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Cretaceous magmatism in the Antarctic Peninsula and its tectonic implications

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Abstract

Periods of cessation, resumption and enhanced arc activity are recorded in the Cretaceous igneous rocks of the Antarctic Peninsula. We present new geochronological (LA-ICP-MS zircon U-Pb) analyses of 36 intrusive and volcanic Cretaceous rocks, along with LA-ICP-MS apatite U-Pb analyses (a medium-temperature thermochronometer) of 28 Triassic–Cretaceous igneous rocks of the Antarctic Peninsula. These are complemented by new zircon Hf isotope data along with whole-rock geochemistry and isotope (Nd, Sr and Pb) data. Our results indicate that the Cretaceous igneous rocks of the Antarctic Peninsula have geochemical signatures consistent with a continental arc setting and were formed during the interval ~140–79 Ma, while the main peak of magmatism occurred during ~118–110 Ma. Trends in \(\varepsilon\)Hf (zircon) combined with elevated heat flow that
remagnetised rocks and reset apatite U-Pb ages suggests that Cretaceous magmatism formed within a prevailing extensional setting that was punctuated by periods of compression. A noteworthy compressive period probably occurred during \(\sim 147-128\) Ma, triggered by the westward migration of South America during opening of the South Atlantic Ocean. Cretaceous arc rocks that crystallised during \(\sim 140-100\) Ma define a belt that extends from southeastern Palmer Land to the west coast of Graham Land. This geographic distribution could be explained by (i) a flat slab with east-dipping subduction of the Phoenix Plate, or (ii) west-dipping subduction of the lithosphere of the Weddell Sea, or (iii) an allochthonous origin for the rocks of Alexander Island. A better understanding of the geological history of the pre-Cretaceous rocks of Alexander Island and the inaccessible area of the southern Weddell Sea is required.

1. Introduction

The Antarctic Peninsula hosts one of the major Mesozoic-Cenozoic continental magmatic arcs of the circum-Pacific, which extends almost continuously for \(\sim 1350\) km along the length of the peninsula (Pankhurst, 1982; Leat et al., 1995; Millar et al., 2002). Arc rocks were emplaced from the Late Triassic (Leat et al., 1995; Bastias et al., 2020) to the Miocene (e.g. Leat et al., 1995; Jordan et al. 2014), with a surge in magmatic volume during the Cretaceous (Leat et al., 1995; Riley et al., 2018; Jordan et al., 2020). These arc-related rocks intrude late Palaeozoic–Triassic sedimentary sequences in Graham Land (e.g. Pankhurst, 1983; Castillo et al., 2016) and Triassic metamorphic orthogneisses (Millar et al., 2002; Flowerdew et al., 2006) associated with an active margin in Palmer Land (Bastias et al., 2020; Riley et al., 2020a).

Globally, Cretaceous arc magmatism is considered to represent a significant Phanerozoic phase of growth of the continental crust (e.g. Kemp et al., 2009; Ducea et al., 2015). Regionally, the Cretaceous is also characterised by significant deformation along much of the western margin of Gondwana (e.g. Vaughan and Livermore, 2005; Bryan and Ferrari,
which was accompanied by a global plate reorganisation event (Matthews et al., 2012). Arc magmatism along the Antarctic Peninsula formed during east-dipping subduction of Pacific oceanic lithosphere beneath the Antarctic plate in south-western Gondwana (Fig. 1a; e.g. Pankhurst, 1990; Burton-Johnson & Riley, 2015; Bastias et al., 2021a). Evidence of arc magmatism includes individual plutons, composite intrusions and extensive batholith-like units (e.g. Leat et al., 1995). Previous studies of the Cretaceous peak of arc magmatism in the Antarctic Peninsula have focused on their episodicity (Riley et al., 2018) and magmatic-tectonic relationships (Burton-Johnson et al., 2022), although the regional processes that controlled and triggered a higher rate of magma addition to the crust remain unclear.

The aim of this study is to further constrain the magmatic and tectonic evolution of the Cretaceous arc of the Antarctic Peninsula by providing new geochronological, geochemical and isotopic data, and integrating our data with the timing of magmatism, subduction architecture and tectonic history presented in previous studies. We present 36 new zircon U-Pb (crystallisation) dates (obtained using Laser Ablation – Inductively Coupled Plasma Mass Spectrometry; LA-ICPMS), and geochemical (whole rock) and isotopic (whole rock Nd, Sr, Pb; zircon Hf) data acquired from Cretaceous igneous units exposed in the Antarctic Peninsula (Graham and Palmer Land; Fig. 1b). These are complemented by mid-temperature (>350°C) apatite U-Pb thermochronology data obtained by LA-ICP-MS. The igneous rocks crop out in remote locations that were either sampled during two field seasons as part of this study, or samples were provided by the British Antarctic Survey archive and the Polar Byrd Polar and Climate Research Center, USA. We combine our data with previous results from the Antarctic Peninsula (Riley et al., 2001; 2016, 2018, 2020b; Ryan, unpub., 2007; Leat et al., 2009; Haase et al., 2012; Bastias 2014, 2020; Bastias et al., 2019, 2020, 2021a, 2021b; Burton-Johnson et al., 2022).

2. Geological framework and previous work

The continental crust of the Antarctic Peninsula was interpreted by Suárez (1976) to represent an autochthonous segment of an extensive continental arc that spanned
Mesozoic western Gondwana. Alternatively, other authors have suggested that the Antarctic Peninsula crust formed by collision and accretion of an allochthonous arc with a block of Gondwanan affinity either during the middle of the Cretaceous (Vaughan and Storey, 2000) or earlier, close to the Jurassic-Triassic boundary (Vaughan et al., 2012). More recently, Burton-Johnson & Riley (2015) and Bastias et al. (2020) provided substantial geochronological and isotopic evidence for an autochthonous to parautochthonous Mesozoic evolution, with subduction initiation during the Late Palaeozoic, supporting the initial interpretation of Suárez (1976).

Arc magmatism along the Antarctic Peninsula occurred from at least the Late Triassic (Pankhurst, 1982; Bastias et al., 2020; Riley et al., 2020a), when it formed a segment of the Terra Australis margin of western Gondwana (e.g. Cawood, 2005). Subsequently, a Late Triassic active margin was associated with the Rymill Granite Complex (Bastias et al., 2020), which is mostly comprised of orthogneisses and is widely exposed in the central Antarctic Peninsula and formed during an extensional tectonic regime that modified the entire Pacific margin of west Gondwana (Spikings et al., 2016). Early Jurassic arc magmatism was concentrated in Palmer Land (Riley et al., 2017; Bastias et al., 2021a) and shifted to Graham Land during the Middle-Late Jurassic (e.g. Bastias et al., 2021a). Most of the Jurassic magmatic rocks in the Antarctic Peninsula have been linked to the influence of an active margin and perhaps the migration of the Karoo mantle plume from southern Africa as well (Pankhurst et al., 2000; Riley et al., 2001). However, Bastias et al. (2021a) recently suggested that most Jurassic magmatism probably formed within an active margin that was characterised by a flat-slab setting.

Cretaceous magmatic rocks are exposed along the west coast of Graham Land and in eastern Palmer Land (Fig. 2a). Magma addition rates to the Antarctic Peninsula peaked during the Early Cretaceous (e.g. Leat et al., 1995, 2009; Riley et al., 2018), which is considered to be the most voluminous episode of Phanerozoic plutonism in the Antarctic Peninsula (e.g. Leat et al., 1995, 2009; Vaughan et al., 2012; Riley et al., 2018; Burton-Johnson et al., 2022). These rocks range from mafic to felsic compositions, but are
predominantly intermediate, and the published radiometric dates (K-Ar, Rb-Sr, $^{40}$Ar/$^{39}$Ar
and U-Pb methods) range between $\sim$141 and $\sim$67 Ma (Leat et al., 1995).

Early Cretaceous volcanic rocks are abundant along the west coast of the Antarctic Peninsula and the South Shetland Islands (Fig. 2a; e.g. Leat et al., 1995). Most of these are basalts and andesites with a calc-alkaline affinity (e.g. Haase et al., 2012). The Early Cretaceous plutonic record includes a few exposures on the South Shetland Islands (~137-109 Ma; Hervé et al., 2006; Bastias et al., 2019) and in southeast Palmer Land, where the Lassiter Coast Intrusive Suite is exposed (Fig. 2a; Rowley et el., 1983; Riley et al., 2018; Burton-Johnson et al., 2022). These rocks are mainly tonalite, quartz diorite and granodiorite and crop out over an area of $\sim$80,000 km$^2$ (Fig. 2a; Burton-Johnson et al., 2022). Zircon U-Pb concordia dates suggest the Lassiter Coast Intrusive Suite was emplaced in three pulses at 130 – 126 Ma, 118-113 Ma and 108 – 102 Ma (Riley et al., 2018). Burton-Johnson et al. (in press) further resolved the central episode of magmatism with secondary pulses at $\sim$118-116 Ma, $\sim$114-112 Ma and $\sim$110-109 Ma, which are consistent with the model of Paterson and Ducea (2015). Pankhurst and Rowley (1991) and Leat et al. (2009) obtained whole rock $^{87}$Sr/$^{86}$Sr and $\varepsilon$Nd values from the Early Cretaceous volcanic rocks of the Antarctic Peninsula, which span 0.7080–0.7056 and -0.4 to -1.8, respectively, from rocks that yielded Rb-Sr ages of $\sim$132-116 Ma.

Late Cretaceous igneous rocks are less widely exposed (Fig. 2a; e.g. Leat et al., 1995), with isolated calc-alkaline granodioritic plutons associated with Late Cretaceous mafic dykes in the central Antarctic Peninsula (Wever et al., 1994; Leat et al., 1995). Most of the mafic dykes yield calc-alkaline compositions, although some Ocean Island Basalt-like mafic dykes occur locally (Leat and Riley, 2021), which Leat et al. (1995) utilised to infer an extensional setting. Ryan (unpub. Ph.D. thesis, Univ. Brighton, 2007) obtained zircon LA-ICP-MS U-Pb concordia dates that range between $\sim$92-89 Ma, and $^{87}$Sr/$^{86}$Sr and $\varepsilon$Nd values that span 0.7047 - 0.7045 and 2.5 - 2.2, respectively, for plutons exposed in west-central Graham Land (Fig. 2a). Leat et al. (2009) report Rb-Sr isochron ages between $\sim$96 and $\sim$71 Ma for volcanic rocks located within the central-western Antarctic Peninsula, which yield whole
rock $^{87}\text{Sr}/^{86}\text{Sr}$, and $\varepsilon\text{Nd}$ values of 0.7112–0.7056, and 0.0 – -1.8, respectively. Recently, Riley et al. (2020b) published U-Pb zircon dates ranging between ~94 and 64 Ma from felsic volcanic rocks located in northwestern and central Palmer Land and suggested that arc magmatism migrated trenchward during the Late Cretaceous along the southern Antarctic Peninsula, which is consistent with previous work (e.g. Thomson et al., 1983; Leat et al., 1995). In contrast, the locus of magmatism in Graham Land does not appear to change with respect to the trench throughout the Cretaceous.

An extensional regime dominated the Antarctic Peninsula during the Cretaceous, as evidenced by the emplacement of large volumes of magmatic rocks as plutons and dykes, accompanied by normal faults (Meneilly et al., 1987; Leat et al., 1995; Wever et al., 1994). However, the Cretaceous period was also associated with brief compressional events at ~138, ~113 and ~107–100 Ma in the Antarctic Peninsula (e.g. Meneilly, 1988; Leat et al., 1995; Vaughan & Storey, 2000; Riley et al., 2020b). These compressional events have been linked either to increases in the subduction convergence rate (at ~138 and ~113 Ma; e.g. Riley et al., 2020b) or to the collision of an allochthonous terrane (~107–100 Ma Vaughan & Storey, 2000). The latter collisional event has been disputed in more recent studies (Burton-Johnson & Riley, 2015; Bastias et al., 2020). A more extensive compressional episode along western Gondwana has been proposed (e.g. Vaughan, 1995; Vaughan & Livermore, 2005; Mpodozis et al., 2005; Burton-Johnson & Riley, 2015; Spikings et al. 2015; Boyce et al., 2020).

3. Methods

We present new zircon U-Pb geochronological, geochemical and isotopic data from 36 igneous rocks of the Antarctic Peninsula (Fig. 1). The rocks were taken from the Lassiter Coast Intrusive Suite in eastern Palmer Land, and from intrusions that are scattered along the west coast of central Palmer Land at the latitude of the Black Coast. Additional plutonic rocks were collected from the west coast of Graham Land and the South Shetland Islands. The methods used in this work are described in detail in the Supplementary Material Methodology.
4. Results

4.1. Zircon LA-ICP-MS U-Pb geochronology

We present U-Pb zircon concordia ages from 36 igneous rocks that vary in age between 139 ± 1 and 79 ± 1 Ma (Table 1; Figure 2a). Early Cretaceous ages were obtained from 33 samples, and range from 139 ± 1 to 101 ± 1 Ma, with no particular geographic trend (Fig. 2a). Three samples yield Late Cretaceous ages from 92 ± 1 to 79 ± 1 Ma and are located along the west coast of the Antarctic Peninsula. The kernel density estimate (KDE) of the $^{206}$Pb/$^{238}$U concordia ages yields several peaks during the Cretaceous, and these have been separated into three groups to facilitate the presentation of the data. These groups are (i) a cluster of older ages at ~140-132 Ma (Berriasian-Valanginian-Hauterivian), (ii) a younger group that includes several KDE peaks from 126 to 100 Ma (Barremian-Albian), and (iii) the youngest group with Late Cretaceous ages spanning ~92-79 Ma (Turonian-Campanian; using the International Chronostratigraphic Chart time scale of Cohen et al., 2020; Fig. 2b). Cathodoluminescence images (see a few examples in Fig. 2c) show that most zircons have patchy or oscillatory zonation, mostly with no clear rim-core relationships; all are typical of igneous zircon (e.g. Chelle-Michou et al., 2014).

Six granodiorites and monzogranites of the Lassiter Coast Intrusive Suite yield $^{206}$Pb/$^{238}$U concordia dates of ~126-112 Ma (Fig. 2a), consistent with previous studies (~130-102 Ma; Pankhurst and Rowley, 1991; Riley et al., 2018; Burton-Johnson et al., 2022). Further north, seven samples from the west coast of Palmer Land yield zircon $^{206}$Pb/$^{238}$U concordia dates of ~140-79 Ma (Fig. 2a), while five monzogranites, syenogranites, tonalites and quartz-monzonites are Early Cretaceous in age (~139-114 Ma), and two syenogranites have Late Cretaceous ages (92 ± 1 and 79 ± 1 Ma). At the latitude of Adelaide Island (~67°S), eight alkali granites, granodiorites and quartz-monzonites yield Early Cretaceous dates that span ~118-101 Ma (Fig. 2a). Further north, seven alkali granites, syenogranites, monzogranites and monzodiorites from the west coast of southern Graham Land also yield Early Cretaceous ages that span ~135-101 Ma, while a gabbro yields a Late Cretaceous date of 81 ± 1 Ma (Fig. 2a). The northernmost Cretaceous $^{206}$Pb/$^{238}$U concordia
dates were obtained from three monzogranites and a granodiorite from the South Shetland Islands, which span ~138-101 Ma, and are consistent with previous age estimates of volcanic and intrusive rocks from that region (Hervé et al., 2006; Bastias, 2014; Israel, 2015; Bastias et al., 2019). These data show that Early Cretaceous rocks occur extensively along the Antarctic Peninsula from the southeast in Palmer Land to the northwest in Graham Land, while Late Cretaceous plutons are less abundant, and crop out along the west coast of the central and northern Antarctic Peninsula (Fig. 2a). The complete dataset is presented in Supplementary Material Table 1.

4.2. Apatite LA-ICP-MS U-Pb thermochronology

Apatite U-Pb LA-ICP-MS dates have been obtained from the Cretaceous rocks that were used for U-Pb zircon LA-ICP-MS geochronology in this study, and also from Late Triassic (Bastias et al., 2020) and Jurassic igneous rocks (Bastias et al., 2021a; Table 2; Fig. 3) previously dated by the U-Pb zircon LA-ICP-MS method. For each sample, single spot analyses are plotted in Tera-Wasserburg space where they represent a mixture of radiogenic ($^{206}\text{Pb}$) and initial (common) lead ($^{207}\text{Pb}/^{206}\text{Pb}$). In the case of rapid cooling and no subsequent perturbation of the U-Pb system, a sample containing a suite of cogenetic crystals with a large spread in radiogenic Pb/common Pb ratios (Fig. 4), can be used to define a well-constrained linear array in Tera-Wasserburg space (e.g. Kirkland et al., 2018). However, this assumes U-Pb concordance in the sample (e.g. Petrus & Kamber, 2012) and requires a significant spread in the radiogenic Pb/common Pb ratios to ensure a well-constrained linear array (Kirkland et al., 2018). Linear regressions through the data from each sample yield $^{238}\text{U}/^{206}\text{Pb}$ (Tera-Wasserburg concordia lower intercept) dates that range between 147 ± 15 and 76 ± 25 Ma, while the $^{207}\text{Pb}/^{206}\text{Pb}$ initial ratio was constrained by the Tera-Wasserburg concordia upper intercept. Several results have large uncertainties (up to ±26 Ma) due to the high common to radiogenic Pb ratios in the apatites and a resultant small spread in U/Pb ratio with some analyses clustering close to the y-axis of the Tera-Wasserburg concordia. Nevertheless, most apatites have relatively
high U concentrations (>20 U ppm) and yield useful uncertainties that are lower than ±7 Ma (Table 1).

A comparison of the zircon U-Pb crystallisation age and the apatite lower intercept \(^{206}\text{Pb}/^{238}\text{U}\) age (Fig. 4) reveals an approximately linear 1:1 correlation for rocks with zircon U-Pb crystallisation ages younger than ~156 Ma, suggesting that these apatite U-Pb ages record rapid cooling (thermal relaxation) following magmatic crystallization. On the other hand, rocks that crystallised before ~156 Ma yield apatite \(^{238}\text{U}/^{206}\text{Pb}\) lower intercept ages of ~147-128 Ma (Fig. 4). Significantly, four of the five samples that yield apatite Tera-Wasserburg lower intercepts with MSWDs > 2 come from rocks that crystallised at ~153 Ma and older. The origin of this elevated dispersion is discussed in section 5.2.

4.3. Whole rock geochemistry

Whole rock major oxides, trace and rare earth element (REE) concentrations have been determined in the same 36 rocks that were dated using the zircon U-Pb method (Supplementary Material Table 1). The majority of the Cretaceous plutonic rocks are classified as alkali granite to granodiorite in the cationic scheme of de la Roche et al. (1980; Fig. 5a), although a few diorites, gabbros and olivine gabbros were also sampled. The Early Cretaceous intrusions span the calcic and alkali-calcic differentiation trends on the modified alkali-lime index of Peacock (1931; Fig. 5b). The two Late Cretaceous rocks have calc-alkaline to alkali-calcic compositions (Fig. 5b). The Cretaceous rocks yield aluminium saturation indices (ASI) (Maniar and Piccoli, 1989) that straddle the metaluminous–peraluminous fields, and range between 0.74–1.61 (Fig. 5c), with no relationship with crystallisation age. N-MORB normalised trace element abundances (Fig. 5d) reveal no distinct changes through the Cretaceous, with an enrichment in large ion lithophile elements (LILE), and negative Nb, Ta and Ti anomalies, suggesting a subduction-derived component in the magma source regions, and that they may have formed within a continental arc (Fig. 5d). Minor negative Ba, Eu and Sr anomalies, combined with a strong negative Ti anomaly, suggest that plagioclase and Fe-Ti oxides have fractionated, and the
positive Pb anomaly is probably derived from an upper crustal source. Trace element concentrations of the Cretaceous rocks normalised to average upper continental crust scatter close to unity (Fig. 5e), supporting a significant crustal origin for the Cretaceous rocks. Tectonic discrimination using (Y+Nb) vs Nb/Y (Whalen and Hildebrand, 2019) supports an arc setting for the Cretaceous rocks (Fig. 5f), which is consistent with direct comparisons of Y and Nb (Fig. 5g; Pearce et al., 1984). A comparison of Sr/Y vs Y (Fig. 5h) shows that the rocks that formed at ~140-132 Ma and ~92-73 Ma plot in the fields of volcanic arc and adakite, respectively, while the rocks that formed during ~126-100 Ma straddle these two fields.

A lack of temporal trends in La\textsubscript{n}/Yb\textsubscript{n}, Sr/Y and Eu/Eu* (Fig. 6) through the Cretaceous suggests that the crustal thickness of the arc did not significantly change during this period (e.g. Hildreth & Moorbath, 1988; Mantle & Collins, 2008; Chiaradia, 2015; Profeta et al., 2015). However, we acknowledge that estimates of the thickness of continental arc crust using geochemical indices are problematic due to the multiple petrogenetic processes that occur in such settings (Ducea et al., 2015), and these should perhaps only be used as qualitative indicators (e.g. Kay & Mpodozis, 2001; Best et al., 2009; Oliveros et al., 2019).

4.4. Sr-Nd-Pb bulk rock isotopes

The $^{87}\text{Sr}/^{86}\text{Sr}$\textsubscript{i} and $\epsilon\text{Nd}$\textsubscript{i} values of the Cretaceous intrusions (139 ± 1 to 79 ± 1 Ma) range between 0.7100–0.7040 and +4.1 – -9.7, respectively (Fig. 7). These values reveal no significant trends with time, although $\epsilon\text{Nd}$\textsubscript{i} and $^{87}\text{Sr}/^{86}\text{Sr}$\textsubscript{i} values span a wider range between ~139-112 Ma, compared to the rocks that crystallised between ~112-79 Ma (Fig. 7a, b and c). These data are consistent with Leat et al. (2009), who report from a smaller dataset: (i) $^{87}\text{Sr}/^{86}\text{Sr}$\textsubscript{i} ratios of 0.70634 - 0.70563, and $\epsilon\text{Nd}$\textsubscript{i} values of -0.4 and -0.5 from a rock that yields a Rb-Sr isochron date of 132 Ma ± 9 Ma, (ii) $^{87}\text{Sr}/^{86}\text{Sr}$\textsubscript{i} ratios of 0.7080 - 0.7061 and a $\epsilon\text{Nd}$\textsubscript{i} value of -1.8 from a rock that yields a Rb-Sr isochron date of 116±2 Ma, and (iii) $^{87}\text{Sr}/^{86}\text{Sr}$\textsubscript{i} ratios of 0.7112 - 0.7044 and $\epsilon\text{Nd}$\textsubscript{i} values ranging between 2.6 and 0.0, from rocks that yield K/Ar dates spanning ~96–71 Ma (Fig. 7a, b and c). These results yield
similar age and Sr isotopic data to previous work (Pankhurst, 1982; Pankhurst and Rowley, 1991). In addition, Ryan (unpub. Ph.D. thesis, Univ. Brighton, 2007) report $^{87}\text{Sr}/^{86}\text{Sr}$, ratios between 0.7047 and 0.7045 and $\varepsilon$Nd values spanning between 2.5 and 2.3 from rocks that yield U-Pb zircon dates of 92 ± 1 and 89 ± 1 Ma (Fig. 7a, b and c).

Whole rock Pb isotopic compositions of the granitoids that intruded during 139 ± 1 to 79 ± 1 Ma are 19.00–18.31 ($^{206}\text{Pb}/^{204}\text{Pb}$)$_i$, 15.67–15.60 ($^{207}\text{Pb}/^{204}\text{Pb}$)$_i$, and 38.71–38.05 ($^{208}\text{Pb}/^{204}\text{Pb}$)$_i$; Table 1; Figs. 7d, e), and plot between the upper crust and orogenic curves of Zartman and Doe (1981). There are no significant variations throughout the Cretaceous, although the granitoids that formed during ~126–101 Ma are slightly depleted in $^{208}\text{Pb}$ relative to $^{206}\text{Pb}$, compared to the older and younger Cretaceous intrusions, and thus they plot slightly closer to upper crustal compositions (Fig. 7e).

4.5. Zircon in-situ Hf isotopes

In-situ Hf isotopic compositions of zircon have been determined from a suite of the same Cretaceous zircons that were dated using the U-Pb method. Similar to the Nd, Sr and Pb isotopes, there is no systematic variation of $\varepsilon$Hf$_t$ through the Cretaceous, which varies between +9.3 and -6.4 (Fig. 8). Two Early Cretaceous granitoids (~139 to 136 Ma) from the northwestern coast of Palmer Land yield $\varepsilon$Hf$_t$ values that range from 7.9 to 6.4 and -2.4 to -4.8, respectively. Eleven Aptian–Albian intrusions (126 ± 1 to 101 ± 1 Ma), located in southeastern Palmer Land to northwestern Graham Land and the South Shetland Islands (Fig. 8), yield $\varepsilon$Hf$_t$ values that range from 9.3 to -6.4. Finally, three Late Cretaceous intrusions (92 ± 1 to 79 ± 1 Ma), yielded $\varepsilon$Hf$_t$ values that range between 7.9 and -2.2.

The zircons that crystallised during ~139-132 Ma yield a large range of Lu-Hf model ages ($TDM_{Hf}$), which span between 1.07 and 0.36 Ga. Similarly, younger intrusions that formed during 126 ± 1 to 101 ± 1 Ma yield $TDM_{Hf}$ ages that span between 1.14 and 0.27 Ga, while the model ages of the Late Cretaceous intrusions lie between 0.89 and 0.32 Ga. The full dataset is presented in Supplementary Material Table 4.
5. Interpretation

5.1. The origin of Cretaceous magmatism in the Antarctic Peninsula

Early Cretaceous igneous rocks crystallised between 139 ± 1 Ma and 101 ± 1 Ma, and crop out in eastern Palmer Land, the west coast of northern Palmer Land and along the west coast of Graham Land, and within the South Shetland Islands (Fig. 2a). Late Cretaceous intrusions are more spatially restricted and have been identified along the west coast of the central and northern Antarctic Peninsula, and crystallised between 92 ± 1 and 79 ± 1 Ma. Our compilation (Supplementary Material Table 3) of 85 well constrained crystallisation ages (79 U-Pb concordant zircon and six $^{40}$Ar/$^{39}$Ar whole rock plateau dates) shows that Cretaceous arc magmatism peaked at ~118-110 Ma, with minor peaks at ~137-136 Ma, ~103-102 Ma, ~94-93 Ma, ~81-80 Ma and ~71-70 Ma (Fig. 2b), which are consistent with the results of Riley et al. (2020b) and Jordan et al. (2020). However, peak magmatism at ~118-110 Ma revises previous suggestions that Cretaceous magmatism peaked at ~142 Ma (Leat et al., 1995) or ~141-129 Ma (Vaughan et al., 1998).

Our new geochemical data are consistent with a continental arc setting for the Cretaceous igneous rocks of the Antarctic Peninsula. An arc interpretation is supported by (i) the geographic distribution of intrusions that are generally parallel to the margin (Fig. 2a), (ii) enriched N-MORB normalised LILE and LREE, with negative Nb, Ta and Ti anomalies (Fig. 5d), which are typically associated with slab-dehydration reactions at active margins, and (iii) whole rock Nd, Sr and Pb (Figs. 7a, b, d and e), and zircon Hf isotopic compositions (Figs. 8) of Cretaceous igneous rocks show that the magmas formed from mixed sources within the continental crust, which is common in continental arc settings (e.g. Stern, 2002). This is consistent with previous interpretations (e.g. Leat et al., 1995; Riley et al., 2018, 2020b) of the Cretaceous intrusions in the Antarctic Peninsula. Our results also reveal no temporal geochemical or isotopic (Nd, Sr, Pb and Hf) trends through the Cretaceous.
5.2. Thermal histories of Mesozoic arc crust through 550 – 380°C

Igneous rocks that yield zircon U-Pb concordia ages between ~156 ± 1 and ~81 ± 1 Ma yield lower intercept apatite concordia dates (206Pb/238U) on Tera-Wasserburg plots that are indistinguishable from their zircon 238U-206Pb concordia ages (Fig. 4), suggesting they cooled to below ~380°C rapidly after magmatic intrusion. In contrast, apatites from older intrusions that yield zircon U-Pb concordia dates between ~217 and ~184 Ma yield significantly younger apatite lower intercept concordia dates (206Pb/238U), consistently ~147 to ~128 Ma. These apatite dates are interpreted to record cooling through the Pb-in-apatite partial retention zone (~550–380°C; e.g. Cochrane et al., 2014; following the Pb-in-apatite diffusion parameters of Cherniak et al., 1991) during ~147–128 Ma. The older plutonic samples (zircon dates between ~217 and ~184 Ma) yield apatite lower intercept ages with slightly elevated MSWD values compared to the apatite intercept ages from the younger igneous rocks (zircon dates between ~156 ± 1 and ~81 ± 1 Ma). This slight dispersion is considered to be a consequence of (i) partial diffusive loss of Pb during cooling through the Pb-in-apatite partial retention zone, and (ii) laser sampling of intra-grain regions that were more retentive (e.g. cores of large grains) or less retentive (e.g. small grains or rims of large grains) of Pb.

The older rocks that yield U-Pb zircon ages of ~217 to ~184 Ma and apatite U-Pb ages of ~147–128 Ma form parts of intrusions that are dispersed over a distance of ~400 km (Fig. 3), and thus reveal a regional magmatic emplacement event and subsequent cooling that affected most of the Antarctic Peninsula. Poblete et al. (2011) report significant remagnetization of pre-Jurassic igneous and sedimentary rocks on the Antarctic Peninsula, which would require temperatures of at least 500°C (Hunt et al., 1995). This same event was probably responsible for heating the intrusions that formed during ~217 and ~184 Ma to temperatures higher than the apatite Pb partial retention zone, which then subsequently cooled through ~550–380 °C at ~147–128 Ma. The cause(s) of the heating event is unclear, although we hypothesise that it may be due to burial and high heat flow. Jurassic turbidite-like deposits exposed along west coast of Antarctic Peninsula in Adelaide
and Alexander Island (Riley et al., 2012) and South Shetland Islands (Bastias et al., 2019) may be evidence for the formation of depocenters and burial during this period.

The narrow spread in U-Pb apatites dates (147 – 128 Ma) from plutons that crystallised during 217 – 185 Ma suggests these record a general phase of Early Cretaceous cooling through the Apatite Pb Partial Retention Zone (e.g. Cochrane et al., 2014), which may be a consequence of tectonic exhumation. However, the driving mechanism for Early Cretaceous tectonic exhumation of the Antarctic Peninsula is unclear and our interpretation is speculative. The Early Cretaceous Andean margin experienced rock uplift and erosion during the Early Cretaceous during westward migration of South America, induced by the opening of the South Atlantic (e.g. Mpodozis and Ramos, 1990). Additionally, ridge formation is also recorded in the Weddell Sea (e.g. Konig and Jokat, 2006) and Rocas Verdes (e.g. Calderon et al., 2007), located in the South Atlantic and Patagonia, respectively. Tectonic exhumation related to the opening of the Atlantic Ocean has been already suggested for the western margin of Patagonia during the Mesozoic (Homovic and Constantini, 2001). Furthermore, Gianni et al. (2018, 2020) report Early Cretaceous compression in Patagonia, and Sarmiento and Rangel (2004), Martin-Gombajov and Winkler (2008), Villagomez and Spikings (2013) and Spikings et al. (2015) report compression and exhumation of the Colombian and Ecuadorian margin during ~120 – 110 Ma, leading to the emplacement of HP-LT complexes (e.g. Raspas Complex; Spikings et al., 2015). It is noteworthy that HP-LT rocks are also exposed along the South Shetland Islands (Smith Island; e.g. Grunow et al., 1992) within the Antarctic Peninsula, and they reside in the same structural position to the west of the Mesozoic intrusions as they do elsewhere in the Andes. Therefore, it is feasible to suggest, pending future work, that these HP-LT rocks were exhumed during Early Cretaceous compression.

Summarising, we suggest that the small variation in apatite U-Pb dates in plutons that crystallised during ~217 to ~184 Ma reflects Late-Jurassic – Early Cretaceous burial, followed by tectonic exhumation caused by the early opening of the Atlantic Ocean. This
event is not recorded by the younger plutons (~156–81 ± 1 Ma) because these were probably cooler than the apatite Pb partial retention zone prior to the exhumation event.

5.3. Sources of magmatism, magma addition rates and petrogenesis

The general uniformity in whole rock geochemical compositions (Figs. 5, 6) suggests that there were no significant changes in tectonic setting during ~140 Ma and ~79 Ma. The exhumation phase identified by the apatite U-Pb data may have been slow, and did not result in significant changes in crustal thickness. The intrusions are mostly calcic and alkali-calcic alkali-granite and granodiorites that formed in a continental subduction zone setting (Fig. 5). Exceptions to the general geochemical uniformity of the igneous rocks throughout the Cretaceous is the identification of adakite-like magmas in the interval ~126-100 Ma, which immediately followed a period of elevated compression and higher exhumation rates (Figs. 5f) as well as higher magma addition rates from ~118-100 Ma (Fig. 2b).

A comparison of the Hf-isotopic compositions reveals significant differences in the source regions of Cretaceous (this study; Zheng et al., 2018; Riley et al., 2020b) and pre-Cretaceous zircons (Bastias et al., 2020, 2021a). Zircons from Ordovician to Triassic plutons show a steady trend towards less radiogenic \( \epsilon_{Hf} \) values with time (Fig. 9a; Bastias et al., 2020). With the exception of a Late Jurassic granite (sample R.5957.3; Bastias et al., 2021) that yielded \( \epsilon_{Hf} \) values between 7.8 and 5.6, Triassic and Jurassic zircons yield broadly similar \( \epsilon_{Hf} \) values that span between 0.6 and -9.2 (Fig. 9a; Bastias et al., 2020; 2021). These trends contrast with the Cretaceous zircons that yield more radiogenic \( \epsilon_{Hf} \) values which range between 12.5 and -6.5, revealing the involvement of more radiogenic source regions in the Early Cretaceous. With the exception of granite R.5957.3, Ordovician to Jurassic intrusions yield a consistent range of Lu-Hf model ages that span from 1.37 Ga (at ~212 Ma; Bastias et al., 2020) to 0.78 Ga (at ~440 Ma; Bastias et al., 2020), with the majority spanning between 1.2 and 0.8 Ga (Fig. 9c). This suggests that the Ordovician-Jurassic arc magmas mainly incorporated juvenile Sunsas-aged crust (1.19–0.92 Ga; Cordani and Sato et al., 2000) that is exposed in South America and crust of similar age.
that is exposed in East Antarctica (1.1-1.0 Ga; Goodge and Fanning, 2016). Cretaceous zircons yield Lu-Hf model ages that range between 1.14 Ga (at ~112 Ma) and 0.28 Ga (at ~106 Ma), while the majority of Cretaceous zircons yield Lu-Hf model ages of <0.8 Ga (Fig. 9b), suggesting the structure of the crust may have been modified after the Jurassic, reducing the volume proportion of material derived from Precambrian basement (Fig. 9d).

5.4. Cretaceous tectonic history

5.4.1. Evidence for a prevailing extensional setting

The combination of U-Pb zircon dates, geochemical and isotopic data, and mid-temperature thermochronological constraints is consistent with an extensional regime during the Late Jurassic – Early Cretaceous, which may have been interrupted by a mild compressional phase that exhumed the pre-~184 Ma intrusions during ~147–128 Ma. Evidence for compressive pulses at ~107 Ma and ~103 Ma (Vaughan & Pankhurst, 2008; Vaughan et al., 2012; Riley et al., 2020b), has been accounted for by an increase in plate convergence rates. First, Hf-isotopic compositions of zircons show that more isotopically juvenile crust was incorporated into Cretaceous magmas compared to older intrusions, which is in agreement with the interpretation of Pankhurst (1982) based on Sr isotopes. Extension may have driven decompression of the underlying mantle, promoting the incorporation of mantle melts into the arc magmas (e.g. Cochrane et al. 2014). Second, re-magnetisation of pre-Jurassic igneous and sedimentary rocks (Poblete et al., 2011), along with resetting of apatite U-Pb dates (via diffusive Pb-loss) was probably caused by increased heat flow and burial during extension (e.g. Lachenbruch et al., 1994). Finally, synchronous extension has been recorded in adjacent regions of the Antarctic Peninsula throughout most of the Cretaceous, which was related to the break-up of Gondwana. Oceanic lithosphere formed in the Weddell Sea at ~147 Ma, outboard of the north-eastern Antarctic Peninsula (Fig. 1a; König & Jokat, 2006), which led to the opening of the Southern Atlantic. An extensional setting is also documented along the western margin of Patagonia, where it formed the Rocas Verdes Basin, a marginal back-arc basin that developed oceanic lithosphere during the Late Jurassic to Cretaceous (e.g. Dalziel et al.,
1974; Dalziel 1981; Calderón et al., 2007). Moreover, most of the South American western margin was dominated by an extensional setting during the Late Jurassic – Early Cretaceous (e.g. Atherton & Aguirre, 1992; Mpodozis & Allmendinger, 1993; Morata & Aguirre, 2003; Spikings et al., 2015).

5.4.2. ~148-140 Ma: magmatic quiescence
The period between ~148–140 Ma is characterized by magmatic quiescence along the entire length of the Antarctic Peninsula. Most Late Palaeozoic–Jurassic plate reconstructions show subduction of Pacific oceanic lithosphere beneath the western margin of Gondwana at this time (e.g. Meert & Lieberman, 2008; Nelson & Cottle, 2017, 2018) and thus the mechanism responsible for this quiescence remains unclear, although it may indicate high convergence obliquity or a lack of net convergence.

5.4.3. ~140-100 Ma: oceanic subduction
Arc magmatism resumed along the Antarctic Peninsula in the Berriasian-Valanginian transition (~140 Ma; Fig. 10) due to subduction of the Phoenix Plate. Magmatic pulses occurred at ~137-136, ~118-110 and ~103-102 Ma (Fig. 2b), although the margin was continuously active throughout the Early Cretaceous, corroborating previous studies (e.g. Leat et al., 1995; Riley et al., 2018). Early Cretaceous intrusions include the Lassiter Coast Intrusive Suite in eastern Palmer Land, and the west coast of southern Graham Land in the Black Coast sector. Further north, arc magmatism from ~140 to 100 Ma occurs along the west coast of Graham Land up to its northernmost exposure in the South Shetland Islands (Fig. 2a). This geographic distribution of Early Cretaceous igneous rocks from ~140 to 100 Ma could be accounted for by either flat-slab, east-dipping subduction of the Phoenix Plate, west-dipping subduction of the lithosphere of the Weddell Sea, or an allochthonous origin for the rocks of Alexander Island, each of which are discussed below.
5.4.3.1. Flat-slab

Most Early Cretaceous paleogeographic reconstructions show east-dipping subduction of oceanic lithosphere of the Phoenix Plate beneath the Antarctic Peninsula (e.g. Barker, 1982; Larter & Barker, 1991; Sutherland & Hollis, 2001; Jordan et al., 2020). Assuming that the rocks of Alexander Island are autochthonous to the Antarctic Peninsula and there was no significant strike-slip displacement along the margin, this implies a distance of ~700 km between the trench and arc rocks of the Lassiter Coast Intrusive Suite (Fig. 10a), which have a trench-parallel extent of at least ~300 km. Consequently, in this scenario the rocks of the Lassiter Coast Intrusive Suite (~130-102 Ma, Pankhurst and Rowley, 1991; Riley et al., 2018) formed above a flattened slab (Fig. 10a). To the north of the Black Coast, igneous rocks were emplaced along the west coast of the Antarctic Peninsula, suggesting that the extent of the flat-slab was constrained to a segment of Palmer Land (Fig. 10a).

5.4.3.2. West-dipping subduction

Arc rocks of the Lassiter Coast Intrusive Suite of eastern Palmer Land may have formed within an active margin associated with west-dipping subduction of lithosphere of the Weddell Sea beneath eastern Palmer Land (Fig. 10b). This hypothesis was proposed by Grunow et al. (1993), who suggested that counter-clockwise rotation of the Antarctic Peninsula during the Jurassic in conjunction with the general southward motion of East Antarctica may have driven west-dipping subduction. However, this hypothesis is inconsistent with paleogeographic reconstructions based on seafloor magnetic anomalies in the Weddell Sea region (e.g. Jokat et al., 2003; Ghidella et al., 2002, 2007; König & Jokat, 2006), and the accommodation of lithosphere that may have been subducted during ~140-100 Ma. Extension in the South Atlantic leading to the development of seafloor spreading and the formation of the Weddell Sea occurred during the Late Jurassic (e.g. Ghidella et al., 2002); most of this seafloor is still present to the east of the Scotia Plate (Fig. 2a; Ghidella et al., 2002, 2007; König & Jokat, 2006), and thus poses a problem when trying to account for subduction east of Palmer Land. However, this argument is not
conclusive considering that the age of significant portions (e.g. the southern sector) of the Weddell Sea remains unknown, therefore west-dipping subduction remains a possibility.

5.4.3.3. An allochthonous origin for Alexander Island

The present sinuous spatial trend of Early Cretaceous magmatism (~140-100 Ma) may be a consequence of post ~100 Ma bending and rotation of the peninsula, implying that the original Early Cretaceous arc was parallel to the ocean-continent interface, with an approximately similar, trench-parallel arc-trench gap. This hypothesis also requires that Alexander Island is part of an allochthonous or para-autochthonous crustal block that was located elsewhere prior to ~100 Ma, and that the Early Cretaceous trench would have been located close to the present position of George VI Sound (Fig. 10c). In this model, Alexander Island arrived close to its present position after ~100 Ma. However, Alexander Island hosts Mesozoic fore-arc sequences (Fossil Bluff Group; Butterworth et al., 1988), which have been chronologically and lithostratigraphically correlated with Mesozoic fore-arc sequences further north in Adelaide Island (Riley et al., 2012) and in the South Shetland Islands (Bastias et al., 2019). Thus, an allochthonous origin for Alexander Island suggests it may have been accreted along the west Antarctic margin via displacement along the Eastern Palmer Land Shear Zone (Fig. 2a), which is a major ductile to brittle-ductile shear zone with a lateral extent of at least 1500 km (Vaughan & Storey, 2000; Vaughan et al., 2012; Fig. 2). Translation of Alexander Island and emplacement close to its current location would have occurred after ~100 Ma, although U-Pb zircon and $^{40}$Ar/$^{39}$Ar biotite dates of syn-tectonic intrusions within this shear zone suggest it was active during ~106–102 Ma (Vaughan et al., 2002a, b), and there is no evidence for displacement since ~102 Ma.

5.4.4. ~100-79 Ma

Exposures of Late Cretaceous igneous rocks are less voluminous than the Early Cretaceous units (Fig. 2a) and occur along the west coast of the central and northern Antarctic Peninsula (Fig. 11). Late Cretaceous igneous rocks in Graham Land formed with similar
trench-arc distances at its west coast. However, arc magmas migrated westward during the Late Cretaceous-Paleogene at the latitude of northern Alexander Island in Palmer Land (Pankhurst, 1982; Storey et al., 1996; McCarron & Millar, 1997; Riley et al., 2020b). The absence of Late Cretaceous or Paleogene intrusive rocks at the latitudes of the Lassiter Coast Intrusive Suite suggests that subduction had ceased at ~112 Ma in more southerly latitudes, which probably signals subduction of the last remaining oceanic lithosphere of the Phoenix Plate under the margin of the Antarctic Peninsula (e.g. Barker, 1982; Larter & Barker, 1991).

6. Conclusions

1. Arc magmatism resumed in the Antarctic Peninsula at ~140 Ma followed a magmatic hiatus during the interval ~148–140 Ma, forming abundant intrusions that are exposed along Graham and Palmer Land. Magmatism was continuous until ~79 Ma, with the main peak of activity at ~118-110 Ma, which represents one of the main periods of Mesozoic magmatism in the Antarctic Peninsula. This magmatism was formed within a continental active margin setting, which is supported by (i) the trench-parallel distribution of the igneous rocks, (ii) chemical compositions that reveal an enrichment in LILE and LREE, with negative Nb, Ta and Ti anomalies, which are typical of slab-dehydration reactions and thus active margins, and (iii) whole rock Nd and Sr, and zircon Hf isotopic compositions reveal mixed sources that resided within the continental crust.

2. Apatite U-Pb dates show that intrusions that crystallised during ~217 and ~184 Ma within the Antarctic Peninsula cooled through the Pb-in-apatite partial retention zone (~550–380°C) during ~147–128 Ma. First, these intrusions were probably heated to temperatures hotter than ~550°C via increased flow and burial during Late Jurassic – Early Cretaceous extension, which also remagnetised the pre-Jurassic igneous and sedimentary rocks of the Antarctic Peninsula. Subsequent cooling may have been a consequence of exhumation driven by compression and rock uplift, caused by the westward migration of South America during the early opening of the South Atlantic.
3. An overall extensional setting during the Cretaceous is supported by (i) progressively more radiogenic $\varepsilon$Hf compositions of Cretaceous zircons revealing the incorporation of mantle melts during attenuation of the crust and (ii) evidence for high Late Jurassic to Cretaceous heat flow that magnetised pre-Jurassic rocks and reset apatite U-Pb ages of pre-Middle Jurassic rocks. However, this extensional period was punctuated by compressive events, the most pronounced of which may have been at the beginning of the Early Cretaceous (see conclusion 2).

4. Early Cretaceous exposures of arc rocks crop out from the east to the west coast at the latitude of the Black Coast in Palmer Land. This spatial trend may be due to either (i) continuous subduction beneath the western margin of the Antarctic Peninsula with a flat-slab episode in Palmer Land, (ii) east-dipping subduction of the Phoenix Plate in Graham Land and west-dipping subduction in Palmer Land, or (iii) an active western margin with east-dipping subduction of the Phoenix Plate, along with an allochthonous or parautochthonous origin for Alexander Island. Our current data set is unable to distinguish between these possibilities, and testing these hypotheses would require a better understanding of the geological history of the pre-Cretaceous rocks of Alexander Island and the inaccessible areas of the Weddell Sea in the Filchner-Ronne Ice Shelf sector.

5. The geochemical and isotopic compositions of the Late Cretaceous arc rocks are extremely similar to their Early Cretaceous counterparts. Therefore, we suggest that active margin magmatism was continuous throughout the Cretaceous in the Antarctic Peninsula, which is consistent with previous studies (e.g. Leat et al., 1995; Riley et al., 2020b). Late Cretaceous arc magmatism occurred during the closing stages of subduction of the oceanic lithosphere of the Phoenix Plate in Palmer Land, which gradually ceased moving northward throughout the Cenozoic (e.g. Barker, 1982; Larter & Barker, 1991).

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Figure captions

Figure 1. (A) Paleogeographic reconstruction of the Pacific active margin of Gondwana during the Jurassic-Cretaceous (e.g. Ghidella et al., 2002; Jokat et al., 2003; Martin, 2007), showing the Antarctic Peninsula crustal block in green. BB: Byers Basin (Bastias et al., 2019); EWT: Ellsworth Whitmore Mountains, Larsen Basin (Hathway, 2000), MAD: Madagascar; MBL: Marie Byrd Land; M10: ~134 Ma (e.g. Martin, 2000); NZ: New Zealand; RVB: Rocas Verdes Basin (e.g. Calderon et al., 2007); TI: Thurston Island; NZ: New Zealand. (B) Present-day map of the Antarctic Peninsula showing the location of the studied rocks. These samples were either collected in the field during the 2015 and 2016 Antarctic campaign of the Instituto Antártico Chileno (INACH) or provided by the British Antarctic Survey and the Polar Rock Repository at Ohio State University. Sample locations are presented along with its dating method, U-Pb LA-ICP-MS zircon (green), U-Pb LA-ICP-MS apatite (blue) and combined U-Pb LA-ICP-MS zircon and apatite (red).

Figure 2. (A) Geological map of the Antarctic Peninsula, showing the distribution of intrusive rocks (red) and the Rymill Granite Complex (purple), modified from Burton-Johnson and Riley (2015). Zircon \(^{206}\text{Pb}/^{238}\text{U}\) concordia (LA-ICP-MS) and \(^{40}\text{Ar}/^{39}\text{Ar}\) plateau ages collected in this study are shown along with published, pre-Jurassic U/Pb ages and correspond to (¹) Bastias et al. (2019), (²) Hervé et al. (2006), (³) Riley et al., 2018, (⁴)
Burton-Johnson et al. (2022) and (5) Ryan (unpub. Ph.D. thesis, Univ. Brighton, 2007). All uncertainties are quoted at ±2σ. Three periods are outlined, ~140-132 Ma (dark green), ~126-100 Ma (light green) and ~92-79 Ma (yellow). EPLSZ: Eastern Palmer Land Shear Zone, from Vaughan and Storey (2000) and Vaughan et al. (2012). (B) Kernel Density Estimates of the distribution of crystallization ages during the Cretaceous (black line, this study; grey dotted line, this and previous work). An age peak occurs at ~118-110 Ma (main peak at ~115-114 Ma) with minor peaks at ~137-136 Ma, ~103-102 Ma, ~94-93 Ma, ~81-80 Ma and ~71-70 Ma (all in red). Magmatic quiescence is recorded at ~148-140 Ma (in blue). (C) Representative Wetherill concordia plots of zircon U–Pb data obtained from the Cretaceous igneous rocks of the Antarctic Peninsula. Bars represent single ablation spots and represent an uncertainty of 2σ. Representative cathodoluminescence (SEM) images of the dated zircons are presented.

Figure 3. Map of the Antarctic Peninsula, showing the distribution of Jurassic-Neogene intrusive rocks (red) and the Late Triassic Rymill Granite Complex (purple, dotted line), modified from Burton-Johnson and Riley (2015) and Bastias et al. (2020). Apatite U-Pb Tera–Wasserburg lower intercept concordia dates acquired from Triassic-Cretaceous igneous rocks are shown.

Figure 4. (B) A comparison of the zircon U-Pb crystallization ages of Mesozoic igneous rocks of the Antarctic Peninsula and their apatite U-Pb Tera–Wasserburg lower intercept concordia dates. Rocks that yielding apatite U-Pb Tera–Wasserburg lower intercept concordia dates that are indistinguishable from their crystallization ages (zircon LA-ICP-MS) are presented in red, otherwise in blue. (C) Representative apatite Tera-Wasserburg concordia plots of the igneous Mesozoic rocks of the Antarctic Peninsula. U-Pb Tera–Wasserburg lower intercept concordia dates are shown.

Figure 5. Geochemical compositions of Cretaceous igneous rocks from the Antarctic Peninsula, divided into time slices at ~140-132 Ma (dark green), ~126-100 Ma (light green), and Late Cretaceous (yellow). (A) Multi-cation discrimination plot from De La Roche et al. (1980). (B) Na2O+K2O-CaO versus SiO2 classification diagram of Peacock.
(1931). (C) Molar (Al/Na+K) and Al/(Ca+Na+K) are defined as molecular ratios and take into account the presence of apatite so that rocks with ASI>1.0 are corundum normative and are termed peraluminous. (D) Rare earth element and trace element abundances normalised to N-MORB (Sun and McDonough, 1989). (E) Trace element abundances normalised to Upper Continental Crust (Taylor and McLennan, 1995). (F) Nb+Y versus Nb/Y diagram of Hildebrand et al. (2018) to differentiate magmatic arc and slab failure (slab break-off) environments. (G) Tectonic discrimination diagram of Pearce et al. (1984) based on a comparison of Y and Nb. ORG: ocean ridge granites; VAG: volcanic arc granites; WPG: within-plate granites. (H) Discrimination of adakitic and normal volcanic arc rocks (andesites, dacites and rhyolites) based on Sr/Y versus Y of Defant and Drummond (1990).

Figure 6. The temporal evolution of some geochemical indexes at ~140-132 Ma (dark green), ~126-100 Ma (light green), Late Cretaceous (yellow). (A) Molar Al/(Ca+Na+K) index from de La Roche et al. (1980). (B) La\textsubscript{n}/Yb\textsubscript{n}. (C) Sr/Y. (D) SiO\textsubscript{2} % wt. (E) Eu/Eu* = Eu\textsubscript{n}/(Sm\textsubscript{n}*Gd\textsubscript{n})\textsuperscript{1/2}.

Figure 7. Whole-rock isotopic compositions of Cretaceous igneous rocks of the Antarctic Peninsula at ~140-132 Ma (dark green), ~126-100 Ma (light green) and Late Cretaceous (yellow). (A, B) Temporal evolution of whole rock (A) \textsuperscript{87}Sr/\textsuperscript{86}Sr\textsubscript{i} and (B) εNd\textsubscript{t}. Data are only reported from samples that are considered to yield accurate crystallisation ages. (C) Comparison of the εNd\textsubscript{t} and \textsuperscript{87}Sr/\textsuperscript{86}Sr\textsubscript{i} values that are shown in (A) and (B). The full dataset is a combination of this study, including some data (Rb-Sr, \textsuperscript{40}Ar/\textsuperscript{39}Ar, U-Pb zircon and field relationships) from Late Cretaceous rocks presented in Ryan (unpub. Ph.D. thesis, Univ. Brighton, 2007) and Leat et al. (2009). (D) and (E) Pb isotopic compositions of the Cretaceous igneous whole rocks showing the lead-isotope evolution curves of Zartman & Doe (1981) for Upper Crust and Orogen. Approximate composition of EM1 (enriched mantle with recycled lower continental crust), EM2 (enriched mantle with upper continental crust and continental derived sediments) and DMM (depleted MORB-mantle) are from Hanan & Graham (1996) and Stracke et al. (2003). HIMU: high U/Pb mantle composition. NHRL: Northern Hemisphere Reference line (Dupre & Allegre, 1980).
Figure 8. (A) A comparison of the $^{206}$Pb–$^{238}$U zircon concordia ages and zircon $\epsilon$Hft for grains that crystallised during ~140-132 Ma (dark green), ~126-100 Ma (light green) and ~Late Cretaceous (yellow). 2σ uncertainties are ~±5% for U–Pb zircon ages. (B) Present-day map of the Antarctic Peninsula showing the location of the analysed rocks presented in (A). Data from Zheng et al. (2018) and Riley et al. (2020a) are included.

Figure 9. (A) A comparison of $^{206}$Pb–$^{238}$U zircon concordia ages and zircon $\epsilon$Hft for grains extracted from Mesozoic igneous rocks of the Antarctic Peninsula (this study; Bastias et al., 2020, 2021a, 2021b). 2σ uncertainties are ~±5% for U–Pb zircon ages. (B) Present-day map of the Antarctic Peninsula showing the location of the analysed rocks presented in (A). (C) A comparison of the $^{206}$Pb–$^{238}$U zircon concordia ages and the Lu-Hf model ages (this study; Bastias et al., 2020, 2021a). (D) A comparison of $^{206}$Pb–$^{238}$U zircon concordia ages and crustal residence, which is defined as the difference between the zircon U-Pb crystalisation age and the TDM$_{HF}$ age. The Cretaceous dataset is divided into ~140-132 Ma (dark green), ~126-100 Ma (light green) and ~Late Cretaceous (yellow). Data from Riley et al. (2020b) are included.

Figure 10. Schematic paleo-reconstruction of western Gondwana including the Antarctic Peninsula and Patagonia during the Early Cretaceous, showing the Rocas Verdes Basin (~152-142 Ma; Calderon et al., 2007), Byers Basin (Bastias et al., 2019), Larsen Basin (Hathway, 2000), and the Weddell Sea including the magnetic anomalies of Ghidella et al. (2002). Arrows in the Antarctic Peninsula indicate drift direction due to the opening of the Weddell Sea. Different geodynamic scenarios are proposed for this text: (A) Continuous east-dipping subduction of the Phoenix Plate beneath the Antarctic Peninsula with a low angle subducted sector at the latitude of Alexander Island. (B) Double subduction beneath the Antarctic Peninsula. (C) Continuous subduction of the Phoenix Plate beneath the western Antarctic Peninsula and an allochthonous or parautochthonous origin of the crustal block of Alexander Island.

Figure 11. Schematic paleo-reconstruction of the Antarctic Peninsula during the Late Cretaceous. The margin was dominated by west-dipping subduction of oceanic lithosphere
of the Phoenix Plate. A lack of Late Cretaceous arc magmatism in the southern Antarctic Peninsula, suggests the margin was inactive. Active margin magmatism continued along Graham Land during the Late Cretaceous.

Table captions

Table 1. Summary of the geochronological and isotopic tracing data collected from the Cretaceous igneous rocks in the Antarctic Peninsula presented in this work.

Table 2. Summary of the U-Pb apatite and zircon data of the Triassic – Cretaceous rocks of the Antarctic Peninsula.

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Figure 2
Figure 3

Apatite LA-ICP-MS U-Pb
Figure 4

(A) R.6360.7
MSWD=1.4
0.8335 ± 0.013
Lower intercept:
135 ± 10 Ma

(B) N11.3.1
MSWD=0.9
0.8132 ± 0.014
Lower intercept:
112 ± 5 Ma

(C) 
Apatite Tera-Wasserburg
Lower intercept Age ±2σ (Ma)

Zircon $^{206}$Pb-$^{238}$U Age ±2σ (Ma)

1:1 line

~147-128 Ma
Figure 5
Figure 6

(A) La$_{ni}$/Yb$_{ni}$ vs. Crystallisation age
(B) Sr/Y vs. Crystallisation age
(C) Eu/Eu* vs. Crystallisation age
Figure 7

(A) Sr/Sr²⁺ and (B) εNd/²⁰⁶Pb vs. Crystallization age. (C) εNd/²⁰⁶Pb vs. εSr/²⁰⁶Sr. (D) Upper crust, Orogen, EM1, EM2, DMM, HMU, NHRL. (E) U-Pb crystallization ages: 132 ± 9 Ma, 116 ± 2 Ma, 96 ± 7 Ma. Rb/Sr and field relationship.
Figure 8

[Diagram showing geological data with labels and annotations related to U-Pb isotopes and age distribution, with specific markers for different periods and locations.]
Figure 9

A) Depleted mantle evolution
B) Ancient enriched atmosphere (t/HF = 0.015)
C) Riley et al. (2020)
D) Sunias and Grenville orogens ~1.19-0.92 Ga

- Late Triassic
- Early Jurassic
- Middle Jurassic
- Late Jurassic
- Early Cretaceous
- Late Cretaceous
- 140-132 Ma
- 126-100 Ma
- 92-79 Ma

Crustal residence evolution of Sunias and Grenville-aged products

Granite R.5957.3
<table>
<thead>
<tr>
<th>Sample</th>
<th>South</th>
<th>West</th>
<th>Age</th>
<th>Error</th>
<th>MSWD</th>
<th>$^{87}$Sr/$^{86}$Sr</th>
<th>εNd</th>
<th>$^{206}$Pb/$^{204}$Pb</th>
<th>$^{207}$Pb/$^{204}$Pb</th>
<th>$^{208}$Pb/$^{204}$Pb</th>
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</thead>
<tbody>
<tr>
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All the ages were obtained by LA-ICP-MS U-Pb