1 Ma (Siddoway & Fanning 2009; Tulloch et al. 2009, 2019). These plutons are a record of subduction-related magmatism of the Phoenix plate.

Gondwana break-up magmatism

Large igneous province rocks

Gondwana break-up-related magmatism in Antarctica is represented by two major volcanic provinces, one mafic [the Ferrar large igneous province (FLIP)] the other felsic (Chon Aike), which crop out in different areas (Fig. 2). There is no counterpart of the felsic province in New Zealand. However, coeval equivalents of the mafic FLIP are present in New Zealand as the Kirwins Dolerite (Mortimer et al. 1995; Fig. 1), as well as in southern Africa and Tasmania. In New Zealand, the Kirwans Dolerite (c. 1 km^2) is composed of sills and dykes. It is chemically similar to low-Ti tholeiite rocks and is considered part of the Jurassic-aged FLIP. The FLIP in Antarctica was characterised by intrusion of thick dolerite sills (Ferrar dolerite) throughout the Transantarctic Mountains, the large intrusive Dufek Massif and a contemporaneous, similarly-widespread but now much-eroded flood lava flow cover (Kirkpatrick basalts; Fig. 2). The intrusive rocks and lava flows were probably emplaced in less than 0.4 m.y. at c. 183 Ma, which is remarkable given that the estimated volume of tholeiitic magma is > 0.5 x 10^6 km^3 (Burgess et al. 2015). No major feeder dykes or vents have been reported. Conversely, the earliest activity consisted of major phreatomagmatism that erupted from multiple overlapping coalesced maar—diatreme complexes, called phreatocauldrons (White & McClintock 2001). The mafic volcanism coincided geographically with the locus of a major long-lived sedimentary basin, now represented by the sedimentary Beacon Supergroup, and the volcanism probably completed the infilling of that basin. The eruptions exerted a major environmental impact of global extent and may have been responsible for the Toarcian mass extinction event (Ernst & Youbi 2017).

Late Cretaceous rift-related plutonic rocks

Rifting and break-up of Gondwana is typified by a metamorphic core complex in the Fosdick Mountains, Marie Byrd Land (Fig. 1) with exhumation ages between 109 and 102 Ma (Richard et al. 1994; Siddoway 2008; McFadden et al. 2010; Brown et al. 2016). Equivalent metamorphic core complexes related to the separation of Antarctica and New Zealand are observed in Stewart Island, New Zealand as the Sister Shear Zone (Kula et al. 2007, 2009), later named Pegasus (89 to 80 Ma; Ring et al. 2015; Fig. 1). The Paparoa Core Complex (Fig. 1) is as likely to be associated with separation of New Zealand and Australia (102 to 89 Ma; Tulloch & Kimbrough 1989). Rift-related magmatism associated with the separation of Antarctica and Zealandia is found in Marie Byrd Land (Storey et al. 1999). Australia—New Zealand—Antarctica were undergoing Late Cenozoic separation contemporaneously (e.g. Gaina et al. 1998), and magmatism on the east coast of New Zealand (Weaver & Smith 1989; Weaver & Pankhurst 1991a; Baker et al. 1994; Fig. 1) and west coast of New Zealand (Waight et al. 1998; van der Meer et al. 2016) may be related to either Antarctica or Australia rifting, the cessation of subduction or mantle melting beneath the accreted Hikurangi Plateau (van der Meer et al. 2017). A-type granitoids of the Byrd Coast Granite were emplaced between 101 and 95 Ma (Weaver et al. 1992). The equivalent granitoid types in Zealandia are found inboard of the Median Batholith, most probably associated with granite intrusions found on The Snares and the Auckland Islands of southern Zealandia (Scott et al. 2015; Scott and Turnbull 2019; Tulloch et al. 2019; Fig. 1).

Post-Gondwana breakup magmatism

Oceanic crust

The earliest evidence for a switch to extensional tectonics in New Zealand is at c. 108 Ma (Scott and Cooper, 2006), with Larter et al. (2002) suggesting rifting between Antarctic and Zealandia probably commenced between West Antarctica and the Chatham Rise (south

Zealandia) at c. 90 Ma. Seafloor spreading commenced near the Bounty Trough (Fig. 1) at c. 85 Ma (Larter et al. 2002; Davy 2006), though the earliest preserved magnetic identification is chron 34y at c. 83 Ma (Wright et al. 2016; Mortimer et al. 2019). Early spreading involved a number of ridge jumps, for example from the Bounty Trough to the margin of Marie Byrd Land. Spreading was asymmetrical and saw the initiation of seafloor spreading between West Antarctica and the Campbell Plateau at chron 33r (83 to 79.1 Ma; Larter et al. 2002). This period of oceanic crust formation post c. 90 Ma is amagmatic in Marie Byrd Land and Victoria Land (Jordan et al. 2020) but is associated with intraplate magmatism in Zealandia (Timm et al. 2010; Mortimer et al. 2019). Dredge samples of primitive basalts along the Australian Antarctic Ridge in the area of sea floor between Antarctica and Zealandia (Park et al. 2019) as well as dredge samples from the Adare Basin seamounts (Panter et al. 2018) located in the northern Ross Sea and the Marie Byrd seamounts (Kipf et al. 2014) located in the Amundsen Sea (Fig. 2) have been studied isotopically and are discussed in the following section on diffuse alkaline magmatic province rocks.

Diffuse alkaline magmatic province rocks

Petrogenesis

Intraplate magmatism found on continental fragments of east Gondwana and the adjacent oceanic lithosphere is grouped together based on age, distribution, volume and similar geochemical and isotopic characteristics as a diffuse alkaline magmatic province (DAMP; Finn et al. 2005). The DAMP encompasses parts of Antarctica, eastern Australia, Tasmania and Zealandia (Fig. 2) and is long-lived, beginning with Late Cretaceous magmatism in New Zealand (Panter et al. 2006) and through the Cenozoic to current activity in Antarctica (e.g. Mount Erebus). In Zealandia, c. 100 Ma magmatism is associated with the Tapuaenuku (Baker et al. 1994) and Mandamus (Weaver & Pankhurst 1991b) igneous complexes (Fig. 1), the Westland Dike Swarm (van der Meer et al. 2016, 2017), and magmatism around 85-82 Ma and younger is associated with Chatham Island (Fig. 1) and eastern Chatham Rise (Grindley et al. 1977; Panter et al. 2006). Large, polygenetic volcanoes occur at Dunedin, Banks Peninsula and the Campbell Plateau (Auckland, Campbell and Antipodes islands), with smaller volume (< 100 km^2) volcanic fields, seamounts and volcanic islands occurring elsewhere (Morris 1984; Timm et al. 2009, 2010; Scott et al. 2015; Gamble et al. 2018; Scott and Turnbull 2019; Mortimer & Scott this volume; Scott et al. this volume). In Antarctica, the Marie Byrd Land Volcanic Group on the eastern WARS rift shoulder is dominated by 19 major volcanoes which penetrate the West Antarctic Ice Sheet (LeMasurier 2013; Panter et al. in press; Wilch et al. in press). Additionally, more than 100 subglacial volcanoes have been identified concentrated along the central-axis of the WARS in Marie Byrd Land (van Wyk de Vries et al. 2018). In Victoria Land, volcanism of the McMurdo Volcanic Group occurs in three regions comprising from north to south the Hallett, Melbourne and Erebus volcanic provinces. Tomographic models show that the upper mantle underlying the DAMP region between East Antarctica and the Australian—Antarctic mid-ocean ridge is characterized by slow velocity anomalies (Lloyd et al. 2019). Furthermore, bathymetric data suggest that a lower density upper mantle in this region may be long-lived (c. 100 Ma) to account for the subsidence history of the Campbell Plateau as Zealandia rifted away from West Antarctica (Sutherland et al. 2010).

A compositional commonality throughout the DAMP has long been recognized and judged to be related to a common mantle source component underlying the once-adjacent continental landmasses (e.g. Coombs et al. 1986; Barreiro & Cooper 1987; Johnson 1989). The trace-element enrichment and isotopic signatures of the basalts from these Gondwana fragments are similar to mantle sources for ocean island types (OIB) and in particular a contribution from a HIMU-like variety characterized by low $^{87}Sr/^{86}Sr$ and high $^{206}Pb/^{204}Pb$ values. This was the compositional basis for the promotion of sub-lithospheric plume sources for regions within DAMP (Fig. 2) by earlier studies (e.g. McDonough et al. 1985; LeMasurier and Rex, 1989; Kyle et al. 1992; Lanyon et al. 1993; Baker et al. 1994; Weaver et al. 1994). Mantle plumes have been proposed as one cause of Late Cretaceous volcanism in New Zealand (Hoernle et al. 2020) and some Late Cenozoic to on-going volcanic activity in West Antarctica (Hole and LeMasurier 1994; Phillips et al. 2018). The presence of a large mantle plume may explain the distribution and origin of the Marie Byrd Land volcanoes (LeMasurier & Landis 1996). The similar compositional characteristics of DAMP rocks has also been explained as being sourced from a single large plume head ('superplume') that was introduced beneath Gondwana in the Late Cretaceous or earlier and became a lithospheric reservoir for the later volcanism (Hart et al. 1997; Panter et al. 2000; Kipf et al. 2014). Recently, Park et al. (2019) supported a Late Cretaceous superplume model to account for the isotopic compositions of basalts dredged from the Australian—Antarctic mid-ocean ridge. They envisaged a deep mantle upwelling that has mixed with asthenosphere to create a widespread sub-lithospheric mantle domain sampled by both oceanic and continental volcanism within the DAMP. Alternatively, sources and mechanisms responsible for DAMP volcanism that do not require mantle plume activity have been proposed. These models call for mantle lithosphere that has been metasomatized by incompatible element-enriched fluids and small degree partial melts to promote radiogenic ingrowth of the HIMU-like signature with the melting of the lithosphere being triggered in a variety of ways (e.g. edge-driven mantle flow, translithospheric faulting, lithospheric delamination) to explain magmatism within DAMP (Rocchi et al. 2002; Panter et al. 2006; Sprung et al., 2007; McCoy-West et al. 2010; Martin et al. 2013; van der Meer et al. 2017; Panter et al. 2018; Day et al. 2019; Scott et al. this volume).

Active volcanism

Active volcanism is widespread in Antarctica (LeMasurier 1990; Smellie et al. in press) and thus similar to New Zealand (e.g. Hopkins et al. 2020). Several large volcanoes are known or inferred to be active in Victoria Land and Marie Byrd Land. Only Mount Erebus (south

Victoria Land) and Deception Island (the Antarctic Peninsula; Fig. 2) have been observed in eruption (Geyer et al. in press). Erebus contains the world's only permanent convecting lava lake with a phonolite composition. It has been monitored and studied intensively since the early 1970s (Kyle 1994; Oppenheimer & Kyle 2008). Mount Melbourne and Mount Berlin (Fig. 2) have also been the source of numerous englacial tephra, together with tephra identified with Mount Takahe, Mount Waesche, Mount Rittman and possibly The Pleiades (Lee et al. 2019; Dunbar et al. in press; Fig. 2). Some eruptions of these volcanoes may have the potential to significantly influence global climate, e.g. by accelerating Southern Hemisphere deglaciation (McConnell et al. 2017). In Victoria Land, the scarcity of pyroclastic rocks is probably due to the eruptions being mainly glaciovolcanic and thus poorly preserved (Smellie, in press), but Late Pleistocene-Holocene tephra have been found in marine sediment cores from the Ross Sea (Del Carlo et al. 2015).

Glaciovolcanic sequences

Both Antarctica and New Zealand record lava—ice interactions studied in a field called glaciovolcanology (Smellie & Edwards 2016). Glaciovolcanic sequences are recorded at Ruapehu, New Zealand, between c. 51 and 15 ka that indicate extensive interactions between alpine glaciers and andesite—dacite lava flows (Conway et al. 2015). By contrast, in Victoria Land the Cenozoic glaciovolcanic rocks indicate interactions with ice sheets. The latter fall into two main groups. Group I is the most common comprising multiple, mafic ʻaʻā lava-fed deltas. Group II includes englacial lava flows and domes (Smellie et al. 2011). The associated glacial cover was generally c. < 250 m; significantly thicker than the alpine glaciers involved with glaciovolcanic sequences at Ruapehu. The combination of geochronology and glaciovolcanology is a powerful technique for palaeoclimate reconstructions that is useful in both Antarctica and New Zealand.

Conclusions

Antarctica and Zealandia were contiguous in eastern Gondwana prior to rifting at c. 84 Ma. Like New Zealand, magmatism has played an important role in the geological evolution of Antarctica. Although volcanism older than c. 200 Ma is present in Antarctica, it is patchily preserved and poorly understood. By contrast, the volcanism younger than c. 200 Ma is well documented and is better understood. A shared magmatic history between Antarctica and Zealandia is evident from preserved Gondwana-aged plutonism, co-occurrence of Ferrar large igneous province (FLIP) rocks in Antarctica and New Zealand and syn-Gondwana breakup plutonism preserved in Marie Byrd Land and Zealandia. Late Cretaceous—Cenozoic intraplate volcanism in Antarctica and Zealandia share isotopic and trace element characteristics within a diffuse alkaline magmatic province (DAMP). The DAMP rocks include at least eight examples of active volcanism in Antarctica, and lava—ice interactions recorded in both Antarctic and New Zealand volcanic rocks are important palaeoclimate proxies.

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Figures

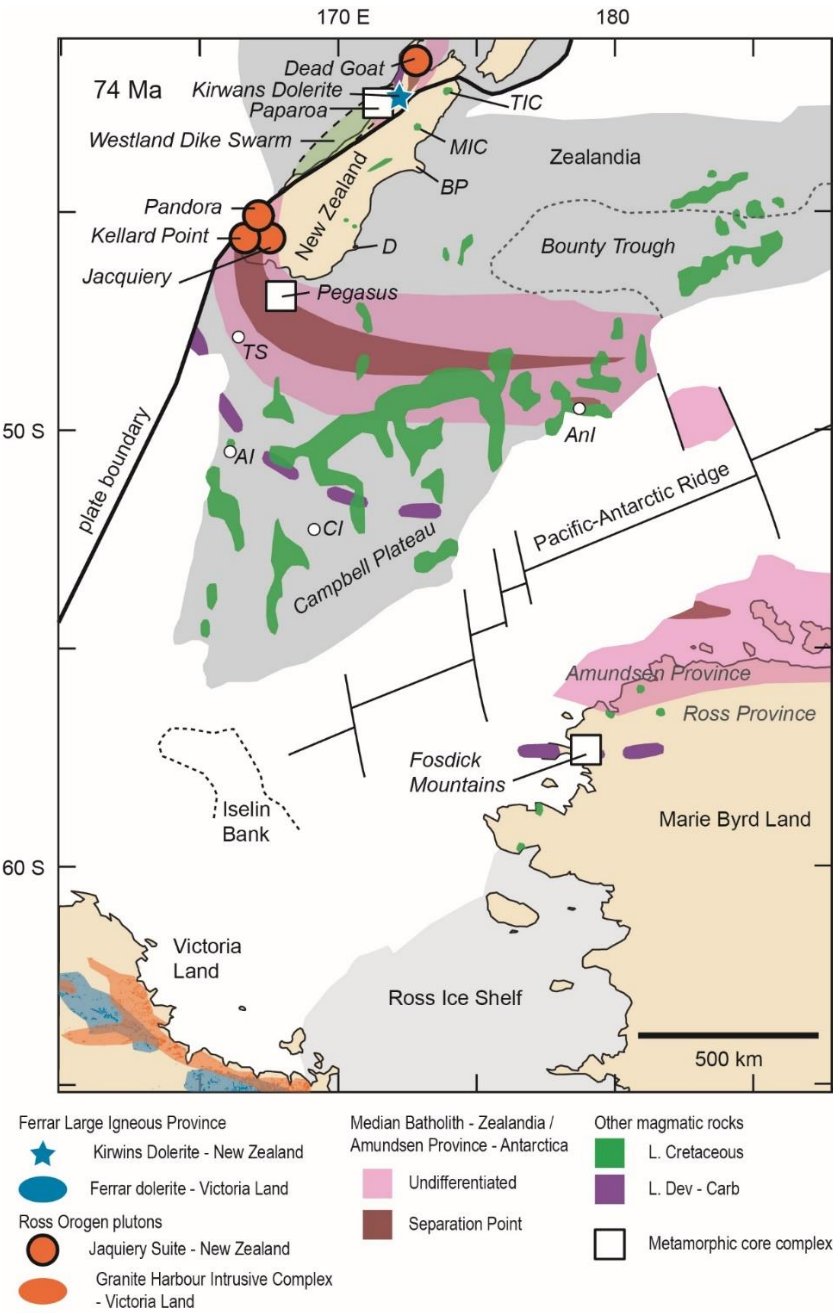

Fig. 1. Schematic diagram showing significant magmatic features shared between Antarctica and Zealandia at c. 74 Ma (adapted from Sutherland 1999; Tulloch et al. 2019). Rock outcrops in Victoria Land (Jurassic magmatic rocks – blue; Cambrian intrusive rocks – orange) are from GeoMap (Cox 2019). AI: Auckland Island; AnI: Antipodes Island; BP: Banks Peninsula; CI: Campbell Island; D: Dunedin MIC: Mandamus Igneous Complex; TIC: Tapuaenuku Igneous Complex; TS: The Snares.

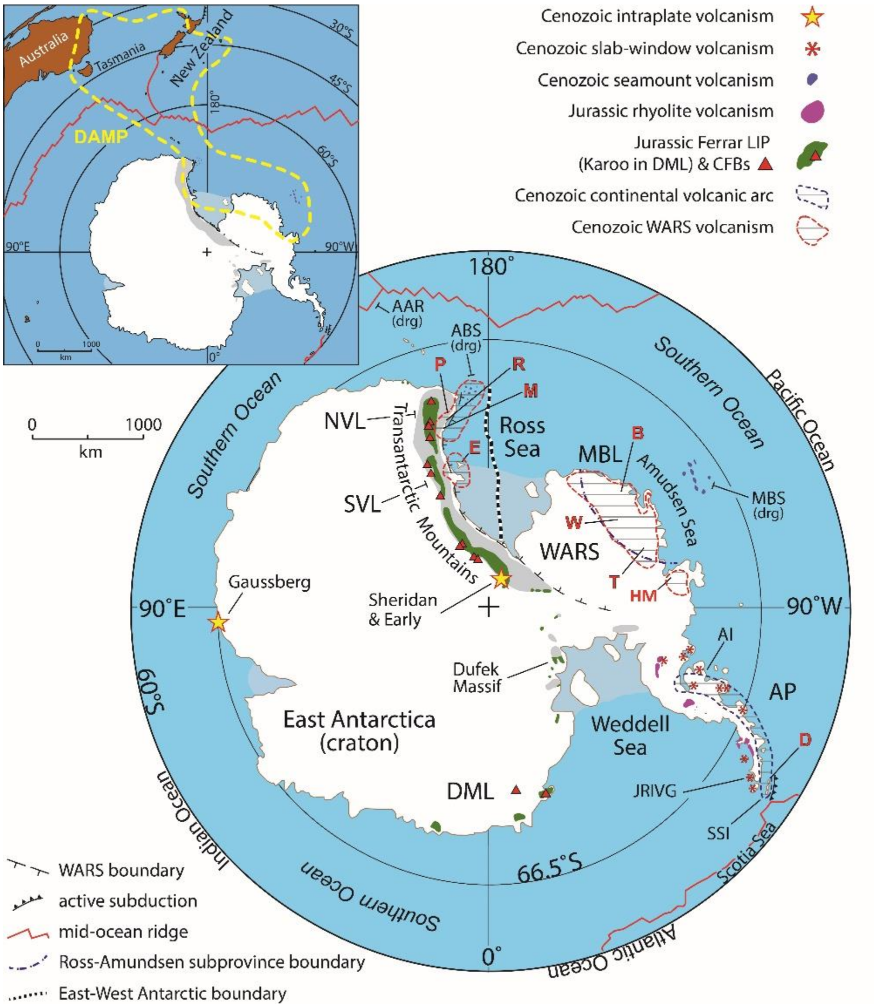

Figure 2. Map of Antarctica showing the distribution of Mesozoic (Jurassic & Cretaceous) and Cenozoic tectonomagmatic provinces and volcanism (modified after Panter in press). Distribution of Ferrar and Karoo Large Igneous Provinces (LIPs) and associated continental flood basalts (CFBs) after Elliot and Fleming (in press) and Luttinen (2018). Locations of Jurassic rhyolite volcanism are from Riley and Leat (in press). 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: AAR = Australian-Antarctic Ridge collected by dredging (drg; Park et al., 2019); ABS = Adare Basin Seamounts collected by dredging (drg; Panter et al., 2018); AI = Alexander Island; AP = Antarctic Peninsula; DML = Dronning Maud Land; HM = Hudson Mountains; JRIVG = James Ross Island Volcanic Group; MBL = Marie Byrd Land; MBS = Marie Byrd Seamounts

collected by dredging (drg; Kipf et al., 2014); NVL = North Victoria Land; SSI = South Shetland Islands; SVL = South Victoria Land. Cenozoic WARS volcanism in MBL belongs to the Marie Byrd Land Volcanic Group (Wilch et al. in press) and Cenozoic volcanism highlighted in NVL and SVL belongs to the McMurdo Volcanic Group. 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).

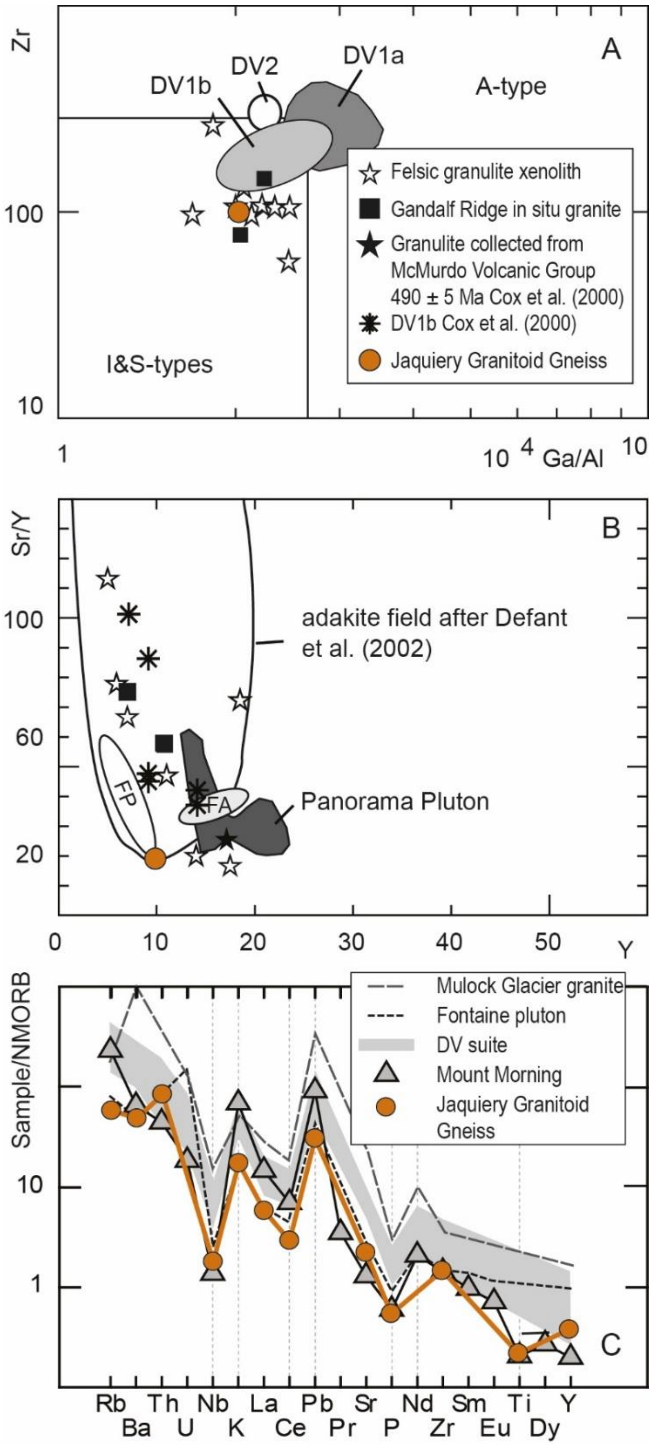

Fig. 3. Whole rock trace element chemistry of Jaquiery granitoid gneiss New Zealand (Fig. 1) relative to select, equivalent Ross Orogen plutonic rocks and xenoliths in Antarctica. The Antarctic comparisons are granulite crustal xenoliths in Cenozoic volcanic rocks in southern Victoria Land (Cox et al. 2000; Martin et al. 2015), the Dry Valleys suites of granites (Cox et al. 2000); granite outcrops at Gandalf Ridge, Mount Morning (Martin et al. 2015); Fontaine Pluton (FP) rocks (Cottle & Cooper 2006a); Fontaine Adakite (FA) rocks (Cottle 2002); Panorama Pluton rocks (Mellish et al. 2002) and; A-Type Mulock Glacier Granite (Cottle & Cooper 2006b). **A**. 10^4Ga/Al versus Zr ppm plot after Whalen et al. (1987) **B**. Y ppm versus Sr/Y plot with adakite fields from Defant et al. (2002). **C**. Normal mid-ocean ridge basalt, normalised (Sun & McDonough 1989) extended element plot.