Palaeozoic – Early Mesozoic geological history of the Antarctic Peninsula and correlations with Patagonia: kinematic reconstructions of the proto-Pacific margin of Gondwana

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ABSTRACT

The Antarctic Peninsula preserves geological evidence of a long-lived continental margin with intrusive, volcaniclastic and accretionary complexes indicating a convergent margin setting from at least the Cambrian to the Cenozoic. We examine the poorly understood units and successions from the Palaeozoic to the Early Mesozoic and develop detailed kinematic reconstructions for this section of the margin. We use existing geochronology, along with newly presented U-Pb detrital zircon geochronology, combined with detailed field evidence to develop correlations between geological units and tectonic events across Patagonia and the proto-Antarctic Peninsula. The continental margin of Gondwana/Pangea was a convergent margin setting punctuated by crustal block translation, deformation, magmatic pulses (flare-ups) and development of thick accretionary complexes. These events are strongly linked to subducting slab dynamics and a para-autochthonous model is proposed for the long-lived margin. Major magmatic pulses are evident during the Ordovician (Famatinian) and Permian, and the magmatic record is reflected in the detrital zircon age profiles of metasedimentary successions of the northern Antarctic Peninsula and Tierra del Fuego. Major tectonic events during the Carboniferous – Permian (Gondwanide Orogeny) and Triassic (Chonide Event – Peninsula Orogeny) are recognised across the Antarctic Peninsula – Patagonia and are correlated to potential terrane suturing and flat slab dynamics. Our kinematic reconstructions developed in GPlates, combined with geological field relationships have allowed us to model the locus of magmatism relative to the active margin and also the likely source for thick sedimentary successions.

Keywords: Gondwana; geochronology; GPlates; continental margin arc; Famatinian

1. Introduction

The tectonics of accretionary orogens are characterized by alternate tectonic cycles (Suárez et al., 2021), switching between retreating stages that trigger crustal extension and the development of retro-arc rifting, and advancing stages leading to short-lived compressional pulses, crustal thickening, and the migration of inland arc magmatism (Cawood et al., 2009; Ramos, 2010). The geological and tectonic evolution of the paleo-Pacific margin of southern South America and West Antarctica is broadly understood from the Jurassic to the present day (e.g. König and Jokat, 2006). However, prior to Gondwana breakup, the pre-Jurassic geological and tectonic evolution of this margin is poorly constrained as a consequence of restricted geochronology, sparse exposure of some units and difficulties in correlating widely dispersed successions across West Antarctica and Patagonia (Hervé et al., 2006a). Nelson and Cottle (2017) suggested that the paleo-Pacific margin of Gondwana was a relatively continuous active convergent margin from at least the Ediacaran through to the Cenozoic, whilst Gianni and Navarrete (2022) have demonstrated an interrupted subduction model through the Late Palaeozoic.

West Antarctica, including the Antarctic Peninsula, preserves a geological record from the Mesoproterozoic, and an extensive continental margin magmatic history through the Palaeozoic, Mesozoic and Cenozoic (Jordan et al., 2020). There are, however, uncertainties regarding the pre-Jurassic understanding of the Antarctic Peninsula's geological history, particularly the relationship with Patagonia, the extent of the Permian Gondwanide Orogeny, the continuity of the magmatic record through the Palaeozoic, the evolution of the proto Weddell Sea and the primary driving mechanisms for magmatism and deformation (e.g. slab dynamics/terrane accretion).

This study examines the pre-Jurassic geological, tectonic and geodynamic evolution of the Antarctic Peninsula and investigates geological and tectonic correlations with Patagonia. In this paper we define the Antarctic Peninsula between northern Graham Land and the Haag Nunataks, although they form separate crustal blocks (Fig. 1), and also include the Ellsworth Mountains in our discussion. We will use recently published, mostly U-Pb (zircon) magmatic and metamorphic ages, combined with recent and newly presented detrital zircon ages from metasedimentary units in an attempt to correlate widely dispersed units across the Antarctic Peninsula, Patagonia and elsewhere in West Antarctica. Through a series of GPlates-derived (Boyden et al., 2011) reconstructions and kinematic analysis we will objectively review and critique the various geodynamic models for southwest Gondwana/Pangea from the Late Cambrian/Ordovician to the Early Mesozoic, prior to Gondwana breakup and the southward migration of the Antarctic Peninsula relative to South America. Our analysis will help understand the role of allochthonous (exotic) terranes during the Late Palaeozoic evolution of the South America – West Antarctic margin by evaluating the geological correlations across the proto Antarctic Peninsula, the North Patagonian Massif and the Deseado Massif.

2. Geological Setting

The Antarctic Peninsula and Haag Nunataks form an arcuate mountainous belt that reaches heights of 3200 m (Fig. 1) and preserves a complex geological and tectonic history from the Precambrian to the present day. Since the Ordovician, its geological record (Fig. 2) has been shaped by subduction along the proto-Pacific margin and rifting in the Weddell Sea sector (Dalziel et al., 2013; Jordan et al., 2020). From the Permian to the Paleogene, the geological setting of the proto-Pacific margin was defined by episodes of significant magmatism, deposition and deformation. These events were originally interpreted as a consequence of subduction and the development of an accretionary continental arc on Palaeozoic basement of the Gondwana margin (Suárez, 1976; Thomson and Pankhurst, 1983), and is thought to form a belt that extends along the whole of the Pacific Margin as part of the Terra Australis Orogen (Cawood, 2005). Whilst there is consensus on the accretionary nature of the orogen, the extent of translation of terranes during its post-Jurassic evolution is debated. Vaughan and Storey (2000) reinterpreted the geology of the Antarctic

Peninsula as a mid-Cretaceous amalgamation of autochthonous, para-autochthonous and allochthonous terranes following the development of similar models elsewhere along the Pacific margin in New Zealand (see review by Robertson et al., 2019). The model was further developed to describe the accretion of terranes onto the Gondwana margin (e.g. Vaughan et al., 2012). However, Burton-Johnson and Riley (2015) challenged this tectonic model and preferred an *in situ* continental arc development for the Peninsula, supported by recent paleomagnetic data from the northern Antarctic Peninsula (Gao et al., 2021).

The magmatic, metamorphic and depositional history of the Antarctic Peninsula is relatively well understood through the Jurassic (e.g. Pankhurst et al., 2000; Riley et al., 2001), Cretaceous (e.g. Vaughan et al., 2012; Riley et al., 2018, 2020a) and Cenozoic (e.g. Leat and Riley, 2021), but the pre-Jurassic history is less well constrained, particularly its initial development and association with an autochthonous or allochthonous Patagonian terrane.

3. GPlates reconstructions

Kinematic reconstructions in this study were developed in GPlates (Boyden et al., 2011), using the 0 – 250 Ma reconstructions and rotation file (supplementary files of van de Lagemaat et al., 2021) as a basis; itself constrained by a global plate circuit. Using these kinematic reconstructions to determine the relative formational locations of pre-Jurassic samples from South America and Antarctica (Table S1), we can interpret their correlations and geological settings back to the Late Proterozoic. Throughout the period of interest (Late Proterozoic – Triassic), South America and the Antarctic Peninsula developed on the supercontinent margin of Gondwana and Pangea. Consequently, whilst the global location of the supercontinent changed, relatively little movement occurred within the area of interest. Kinematic reconstructions are thus used here primarily to explore three aspects of the system: 1) the relative locations of the geological units and samples through time; 2) the progradational growth of the continental margin; and 3) exploring published hypotheses of terrane accretion on the margin.

Due to the region's history on the Gondwanan margin, the most important aspect of reconstructing the pre-Jurassic margin is accurately representing the relative locations of the Antarctic Peninsula and South America prior to the Jurassic extension between Antarctica and South America, and the Cenozoic opening of the Scotia Sea. Van de Lagemaat et al. (2021) determined the relative locations of East Antarctica and South America using the South America – Africa – East Antarctica plate circuit, and used paleomagnetic data to show that no relative motion occurred between the Antarctic Peninsula and East Antarctica since the Early Cretaceous. This approach constrained the relative locations of the Antarctic Peninsula and South America on the Gondwanan margin prior to the breakup of Gondwana, as well as the location and distribution of Jurassic intracontinental extension. The only modification we make to their <250 Ma reconstructions regards the rifting and closure of the Rocas Verdes Basin. This basin reconstruction was modified to follow the line of ophiolitic outcrops and basin sediments of Patagonia (Calderón et al., 2016) rather than the Miocene Magallanes-Fagnano fault system (Betka et al., 2016) used by Eagles (2016) and van de Lagemaat et al. (2021). Based on geological evidence, rifting of the Rocas Verdes Basin commenced during the Late Jurassic (Calderón et al., 2007; van de Lagemaat et al., 2021; Muller et al., 2021) and closed in the mid- to Late Cretaceous (Katz, 1972; Dalziel, 1981; Barbeau et al., 2009; Eagles, 2016). Global plate motions based on marine magnetic anomalies and fracture zones, combined with geological data, constrain this closure to 113 – 102 Ma (van de Lagemaat et al., 2021), with some workers suggesting a later closure (minimum age of ~83 Ma; Muller et al., 2021). This closure is often correlated with the emergence of coarser sediments in Patagonia. In Tierra del Fuego this occurs at ~85 Ma, and older further north (Klepeis et al., 2010; Fosdick et al., 2011).

Different global plate reconstructions have focussed on different regions, resolutions, and timescales. Van de Lagemaat et al. (2021) provides the most accurate and highest resolution reconstruction of the pre-breakup geometry of our region of interest, so is used post-250 Ma. As the

Antarctic Peninsula, South America, and Africa were located adjacently on the Gondwanan margin prior to breakup of the supercontinent, this enables extrapolation of the plate motions of the Antarctic Peninsula and Patagonia back to the Proterozoic by preserving the 250 Ma positions of the Antarctic Peninsula and Patagonia relative to Africa (van de Lagemaat et al., 2021), and extending the plate motion of Africa using other global plate models. To extend the reconstruction from 250 Ma back to 320 Ma we used the African plate rotation of Matthews et al. (2016), and to further extend from 320 to 1010 Ma we used the rotation model of Merdith et al. (2021). Prior to incorporating the 250 Ma relative positions of the Antarctic Peninsula, Patagonia, and Africa, both latter global plate models treat the Antarctic Peninsula and Patagonia as completely overlapping at 250 Ma, reflecting their global scope and low regional resolution.

The one exception to a purely autochthonous history of the Antarctic and South American continental margin through the Paleozoic regards the origin of Patagonia. The history of this region remains debated, with autochthonous (e.g. Dopico et al., 2021; Falco et al., 2022; Gregori et al., 2008; Kostadinoff et al., 2005; Rapalini et al., 2013, 2010), and allochthonous (e.g. Pankhurst et al., 2006; Ramos, 2008; Bahlburg, 2021) models proposed. In the Merdith et al. (2021) reconstructions used here for the >320 Ma rotations, Patagonia is para-autochthonous, rifting from the Gondwanan margin at 390 Ma, before colliding back into the Gondwanan margin at approximately the same relative location at 310 Ma. Consequently, we show two reconstructions for 359 Ma (end Devonian): 1) autochthonous, with Patagonia remaining on the margin in the same relative location with the Antarctic Peninsula (e.g van de Lagemaat et al.,2021); and 2) para-autochthonous, with a rifted Patagonia, located as described by Merdith et al. (2021).

As for most published GPlates reconstructions globally, the above method of kinematic modelling assumes the continental crust behaves as rigid crustal blocks back to the Proterozoic. Whilst this may be largely correct for the cratonic core of Gondwana, the geological evidence for crustal addition, extension, and compression on convergent continental margins disputes this. The reconstructions in this paper aim to correlate the regional lithological and geochronological data between West Antarctica and South America, and so derive and map the changing continental margin of Gondwana, testing published hypotheses of terrane accretion and relative crustal positions. We thus not only extended the continental block rotations back to the Proterozoic, but also the relative locations of their mapped geology (Burton-Johnson and Riley, 2015; Gómez et al., 2019) and the relative locations of geochronological samples. For reference, and to highlight the progressive progradation of the continental margin, reconstructions in this paper also overlay the reconstructed present-day coastlines.

4. Geological evolution of the Antarctic Peninsula and correlations to Patagonia

4.1 Mesoproterozoic – Neoproterozoic

The only recognised Mesoproterozoic rocks crop out at the southern limit of the Antarctic Peninsula on the Fowler Peninsula at Haag Nunataks (Fig. 1) and form a distinct crustal province to the Antarctic Peninsula (Riley et al., 2020b). Haag Nunataks comprises three small (50 – 100 m) outcrops that expose highly strained and foliated granodioritic and dioritic orthogneisses, cut by a suite of aplite and pegmatite sheets, which are intruded by a final magmatic phase of microgranite sheets (Millar and Pankhurst, 1987). Although the areal extent of the rock outcrop at Haag Nunataks is <2 km^2, aeromagnetic data (Golynsky et al., 2018) indicate an area at least 350 km by 350 km with high amplitude magnetic anomalies matching those at Haag Nunataks. This magnetic domain was interpreted by Riley et al. (2020b) to represent similar crystalline basement and to delineate the unexposed extent of the Haag Nunataks crustal block. The block is inferred to have previously formed part of East Antarctica, and was displaced during Gondwana break-up (Jordan et al 2020) to its present position to the south of the Antarctic Peninsula.

The geochronology and field relationships at Haag Nunataks have been examined in detail by Riley et al. (2020b) who established that the granodiorite protolith was emplaced at 1238 ± 4 Ma, aplite/pegmatite sheets were intruded at 1064 ± 4 Ma and the final intrusive phase of microgranite sheets were emplaced at 1056 ± 8 Ma. A separate magmatic event at ~1170 Ma is recorded as inherited zircon grains in the later stage (~1060 Ma) intrusions. The exposed rocks at Haag Nunataks are juvenile in composition with virtually no contribution of remelting of existing crustal rocks indicated by Lu-Hf and Sm-Nd model ages (T_{DM}) of ~1270 Ma (Flowerdew et al., 2007; Storey et al., 1994; Wareham et al., 1998; Riley et al., 2020b). The main deformation phase at Haag Nunataks is interpreted to have developed prior to the emplacement of the microgranite sheet at ~1056 Ma, but after the ~1064 Ma aplite/pegmatite intrusive event. The units at Haag Nunataks are also notable insomuch that they were not subject to subsequent ductile deformation and metamorphism, based on their ~1000 Ma K/Ar mineral cooling ages (Clarkson and Brook, 1977).

Riley et al. (2020b) determined that the Late Mesoproterozoic granodiorite protolith was emplaced in a juvenile arc setting, which is likely to have formed part of the Namaqua-Natal-Maud belt of arc terranes (Fig. 3; Riley et al., 2020b). This suite of juvenile arc terranes is characterized by enhanced magmatism at ~1240 Ma and ~1170 Ma, consistent with the magmatic record identified at Haag Nunataks. The latter phase of magmatism, deformation and metamorphism at Haag Nunataks, which developed at ~1060 Ma is interpreted to be more closely associated with the collision of Laurentia with the proto-Kalahari craton and the Ottawan phase of the Grenville Orogeny.

Proxy evidence for a more widespread Proterozoic source region proximal to the Antarctic Peninsula is provided by analysis of detrital zircon data from Palaeozoic and Mesozoic metasedimentary units of the Antarctic Peninsula. Barbeau et al. (2010), Bradshaw et al. (2012) and Castillo et al. (2016) examined the provenance history of the Late Palaeozoic, Trinity Peninsula Group accretionary complex (Fig. 2). The Trinity Peninsula Group was deposited from the Late Carboniferous and all workers have identified minor Mesoproterozoic age peaks in the detrital zircon population from across a broad region of the metasedimentary succession, including several samples with 5-7% age peaks in the range ~1060 – 1000 Ma (Fig. 4). Barbeau et al. (2010) also investigated the detrital zircon population from the Early Jurassic Botany Bay Group exposed across northeast

Graham Land and again identified a minor (~7%) Late Mesoproterozoic age peak. However, detrital zircon analysis of the metasedimentary units of the Antarctic Peninsula have failed to identify an age peak more closely related to the protolith age at Haag Nunataks at ~1240 Ma. Therefore, the Late Mesoproterozoic ages identified in the detrital zircon population of the metasedimentary units of the Antarctic Peninsula are likely to have been sourced from the more widespread 'Grenvillian' magmatic, metamorphic and deformation event at ~1060 Ma that was ubiquitous during the assembly of Rodinia. This pattern is consistent with the widespread recycling of zircons during the Neoproterozoic – Early Palaeozoic (e.g. Andersen et al, 2016) and so complicate their provenance, it may indicate that the ~1240 Ma and ~1170 Ma ages representative of the Haag Nunataks protolith and juvenile arc terranes of the Namaqua-Natal-Maud Belt are likely to be spatially restricted in West Antarctica.

The Late Mesoproterozoic tectono-thermal and magmatic history of South America is difficult to determine as geological evidence is restricted to isolated basement inliers (Ramos, 2010). Mesoproterozoic rocks from the San Rafael and Las Matras blocks of central Argentina share close similarities with the tectono-magmatic history of the Haag Nunataks crustal block (Riley et al., 2020b) and record juvenile arc magmatism in the interval 1244–1215 Ma (Varela et al., 2011). More widespread Elzevirian-age basement is indicated by a peak at ~1230 Ma in U-Pb detrital zircon ages from Ordovician sandstones of central Argentina (Abre et al., 2011).

4.1.1 Tectonic Setting

Haag Nunataks represents the exposed part of a distinct crustal block (Haag Nunataks, Ellsworth Mountains-Whitmore Mountains; Fig. 1) that forms part of West Antarctica's collage of microcontinents (e.g. Dalziel and Elliot, 1982; Jordan et al., 2020). The absence of inherited/detrital zircons in Antarctic Peninsula lithologies that are representative of the Mesoproterozoic protolith at Haag Nunataks at ~1240 and ~1170 Ma indicate that the paleo-position of the Haag Nunataks crustal block was not proximal to the Antarctic Peninsula during the Palaeozoic. This is consistent with

Gondwana breakup reconstructions (Jordan et al., 2017), stratigraphic and paleomagnetic data (e.g. Dalziel and Grunow, 1992; Randall and Mac Niocaill, 2004), and the interpretation of Riley et al. (2020b) that indicates Haag Nunataks was located close to the Natal Embayment or the Shackleton Range (Castillo et al., 2017), prior to translation in the Early Jurassic (Fig. 3).

Geological evidence for a pre-Cambrian crustal signature in the Antarctic Peninsula region away from Haag Nunataks is limited. Isotopic evidence, including depleted mantle Sm-Nd and Lu-Hf model ages from post-Ordovician intrusions (e.g. Millar et al., 2001; Flowerdew et al., 2006), led Flowerdew et al. (2006) to infer that 'Haag Nunataks-like' basement was widespread at depth across the Antarctic Peninsula. However, this interpretation is now considered to be unlikely based on more recent investigations of the basement provinces of the Antarctic Peninsula (e.g. Riley et al., 2012, 2020b; Bastias et al., 2020).

Conglomerate clast ages, detrital zircon populations and inherited zircons in igneous and metamorphic rocks (e.g. Millar et al., 2002; Barbeau et al., 2010; Bradshaw et al., 2012; Castillo et al., 2016, 2020) would seem to suggest a pre-Ordovician ancestry for parts of the Antarctic Peninsula. However, many of the Cambrian – Neoproterozoic ('Pan-African') and late Mesoproterozoic ('Grenvillian') detrital zircon populations are unlikely to have originated from proximal Antarctic Peninsula sources. This is because the persistent, albeit generally minor, occurrence of zircons of this age is likely to reflect recurrent sediment reworking and recycling during the Early Palaeozoic (Andersen et al., 2016, 2019), so correlation to any of a number of candidate sources with confidence is difficult. Therefore, the occurrence of pre-Ordovician zircons in igneous and metamorphic rocks are most likely to have been inherited from sedimentary units which contain detrital zircons of this age.

4.2 Cambrian (541 – 485 Ma)

There is no recognised bedrock of Cambrian age in the Antarctic Peninsula, but the adjacent Ellsworth Mountains (Fig. 1) are dominated by the Middle to Late Cambrian Heritage Group and Lower Crashsite Group (Webers et al., 1992; Curtis and Lomas, 1999). The Heritage Group is at least 7.5 km in thickness and consists of volcaniclastic and shallow marine/fluvial sedimentary rocks that were deformed during the Palaeozoic Gondwanide Orogeny (Curtis, 1997).

Flowerdew et al. (2007), Craddock et al. (2016) and Castillo et al. (2017), examined the detrital zircon history of the Cambrian – Permian sedimentary successions of the Ellsworth Mountains and determined that the deposition of the Heritage Group at ~520 Ma developed in a continental rift setting at the margin of Laurentia and East Antarctica, with a primary sediment supply from Laurentia and Coats Land in East Antarctica.

Extensive, rift-related volcanism in the Heritage Range of the Ellsworth Mountains has been investigated by Vennum et al. (1992) and Curtis et al. (1999) who reported a range of geochemical rock types, including a distinctive suite of MORB-like rift-axis basalts. Back-arc, rift-related volcanism is also reported from the Queen Maud Mountains of the Transantarctic Mountains (Wareham et al., 2001) and the Pensacola Mountains (Fig. 5; Storey et al., 1992). The basaltic volcanic rocks of the Queen Maud Mountains were emplaced in the interval 525 – 515 Ma and also include MORB-like compositions.

In the Antarctic Peninsula, Barbeau et al. (2010) and Bradshaw et al. (2012) recognised Cambrian age populations (500 – 495 Ma peak) in samples from the Trinity Peninsula Group in northwest Graham Land. Cambrian (~525 Ma) zircons form one of the dominant age populations recorded from the Devonian FitzGerald Beds (Fig. 2) in the southern Antarctic Peninsula at Fitzgerald Bluffs (Elliot et al., 2016). Millar et al. (2002) and Riley et al. (2012) also identified 540 – 515 Ma inherited and detrital zircon grains from the Adie Inlet gneiss complex (Fig. 1), and Flowerdew et al. (2006) reported Cambrian grains from Welch Mountains paragneiss (Fig. 1). Cambrian detrital zircons are ubiquitous components in Gondwana sourced successions and so their appearance in the Antarctic

Peninsula is not surprising, and probably means these zircons are recycled rather than sourced from proximal Cambrian units.

Söllner et al. (2000), Pankhurst et al. (2003), Rapela et al. (2007), Hervé et al. (2010) and Casquet et al. (2018) have all reported Early Cambrian granitoid magmatism (~540 – 520 Ma) from the Deseado Massif (South Patagonian Terrane) region of southern Patagonia. Pankhurst et al. (2003) dated diorite from basement cores of the Magallanes Basin at 523 ± 5 Ma, in agreement with Söllner et al. (2000) who recorded an age of 529 ± 8 Ma from an orthogneiss from a borehole in Tierra del Fuego. Guido et al. (2004) summarised the basement geology of the Deseado Massif and interpreted the Early Cambrian to be a significant crust-forming event. Hervé et al. (2010) defined the crystalline basement of the Deseado Massif as part of the Tierra del Fuego igneous and metamorphic basement complex (Fig. 7). Hervé et al. (2010) tentatively correlated this episode of Fuegian magmatism with the source of Cambrian zircon grains identified from eastern Graham Land. The basement of northeastern Patagonia is also characterized by Early Palaeozoic igneous and metamorphic rocks that do not crop out in the central, western and Andean sectors of the North Patagonian Massif (Rapela and Pankhurst, 2020). Cambrian magmatic rocks of northeastern Patagonia were interpreted to be continuous with those of the Eastern Sierras Pampeanas (Fig. 6) (Rapela and Pankhurst, 2020). Early – Middle Cambrian magmatism and deformation associated with the Pampean Orogeny is also recognised from the Córdoba district (Fig. 6) of northwest Argentina (Tibaldi et al., 2021). Geochemically, the lithologies are diverse, ranging from mafic, OIB-like rocks to granitoids. Elsewhere in Patagonia, González et al. (2018) have identified Early – Middle Cambrian syn-sedimentary volcanism in the eastern region of the North Patagonian Massif (Fig. 6), which is intruded by Famatinian age (Ordovician) granitoids. Rapalini et al. (2013) have also dated deformed granitoids from the northeast North Patagonian Massif at 528.5 ± 3.5 Ma associated with more widespread Ordovician granitoid emplacement at ~470 Ma. A Pampean source is widely attributed to the abundant and prominent Neoproterozoic and Cambrian detrital zircon populations reported from South America (e.g. Casquet et al., 2018).

4.2.1 Tectonic setting

Cambrian reconstructions for the Ellsworth-Whitmore Mountains in a West Gondwana setting have been attempted by several workers (e.g. Schopf, 1969; Watts and Bramall, 1981; Grunow et al., 1987; Dubendorfer and Rees, 1998; Randall et al., 2000; Randall and Mac Niocaill, 2004; Castillo et al., 2017; González et al., 2018) who offer differing tectonic interpretations of the paleo position of the Ellsworth-Whitmore Mountains crustal block. Randall and Mac Niocaill (2004) favour a Natal Embayment origin for the Ellsworth-Whitmore Mountains based on paleomagnetic evidence from the Cambrian Frazier Ridge Formation, but this is in disagreement with their earlier work (Randall et al., 2000). In this study they demonstrated that none of the Early Palaeozoic paleomagnetic data from the Ellsworth-Whitmore Mountains were in agreement with the Gondwana reference poles when the Ellsworth-Whitmore Mountains block was located in the Natal Embayment prior to Gondwana breakup. Dubendorfer and Rees (1998) prefer a paleo position adjacent to the Queen Maud terrane (Fig. 5), although Randall and Mac Niocaill (2004) suggest the terranes have differing tectonic histories for them to have been adjacent during the Cambrian.

Castillo et al. (2017) demonstrated using detrital zircon geochronology that the Ellsworth Mountains have a strong affinity to the Antarctic-Australian plates (Fig. 5), whilst González et al. (2018) suggest that the volcanic and sedimentary sequences of the Ellsworth Mountains, Pensacola Mountains and Transantarctic Mountains are adjacent to the magmatic and metasedimentary units of the North Patagonian Massif and the magmatic rocks of the Deseado Massif (Fig. 5). Their interpretations are further supported by the identification of archeocyath fauna from a meta-conglomerate bed in the El Jagüelito Formation (Sierra Grande area, eastern North Patagonian Massif, Argentina; González et al., 2011), which they correlated with archeocyathan assemblages from Antarctica.

There are no exposed Cambrian rocks in the Antarctic Peninsula which makes paleo positions difficult to define, particularly as there is no evidence of any Proterozoic basement to the Antarctic

Peninsula, as Haag Nunataks is an exotic crustal block (Jordan et al., 2017). The Late Cambrian reconstruction shown in Fig. 7 places the Tierra del Fuego igneous and metamorphic basement complex adjacent to the ortho- and paragneiss complexes of eastern Graham Land (Adie Inlet) and northwest Palmer Land, although there is no direct evidence to suggest that the source of inherited and detrital zircon grains in the Antarctic Peninsula is from the Tierra del Fuego metamorphic complex.

Tibaldi et al. (2021) determined that a convergent margin was active during the Early to Middle Cambrian, with a slab window responsible for the OIB-like magmatism identified from the central Sierras de Córdoba. A back-arc basin setting during the Early – Middle Cambrian led to basaltic magmatism developing in the Ellsworth, Pensacola and Queen Maud mountains of East Antarctica (Fig. 5), with crustal thinning permitting the emplacement of asthenospheric melts (Wareham et al., 2001). In this geodynamic scenario, the basement of the North Patagonian Massif is adjacent to the Ellsworth-Whitmore Mountains crustal block and outboard of the back-arc rifted margin, represented by the Pensacola and Queen Maud mountains (Fig. 5, 7).

During the Late Cambrian, the Ross Orogeny tectonic event is recognised in Cambrian sequences of the Transantarctic Mountains and developed as a consequence of accretion of the outboard Queen Maud suspect terrane with the Antarctic margin of Gondwana (Curtis et al., 2004).

4.3 Ordovician (486 – 444 Ma)

Evidence for the presence of an Ordovician crustal source proximal to the Antarctic Peninsula is indicated from the detrital zircon history of metasedimentary rocks of the northern Antarctic Peninsula (Trinity Peninsula Group; Barbeau et al., 2010; Bradshaw et al., 2012; Castillo et al., 2015, 2016; Fig. 4) and inherited zircons from gneiss complexes exposed at isolated localities across both Graham Land and Palmer Land (Millar et al., 2002; Riley et al., 2012; Castillo et al., 2020). The only direct evidence for Ordovician basement in the Antarctic Peninsula has been presented by Riley et al. (2012), who conducted a field and geochronological investigation of the gneiss complexes of eastern Graham Land and reported an Early Ordovician crystalline basement suite from the Eden Glacier region of the Foyn Coast (Fig. 1). The geology of the Eden Glacier region was initially investigated by Marsh (1968), who described steeply dipping gneisses with melanocratic bands up to 1 cm in thickness. Using the field descriptions of Marsh (1968), Milne (1987) suggested that the Eden Glacier gneiss complex (Fig. 2) was likely to be a continuation of the Carboniferous – Devonian crystalline basement complex exposed at Target Hill. The primary lithology at Eden Glacier is a diorite gneiss protolith, which has been migmatised in part, and cut by mafic intrusions (Fig. 8). The entire assembly is affected by a second phase of deformation and metamorphism; this later phase of deformation and metamorphism is locally intense and has developed a strong foliation defined by mafic minerals, which transposes the earlier gneissic fabric. Riley et al. (2012) dated the diorite gneiss protolith from two separate localities along the Eden Glacier and determined latest Cambrian/ Early Ordovician ages of 487 ± 3 Ma and 435 ± 3 Ma, which represent the oldest in situ rocks identified from the Antarctic Peninsula crustal block and are interpreted to form the Palaeozoic basement.

Further south in eastern Graham Land, Flowerdew (2008) defined the Bowman Metamorphic Complex (Fig. 2), which is exposed at Stubbs Pass and Joerg Peninsula (Fig. 1). The oldest rocks of the Bowman Metamorphic Complex are paragneiss, schist and marble, which are cut by extensive granite to gabbro sheets. The entire assembly is deformed, metamorphosed and migmatised under at least upper amphibolite facies conditions. Riley et al. (2012) dated one of the numerous granite sheets, which cut the paragneiss lithology, exposed on the Joerg Peninsula. The granite sheets are Triassic, but are characterised by abundant inherited zircon core ages in the range 480 – 460 Ma.

The most compelling evidence for an extensive Early Ordovician crustal source is the conglomerate clast ages and detrital zircon record of the metasedimentary Trinity Peninsula Group. Barbeau et al. (2010) reported significant Ordovician age peaks of up to 20% in most analysed samples of the Trinity Peninsula Group from northern Graham Land and also from the Early Jurassic

Botany Bay Group sedimentary succession. Detrital zircon ages were recorded in the range 480 – 420 Ma (Early Ordovician – Silurian), with well-defined peaks at ~475 Ma and ~470 Ma. Castillo et al. (2016) also recognised prominent Ordovician age peaks in the detrital zircon population from the Trinity Peninsula Group of northern Graham Land, with two samples from Hope Bay and Cape Legoupil (Fig. 1) characterised by an Early Ordovician zircon population (up to 20%) with an age peak at ~470 Ma (Fig. 4a). Additional evidence for an Ordovician source contribution to the Trinity Peninsula Group metasedimentary succession was presented by Millar et al., (2002) and Bradshaw et al. (2012), who reported U-Pb zircon ages of 487 ± 4 Ma, 466 ± 3 Ma and 463 ± 5 Ma from volcanic, granite gneiss and granite clasts in a conglomerate from View Point (Fig. 1). Castillo et al. (2016) speculated that the potential source for the Ordovician detrital material could be the Eden Glacier diorite protolith identified by Riley et al. (2012). However, an alternative source region from the Deseado Massif or Cordillera Darwin metamorphic complex of Patagonia (Fig. 7) was also considered possible. Both Riley et al. (2012) and Castillo et al. (2016) suggested potential correlations between the Ordovician metamorphic rocks and detrital zircon population in the Antarctic Peninsula with the sequences of the Famatinian magmatic belt of South America (Rapela et al., 2018). The Famatinian magmatic belt (Fig. 7) represents a major episode of Early Ordovician magmatism extending from Venezuela to Patagonia (Pankhurst et al., 2006; Ramos et al., 2018). The type section for the Famatinian magmatic belt is recognised through the Sierras Pampeanas region of Argentina, which dissects the Famatinian and Pampean orogens (Fig. 6). Rapela et al. (2018) identified the likely onset of Famatinian belt magmatism at ~486 Ma with adakitic trondhjemites emplaced into the foreland region of the margin during an episode of slab roll back. The primary episode of Famatinian belt magmatism developed in the interval 472 – 468 Ma and was regarded as a magmatic 'flare-up' event (Rapela et al., 2018). This episode was coincident with steepening slab roll back and widening of the arc (Rapela et al., 2018). The development of the Puna-Famatinia basins (Fig. 7) led to thick accumulations of volcanic and volcaniclastic rocks, which were deformed during the Famatinian Orogeny at ~470 Ma. Similar detrital zircon age patterns between Early

Paleozoic metasedimentary rocks from the North Patagonian Massif and those from the Sierras Pampeanas and the likely continuation of the Early Ordovician Famatinian magmatic arc into northeastern Patagonia suggest crustal continuity between the Pampia and North Patagonian Massif blocks by the Early Paleozoic. Paleomagnetic data recorded from the North Patagonian Massif (Rapalini et al., 2010) suggests that no wide ocean existed between Patagonia and Gondwana between the Devonian and Permian.

Geochemically, Castillo et al. (2016) recognised that the εHf and $\delta^{18}O$ isotopic compositions of the Ordovician detrital zircon population of the Trinity Peninsula Group differ from the zircon isotopic values of the Famatinian magmatic arc, which may rule out a direct source component for the metasedimentary rocks of the Trinity Peninsula Group and its Patagonian correlative, the Duque de York Complex. Castillo et al. (2016) recorded εHf values in the range, +3.5 to -5.1 for Ordovician detrital zircons from the Trinity Peninsula Group, and Bradshaw et al. (2012) report a similar range of εHf values for the Ordovician granitoid and volcanic conglomerate clasts from View Point, whereas Famatinian magmatic arc rocks have εHf values which are more strongly negative, -3.3 to -14.7 also reported by Bradshaw et al. (2012). However, a more recent analysis of the Famatinian magmatic belt by Rapela et al. (2018) demonstrate that there is considerable isotopic variation across the Famatinian magmatic province from the continental margin to the Foreland Domain. They illustrated that those rocks from the coastal margin and central domains have εHf values that mostly fall in the range -6 to 0, whilst those from the foreland region have a far broader range in εHf, -7 to +10.

The interpreted 'flare-up' event in the Famatinian magmatic belt at ~470 Ma fits well with the primary age peak identified in the Trinity Peninsula Group (Antarctic Peninsula) and the Duque de York Complex of Patagonia (Castillo et al., 2016: Fig. 4) in both the detrital zircon and inherited zircon profiles (Riley et al., 2012; Castillo et al., 2016, 2020). The limited εHf data available from the Trinity Peninsula Group suggests that the potential source is most likely to have been from the Foreland Domain of the Famatinian magmatic belt, or its unexposed equivalents, and not from the Eden Glacier diorite gneiss complex, which is significantly older at ~485 Ma (Riley et al., 2012).

The Early Ordovician Eden Glacier basement gneiss complex at ~485 Ma is interpreted to represent part of the earliest phase of magmatism of the Famatinian magmatic belt that developed in the foreland region (Rapela et al., 2018) and is not considered to be a widespread event, but it helps to pinpoint the paleo-position of the proto Antarctic Peninsula during the Early Ordovician (Fig. 7).

4.3.1 Tectonic setting

The Ordovician period in southwest Gondwana is synonymous with the Famatinian Orogeny and magmatic belt. The onset of Famatinian magmatism is likely to have developed at ~486 Ma with trondhjemite-diorite magmatism in the central and foreland domains of South America and eastern Graham Land (Fig. 7). Rapela et al. (2018) suggested magmatism was initially associated with an episode of slab roll-back (484 – 474 Ma), with melting in a thickened crustal setting. Whereas the main phase of Famatinian arc magmatism developed at ~470 Ma in the Sierra Pampeanas region as a consequence of slab break off (472 – 463 Ma) and intense igneous activity along the continental margin sector of the Famatinian arc (Rapela et al., 2018).

In Patagonia, Ordovician magmatism is rare or absent from the Deseado Massif-Tierra del Fuego region, but is more widespread in the North Patagonian Massif and also the Famatinian magmatic belt in the Chilenia segment of South America. The paucity of Ordovician magmatism in southern Patagonia (Deseado Massif Terrane) and also the Antarctic Peninsula (Riley et al., 2012) has been used by many authors (e.g. Pankhurst et al., 2006) to suggest an allochthonous origin for southern Patagonia with accretion of the Deseado/South Patagonian Terrane to the Gondwana margin in the Late Palaeozoic. González et al. (2021) identified an Ordovician collisional event referred to as the compressional Transpatagonian orogen (Fig. 7), resulting from the accretion of the North Patagonian Massif with southwest Gondwana. The orogen is a NW–SE-trending belt traced from the extra-Andean North Patagonian Cordillera region via the eastern North Patagonian Massif up to the Atlantic coast in the east. A distinct history for the southern Patagonia/Deseado terrane relative to the North Patagonian Massif is also indicated from Re-Os isotope data of mantle xenolith material (Schilling et al., 2017), which demonstrate different Proterozoic basement. Rapalini et al. (2013) suggest that the Pampean (Cambrian) and Famatinian (Ordovician) magmatic belts of the Sierras Pampeanas (Fig. 6) are continuous into Patagonia. U-Pb age spectra from detrital zircons of Cambro-Ordovician metasedimentary rocks show very similar age profiles to those from equivalent units of the Pampia block (Fig. 6), over 500 km further north. The origin of a V-shaped basin (Sierra Grande Sea) separating the North Patagonian Massif from southern Gondwana may have originated during a mid-Cambrian rift event between the North Patagonian Massif and the Río de la Plata craton or as an extended Famatinian back-arc basin (Martínez Dopico et al., 2021), remaining open until the end of the Palaeozoic. Martínez Dopico et al. (2021) do not rule out a pre-Ordovician Antarctic provenance for the North Patagonian Massif, but suggest that it would require very high drift velocities that are geodynamically unlikely. Instead they support a para-autochthonous Palaeozoic evolution of the North Patagonian Massif with respect to Gondwana. A significant ocean basin separating both land masses in the Late Ordovician is therefore unlikely.

4.4 Silurian (444 – 419 Ma)

Barbeau et al. (2010) and Castillo et al. (2016) identified only minor Silurian age peaks (<5%) in the detrital zircon population from the metasedimentary Trinity Peninsula Group (Fig. 4a). The age peaks are consistently lower than the more prominent (up to 20%) Ordovician signature identified throughout the Trinity Peninsula Group (Fig. 4a) and its probable equivalent, the Duque de York Complex of Patagonia (Fig. 4b, c).

Potential primary sources for the Silurian age detrital zircon grains have been suggested (Castillo et al., 2016) from several isolated sites across the Antarctic Peninsula, particularly in eastern Graham Land and northwest Palmer Land. Milne and Millar (1989) calculated a Rb-Sr whole rock isochron age of 426 ± 12 Ma for a granitic orthogneiss from the Target Hill metamorphic suite in eastern Graham

Land (Fig. 2). However, Millar et al. (2002) later reported a much younger U-Pb concordia age of 393 ± 1 Ma for the granitic orthogneiss (Table 1). Elsewhere, Tangeman et al. (1996) recorded an upper intercept U-Pb zircon age of 431 ± 12 Ma for a foliated granite clast from a sheared conglomerate on Horseshoe Island in western Graham Land (Fig. 1). Harrison and Piercy (1992) also reported an imprecise Rb-Sr Silurian age of 440 ± 57 Ma for orthogneiss from northwest Palmer Land.

Millar et al. (2002) undertook a detailed analysis of the metamorphic basement complexes of the Antarctic Peninsula and identified Silurian zircon core ages of 422 ± 18 Ma and 435 ± 8 Ma (Table 1) from orthogneisses at Mount Eissinger in northwest Palmer Land (Fig. 1). These ages are interpreted to date the protolith in an otherwise dominantly Triassic metamorphic suite; Millar et al. (2002) suggested the Silurian protolith from Mount Eissinger was likely to be the source of the granite clast from Horseshoe Island (Tangeman et al., 1996).

Castillo et al. (2020) re-examined one of the samples (R.5257.1) dated by Millar et al. (2002) at Mount Eissinger and recorded zircon core ages of ~440 Ma and ~250 Ma, but with similar δ^{18}O and εHf values to the overgrowths. The analysis of Castillo et al. (2020) illustrates that the zircon core ages to the Triassic metamorphic suite at Mount Eissinger may have a more complex history than suggested by Millar et al. (2002). Inherited zircons of Silurian age have been reported from metamorphic rocks of northwest Palmer Land (Bastias et al., 2020) and indicate that protoliths of this age may be locally important.

The overall assessment of Silurian ages from the metasedimentary and crystalline basement record of the Antarctic Peninsula is that there is little evidence to support any widespread magmatic event. Relative to the Famatinian arc-related magmatism and metamorphism during the Ordovician, the Silurian appears to represent a lull in magmatic activity. Bahlburg (2021) also described a Silurian – Devonian magmatic lull between the flare-ups of the Famatinian and Gondwanide orogenies (Cambrian – Ordovician and Carboniferous – Triassic, respectively). Magmatic lulls are characterized by less than 25% of magma production relative to flare-ups and occur at times of slow landward migration of an arc system. A paucity of any prolonged magmatism during the Silurian is also reflected in the metasedimentary record from Patagonia. Urzi et al. (2011) investigated the Silurian – Devonian siliclastic Ventana Group of the North Patagonian Massif region. The primary sources for detrital zircons were identified as Cambrian – Ordovician age, combined with a significant Neo – Mesoproterozoic age peak. The Silurian age detrital zircon population was very minor across the analysed units (<4%), compared to an Ordovician age peak of up to 30%.

4.4.1 Tectonic setting

Ramos and Naipauer (2014) determined that a magmatic arc developed during the Late Silurian – Devonian, and extended through the western North Patagonian (Somuncura) Massif and central Deseado Massif (Fig. 9). Arc magmatism was mostly Devonian in age, but an episode of Late Silurian magmatism (~425 Ma; Pankhurst et al., 2003) and metamorphism (Fracchia and Giacosa, 2006) is recorded in isolated granitoids from both the Deseado and North Patagonian massifs (Fig. 9) and may form part of the minor magmatic event that is identified in the inherited and detrital zircon record in the Antarctic Peninsula (e.g. Castillo et al., 2020). This magmatism is referred to as the Western igneous belt (Fig. 6; Ramos, 2008) and is located in an intraplate setting cross cutting central Patagonia. A passive margin between Patagonia and East Antarctica has been suggested during the Silurian – Devonian (Ramos and Naipauer, 2014) with sequences from the eastern North Patagonian and Deseado massifs correlated with those from the Pensacola-Queen Maud-Central Transantarctic mountains

4.5 Devonian (419 – 359 Ma)

Evidence for Devonian magmatism in the Antarctic Peninsula is very limited, with the only in situ lithologies reported from the Target Hill metamorphic complex (Fig. 2) of eastern Graham Land (Millar et al., 2002). The metamorphic basement exposed at Target Hill (Fig. 1) was initially considered (Milne and Millar, 1989) to represent a more extensive basement complex to the northern Antarctic Peninsula, but Riley et al. (2012) suggested that the Devonian protolith at Target Hill was in fact a distinct and geographically restricted magmatic event. Millar et al. (2002) recorded ages of 393 ± 1 Ma and 399 ± 9 Ma from the orthogneiss complex at Target Hill which underwent metamorphism and further magmatism during the Carboniferous (327 ± 9 Ma). These ages refined earlier investigations by Pankhurst (1983) and Milne and Millar (1989) who dated Target Hill orthogneiss and foliated granodiorite as Late Silurian to Early Devonian, with Carboniferous metamorphism.

Detrital zircon investigations of the Carboniferous – Jurassic metasedimentary sequences of northern Graham Land (Barbeau et al., 2010; Castillo et al., 2016) to some extent contradict the record of exposed Devonian magmatic rocks in the Antarctic Peninsula. Barbeau et al. (2010) reported an 8% Devonian age peak in the detrital zircon record of one sample from the Permian Trinity Peninsula Group of western Graham Land and a 12% age peak in the Jurassic Botany Bay Group sedimentary rocks exposed at Hope Bay from northern Graham Land (Fig. 1). These sedimentary units are 200 – 300 km from the exposed Devonian protolith at Target Hill and indicate that there is likely to be a more significant Devonian source than that exposed in eastern Graham Land. However, the majority of the Trinity Peninsula Group successions examined by Barbeau et al. (2010) and Castillo et al. (2016) are more consistent with the magmatic record and do not show any significant detrital zircon age peaks from the Devonian (Fig. 4a) and indicate a strong local signature may have been significant in the sedimentary input to the accretionary complexes of the Trinity Peninsula Group.

In southern South America, the Devonian was initially considered to be a period of magmatic and metamorphic quiescence, with a passive margin interpreted along the continental front and limited evidence for Devonian magmatism from northern and central Chile (Bahlburg and Hervé, 1997). However, the regional tectonic and magmatic setting in Patagonia is distinct to the Andean sector north of 40°S, with two almost coeval calc-alkaline belts of Devonian magmatism identified in Patagonia (e.g. Calderón et al., 2020; Dahlquist et al., 2020; Serra-Verala et al., 2021). Hervé et al.

(2013) suggested that subduction-related Devonian magmatism developed during the collision of the Chilenia terrane with Gondwana, which led to the closure of an oceanic basin. Hervé et al. (2016) investigated the age, geochronology and tectonic setting of magmatic rocks from the southern Chilean Andes and identified widespread Devonian magmatism in the interval 404 – 353 Ma termed the Achalian magmatic event. Using $\delta^{18}O$ and εHf isotopes Hervé et al. (2016) were able to distinguish two separate intrusive magmatic belts; a more mantle-like zone of magmatism, which is interpreted as an oceanic island arc and a zone having a stronger crustal signature related to a continental magmatic belt in North Patagonian Massif region. This paired subduction tectonic setting was interpreted to be active throughout the mid-Devonian, with island arc magmatism recorded in the interval 385 – 360 Ma and continental margin arc magmatism continuous from at least 400 – 350 Ma (Hervé et al., 2016).

Dahlquist et al. (2021) examined occurrences of Devonian – Carboniferous magmatism from the Sierras Pampeanas and Frontal Cordillera region (Fig. 6) and identified an almost continuous magmatic episode from 395 – 320 Ma, but with significant compositional variations both spatially and chronologically. They distinguished both a Devonian arc and a Devonian foreland region with the type of magmatism in each domain controlled by changes in the subduction configuration developing along a long-lived active convergent margin. Devonian magmatism resulted from segmented subduction, with calc-alkaline arc magmatism between 34° and 35°S, but magmatism absent between 27° and 33°S above a flat slab. The absence of Devonian arc magmatism was interpreted as the result of flat-slab subduction in the outboard region, while the presence of Devonian (ca. 393–366 Ma) foreland magmatism was attributed to resubduction >800 km inland from the trench. In this configuration, Devonian arc magmatism was absent, but voluminous foreland magmatism developed, including small-scale high silica-adakite mostly derived by the partial melting of the resubducted oceanic slab (Dahlquist et al., 2021).

Detrital zircon provenance analysis from the accretionary complexes that are exposed along the coastal margin of southern and central Chile exhibit a strong Devonian age peak (Fig. 4b), with the primary source determined to be from the continental margin arc exposed in the North Patagonian Massif, as opposed to the oceanic arc (Hervé et al., 2016), although this is also likely to have been strongly influenced by the more felsic compositions from the North Patagonian Massif compared to the coastal margin, where zircon-bearing rocks are rarer.

An anomalous Devonian sedimentary succession is exposed in southern Palmer Land at FitzGerald Bluffs (Fig. 1) where a 300 m sequence of stable margin quartzite beds crop out and provide a clear contrast to the continental margin sequences elsewhere in the Antarctic Peninsula (Elliot et al., 2016). The FitzGerald Bluffs quartzite (Fig. 2) is lithologically similar to the Cambrian – Devonian Crashsite Group in the Ellsworth Mountains (Fig. 1) and Devonian sandstones of the Transantarctic Mountains (Fig. 1). As part of this study quartzite (R.8002.2) was investigated from FitzGerald Bluffs. The sample preserves a primary sedimentary texture, has rounded detrital grains of quartz with other minor detrital grains of muscovite, rutile, zircon and magnetite. The matrix is completely recrystallised polycrystalline quartz, sericite, biotite, muscovite, chlorite and epidote, minerals that grew either during hornfelsing associated with local granite intrusion or earlier metamorphism. The detrital zircon population of the FitzGerald Bluffs beds is dominated by Late Neoproterozoic and Cambrian grains and is comparable with zircon age populations from the upper Crashsite Group of the Ellsworth Mountains and the Alexandra Formation of the central Transantarctic Mountains (Flowerdew et al., 2006; Elliot et al., 2016; Castillo et al., 2017; this study; Fig. 10; Table S2). However, a similar detrital zircon age profile between the FitzGerald Bluffs beds and the Crashsite Group quartzites is not necessarily diagnostic of a shared geological history given the prevalence of Neo – Mesoproterozoic detrital zircons in successions of the Gondwana margin. Elliot et al. (2016) interpreted the FitzGerald Bluffs geology to be representative of a separate crustal block, which became detached from the Haag-Ellsworth-Whitmore Mountains block during West Gondwanan reorganisation (Jordan et al., 2017).

4.5.1 Tectonic setting

The only direct evidence for Devonian magmatism and metamorphism in the Antarctic Peninsula is restricted to the Target Hill metamorphic complex (Fig. 2), although at least part of the detrital zircon record indicates a more significant localised source region for the northern Antarctic Peninsula. Late Devonian magmatism in southern Patagonia developed in two contemporaneous belts, possibly reflecting double subduction along both a continental margin and island arc setting (Hervé et al., 2013) or a function of subduction slab dynamics (Dahlquist et al., 2021), which is favoured here based on our GPlates kinematic reconstructions. The evolution of the Devonian–Carboniferous magmatism between 27° and 35°S is best explained by a segmented tectonic subduction and switch-off and switch-on geodynamic model (push-pull tectonics), including the transition from flat-slab to roll-back subduction involving delamination of the upper plate and break-off of the oceanic slab (Dahlquist et al., 2021). Ramos (2008) suggested that two coeval magmatic arcs; a western belt broadly parallel to the present continental margin that was active from the Late Silurian to the mid-Carboniferous and a southern magmatic arc that eventually led to the collision of Patagonia with southwest Gondwana. The western magmatic arc ceased when Patagonia collided with the Antarctic Peninsula. The two contemporaneous magmatic belts are interpreted to have developed during the Devonian – Early Carboniferous in northern Patagonia (Hervé et al., 2016, 2018; Rapela et al., 2021); one magmatic belt emplaced in a continental crust and a second magmatic belt emplaced in the Chaitenia oceanic island arc terrane (Fig. 6), accreted to the continent during the Carboniferous (Hervé et al., 2016). New U-Pb zircon geochronology combined with whole-rock geochemistry and Hf-O isotopes suggests a para-autochtonous origin for the Chaitenia terrane is likely and is related to roll-back of the subducting slab during the Devonian (Rapela et al., 2021). Herve et al., (2013) suggested the development of an accretionary system related to a subduction zone west of the North Patagonia Massif, which places a northern limit for the position of the Antarctic Peninsula.

The prominence of Devonian magmatism in Patagonia (Hervé et al., 2016) and its relative paucity in the Antarctic Peninsula is reflected in the detrital zircon populations of the Duque de York

Complex (Fig. 4b) and the Trinity Peninsula Group (Fig. 4a) respectively (Castillo et al., 2016) and suggests that parts of the proto Antarctic Peninsula and Deseado Massif (southern Patagonian terrane) were likely to have been isolated from Devonian sources, but remained proximal to the Ordovician arc successions (Fig. 9). The Duque de York Complex and the northern Trinity Peninsula Group both share prominent Devonian zircon age peaks, whereas the majority of the Trinity Peninsula Group lack any significant Devonian zircons. The Duque de York succession from Desolación Island lies to the south of the Magallanes Fault Zone (Fig. 6) and its detrital zircon age profile (Fig. 4c) is distinct to the successions from elsewhere in Patagonia (Fig. 4b). The metasedimentary rocks of Desolación Island have a minor Devonian zircon signal, but are characterised by a prominent Ordovician zircon age peak (Fig. 4c), closer in age structure to the sequences from the southern Trinity Peninsula Group (Fig. 4a). The variation in source units exhibited in the accretionary successions of the Trinity Peninsula Group and Duque de York Complex indicate the complexity of the margin during the Devonian – Carboniferous and how discrete basins were more isolated depending on their paleo-location.

It is uncertain if the ~395 Ma orthogneisses of Target Hill can be directly correlated to the Early Devonian granitoids of the North Patagonian Massif, given the absence of isotopic constraints, but it is likely that both zones of granitoid magmatism occupied a similar position relative to the arc front (Fig. 9).

4.6 Carboniferous (359 – 299 Ma)

The only recognised crystalline basement of Carboniferous age in the Antarctic Peninsula has been reported from the Target Hill metamorphic complex (Fig. 2) in eastern Graham Land (Millar et al., 2002). The orthogneiss protolith is mid-Devonian in age, but also records minor evidence of Carboniferous (327 ± 9 Ma) magmatism and metamorphism, which involved the partial melting of Devonian granitoids.

The Trinity Peninsula Group of northern Graham Land (Fig. 2) is the dominant pre-Jurassic sedimentary succession of the northern Antarctic Peninsula. The Trinity Peninsula Group is a 4 – 5 km succession of variably deformed siliciclastic turbidites (Hyden and Tanner, 1981) with rare interbedded basaltic-andesitic volcanic rocks (pillow lavas and hyaloclastites; Smellie et al., 1996). The Trinity Peninsula Group was deposited in a continental margin fore-arc setting from the mid-Carboniferous to the Triassic (Bradshaw et al., 2012) with part of the succession deposited onto crystalline continental basement (Hervé et al., 1996). The entire succession was incorporated into an accretionary complex with outboard correlatives in the Scotia Metamorphic Complex (Tanner et al., 1982) and Greywacke Shale Formation (Trouw et al., 1997) forming part of the South Orkney Islands/microcontinent (Fig. 1). The Miers Bluff Formation (Fig. 2) was initially considered a correlative of the Trinity Peninsula Group, but U-Pb detrital zircon ages indicate deposition of the Miers Bluff Formation post-dated the Middle Jurassic (Hervé et al., 2006b).

The Trinity Peninsula Group has been subdivided into six separate formations across northern Graham Land (Fig. 2), although many successions lack any detailed geological investigations and have not been assigned to stratigraphic units (Smellie et al., 1996). The three primary sedimentary successions (Fig. 2) are the View Point Formation (Carboniferous – Early Permian in age; Bradshaw et al., 2012), the Hope Bay Formation (Triassic turbidite succession; Birkenmajer, 1992) and the Permian – Triassic Cape Legoupil Formation (Thomson, 1975) from western Graham Land, which is dominated by quartz arenites.

The Carboniferous – Triassic metasedimentary successions of the northern Antarctic Peninsula are considered correlatives, at least in part, to the mainly Permian Duque de York Complex metaturbidites (Sepúlveda et al., 2010). The Duque de York Complex forms part of a series of low-grade metamorphic accretionary complexes of the pre-Andean basement (e.g. Madre de Dios accretionary complex) and crop out extensively along the western margin of Patagonia (Fig. 6). Separate to these accretionary complexes is the Eastern Andes metamorphic complex (Rojo et al., 2021) which was deposited in a passive margin environment and is preserved as polydeformed turbidites metamorphosed to greenschist facies (Ramos, 2008). Its detrital zircon age spectra show Gondwanan affinities (Hervé et al., 2008) with the source areas possibly located in the older rocks of the Atlantic margin of Patagonia (Deseado Massif) or in South Africa and Antarctica (Hervé et al., 2003). It is not known if the Eastern Andes metamorphic complex is in place with respect to the older continental blocks, or if it has been displaced.

There have been several studies examining the detrital zircon age populations of the Trinity Peninsula Group and how they compare to the Duque de York metaturbidites (Barbeau et al., 2010; Fanning et al., 2011; Castillo et al., 2015, 2016). All of these investigations have demonstrated a dominant Permian age of source material (Fig. 4) and likely depositional age, but many sections of the Trinity Peninsula Group also exhibit older age peaks. The older age peaks are overwhelmingly dominated by Ordovician zircon populations (Fig. 4a), but also include a minor Carboniferous detrital zircon population of ~5%, with peaks centred at ~315 Ma and ~350 Ma (e.g. Barbeau et al., 2010). Carboniferous zircon populations in the Duque de York Complex are even more scarce (Castillo et al., 2016) and indicate an absence of any proximal Carboniferous source lithologies.

Riley et al. (2012) suggested that the Devonian – Carboniferous magmatism of the Target Hill metamorphic complex was likely to represent a restricted event in the Antarctic Peninsula, but in contrast, Carboniferous magmatism is widespread in central Chile (e.g. Deckart et al., 2014; Marcos et al., 2020) and also reported from the Deseado Massif (Pankhurst et al., 2003), although a magmatic lull has been identified from the Early Carboniferous (360 – 340 Ma; Renda et al., 2021). A Late Devonian to Late Carboniferous calc-alkaline arc (Western igneous-metamorphic belt) crosscuts Patagonia and has been interpreted by several authors as a paleo-subduction zone that terminated with the collision of southern Patagonia (Antarctic Peninsula-Deseado Massif) during the Late Carboniferous (Pankhurst et al., 2006; Ramos, 2008; Tomezzoli, 2012; Ramos et al., 2020).

Castillo et al. (2016) determined that these potential Carboniferous sources must have been isolated from the northern Antarctic Peninsula and western Patagonia during the fore-arc deposition of the Trinity Peninsula Group and the Duque de York complexes which may be related to terrane translation along the paleo-Pacific margin (e.g. Cawood, 2005; Vaughan and Livermore, 2005).

4.6.1 Tectonic setting

The locus of Late Carboniferous subduction along the West Pangean margin can be determined from a ~1000 km linear belt of calc-alkaline magmatism in the Coastal Batholith region (Fig. 6) of southern Chile (e.g. Deckart et al., 2014). Late Carboniferous (330 – 300 Ma) magmatism also developed in the Deseado Massif (~340 Ma; Pankhurst et al., 2003), as well as isolated evidence from eastern Graham Land in the Antarctic Peninsula (Target Hill). However, the Late Carboniferous onset of deposition in the accretionary complexes of Tierra del Fuego and northern Graham Land show only limited contribution from Carboniferous-age magmatism and indicate the depo-centres were isolated from the Carboniferous magmatic centres, suggesting a complex configuration of crustal blocks and sedimentary basins during the Late Carboniferous (Castillo et al., 2016).

The Carboniferous marks the initiation of Pangea amalgamating with continental margin terranes and the closure of minor oceanic basins, which led to the onset of deformation along the Gondwanide Fold Belt. Pankhurst et al. (2006, 2014) evaluated whether Patagonia was a far-travelled terrane prior to accretion in the Late Palaeozoic represented by a suture south of the North Patagonian Massif (Fig. 9). They concluded that mid-Carboniferous collision occurred between the Deseado Terrane/Antarctic Peninsula and the North Patagonian Massif, closing a Cambrian rift prior to the collision of Patagonia (Deseado and North Patagonian terranes) with southwest Gondwana (Ramos, 2020). The identification of Early Carboniferous magmatism in the North Patagonian Massif sector of South America, but not in the Deseado terrane may indicate that translation of the Deseado terrane did not occur until the mid-Carboniferous, with collision during the Late Carboniferous and associated development of arc magmatism in southern Patagonia and the northern Antarctic Peninsula. Pankhurst et al. (2006) considered that Cambrian rifting south of the North Patagonian Massif occurred along a pre-existing structural weakness, and thus the deep crustal structure of Patagonia south of the San Jorge basin could differ in age and origin from that to the north beneath the North Patagonian Massif. The flora and fauna developed during the Palaeozoic could also have followed significantly different evolutionary paths, depending on the geographical and climatic separation of the two continental areas. Cúneo (2020) reviewed paleoflora information from Patagonia and suggested that the maximum biogeographic separation between Patagonia and southwest Gondwana probably occurred during the latest Carboniferous and earliest Permian. However a para-autochthonous, as opposed to an exotic origin is also considered, with the Deseado Massif remaining isolated from the continental margin arc until docking with the North Patagonian Massif in the Late Carboniferous (Fig. 9). Rojo-Martel et al. (2021) investigated part of the Eastern Andean Metamorphic Complex from Chilean Patagonia and suggested the development of an active back-arc basin to west of the Deseado Massif, generated in response to the westward drift of the Antarctic Peninsula relative to southwestern Gondwana margin, during late Paleozoic times. The tectonic juxtaposition of metasedimentary rocks and metabasalts occurred probably within an accretionary wedge developed during the back-arc basin closure and docking of Antarctic Peninsula.

Several workers (e.g. Serra-Varela et al., 2020) also suggest opposing subduction during the Early Carboniferous, with calc-alkaline magmatism developing in West Antarctica beneath a west-directed subduction zone.

4.7 Permian (299 – 252 Ma)

Many workers (e.g. Riley et al., 2012; Castillo et al., 2016; Elliot et al., 2016; Nelson and Cottle, 2019) have documented extensive continental margin magmatism along the West Pangean (Antarctica) plate margin during the Permian (Fig. 11, 12). Evidence for an enhanced episode of magmatism is also indicated by significant detrital zircon Permian age peaks in the Late Palaeozoic metasedimentary successions of the northern Antarctic Peninsula (Trinity Peninsula Group, Fig. 4a:

Castillo et al., 2016; Erewhon Beds: Elliot et al., 2016; this study; Fig. 13), the central Transantarctic Mountains (Elliot and Fanning, 2008), as well as western Patagonia (e.g. Duque de York Complex; Sepúlveda et al., 2010; Fig. 4b).

Riley et al. (2012) documented the basement inliers of eastern Graham Land and identified a prominent episode of magmatism and metamorphism during the Permian. At Eden Glacier, Adie Inlet and Bastion Peak in eastern Graham Land (Fig. 1), two distinct magmatic and metamorphic events were identified at ~275 Ma and ~255 Ma. Castillo et al. (2020) also confirmed the Late Permian/Early Triassic magmatic event, recording ages of 252 ± 2 Ma from Bastion Peak, and 252 ± 2 Ma and 246 ± 2 Ma from Adie Inlet (Fig. 1). A similar age pattern has been reported from northwest Palmer Land and southwest Graham Land where Millar et al. (2002) dated orthogneiss basement at ~270 Ma (Horseshoe Island), 259 ± 5 Ma (Mount Charity) and 257 ± 2 Ma (Orion Massif; Fig. 1).

The prominent peaks in magmatism and metamorphism during the mid- to Late Permian are also highlighted by Jordan et al. (2020) who suggested that they may form part of a broader magmatic 'flare-up' event. The most striking evidence for a widespread Permian magmatic event is recorded in the detrital zircon record of sedimentary sequences from large parts of the West Gondwana margin. The metasedimentary Trinity Peninsula Group of northern Graham Land (Fig. 2) had a prolonged depositional history from Carboniferous to Triassic age (Bradshaw et al., 2012) but is considered to have been primarily deposited during the Permian (e.g. Barbeau et al., 2010; Castillo et al., 2016). These studies confirmed a prominent Late Carboniferous – Permian age peak in the broad interval 320 – 240 Ma, with Castillo et al. (2016) identifying two separate age peaks of ~266 Ma and ~281 Ma, which represent ~75% of the detrital zircon age population (Fig. 4a). The age of deposition has been constrained from the youngest analysed concordant zircon grains dated from the Trinity Peninsula Group. Castillo et al. (2016) suggested a Late Permian/Early Triassic depositional age of 250 ± 3 Ma based on a group of >3 grains which overlap in age at the 1σ level. Other Trinity Peninsula Group samples from the northern Antarctic Peninsula yielded youngest ages of Late Permian, which are inferred as depositional ages of ~264 Ma and ~260 Ma.

The provenance of the Trinity Peninsula Group was investigated by Castillo et al. (2016) using their zircon age and Hf-O isotope characteristics across several sedimentary successions from the northern Antarctic Peninsula. The broad characteristics of the detrital zircon population are, i) a high abundance of Permian zircon grains, but with different isotope characteristics, ii) a significant Ordovician age peak in the Trinity Peninsula Group sequences, particularly from northern Graham Land, iii) a paucity of Proterozoic, Cambrian, Silurian, Devonian and Carboniferous zircon grains. The scarcity of Proterozoic and Early Palaeozoic (except Ordovician) detrital zircon grains was inferred by Castillo et al. (2016) to indicate the isolation of these magmatic belts from the Permian depositional basins. Whereas an Ordovician age peak is interpreted (section 3.4) to be sourced from the Foreland Domain of the Famatinian magmatic belt or its unexposed equivalents.

The principal detrital zircon component in the Trinity Peninsula Group succession is Permian (290 – 260 Ma; Fig. 4a), with Hf-O isotope values indicating a mantle source and a variable supracrustal component (Castillo et al., 2016) that became more pronounced into the Late Permian. Widespread Permian magmatism is attributed to an extensive continental margin arc in West Gondwana (Nelson and Cottle, 2019), extending from Patagonia into the Antarctic Peninsula and Marie Byrd Land of West Antarctica (Fig. 12). However, accurate correlations between Permian volcanic deposits, magmatic centres and emplacement mechanisms are lacking across large parts of the West Pangean/Gondwana proto-Pacific margin, particularly the Antarctic Peninsula. Castillo et al. (2017) dated magmatism at ~255 Ma from Tierra del Fuego, which represents the southerly extent of Late Permian magmatism in South America (Gianni and Navarrete, 2021) and records a significant crustal component relative to magmatism further north. This episode of magmatism from Tierra del Fuego overlaps with the granitoid gneisses dated from eastern Graham Land and northwest Palmer Land (Millar et al., 2002; Riley et al., 2012; Castillo et al., 2020), and Castillo et al. (2017) suggested a close link between southern Patagonia and the Antarctic Peninsula during the Late Permian (Fig. 11).

Elsewhere in Patagonia, Permian arc volcanism is recorded in the extensive Choiyoi Province (Figs. 6, 11, 12), which has an estimated volume >1.5 million km^3 and a peak in magmatism at ~265

Ma. The outcrop extent of the Choiyoi Province is largely preserved in the subvolcanic record of the North Patagonian Massif and Coastal Batholith of central Patagonia (Sato et al., 2015; Luppo et al., 2018; Bastías-Mercado et al., 2020) and indirect evidence of the volcanic record is preserved in the volcaniclastic accretionary complexes of southern Patagonia (e.g. Duque de York Complex).

Nelson and Cottle (2019) investigated the broader extent of the Choiyoi Province into West Antarctica and the central Transantarctic Mountains by examining the detrital zircon U-Pb and Hf isotope data from Permian volcaniclastic sedimentary rocks from the Ellsworth Mountains, Pensacola Mountains and central Transantarctic Mountains (Fig. 12). They identified a major episode of explosive arc volcanism at ~268 Ma, coincident with the Choiyoi Province. Their findings illustrated the significant extent of magmatism associated with the Choiyoi Province and the wider Permian arc, and may also include Permian volcanism in the Karoo Basin of South Africa (Fig. 12), although along strike variations in isotopic geochemistry are likely.

Away from the main outcrop extent of the Trinity Peninsula Group in northern Graham Land, there are also exposures of Permian sedimentary rocks in the southern Antarctic Peninsula (Palmer Land). Associated with the Devonian FitzGerald Bluffs quartzite beds (section 2.6), Permian sandstones have been reported from Erewhon Nunatak (Fig. 1), which Elliot (2013) suggested were part of a microcontinental block with a geological history closely related to that of the Haag-Ellsworth-Whitmore Mountains block. The Erewhon Beds (Fig. 2) are fine-grained sandstones with a detrital zircon age population akin to the Permian sandstone units of the central Transantarctic Mountains (Elliot et al., 2016). Additional detrital zircon data from the Erewhon Beds is presented here with a sandstone (R.8006.1; Table S3) from Erewhon Nunatak. The Erewhon Beds lack zircon grains with clear volcanic characteristics and have a broad spectrum of ages (Fig. 13a), indicating input from a range of sources, but with a primary peak at ~265 ± 3 Ma. Elliot et al. (2016) interpreted their depositional history was closer to that of the Transantarctic Mountains than the adjacent continental margin Permian arc. A Late Permian depositional age for the Erewhon Beds is also supported by the identification of *Glossopteris* leaves from the quartz-rich sandstones (Gee, 1989).

Approximately 25 km to the south of Erewhon Nunatak is Mount Peterson (Figs. 1, 2) where a ~30 m succession of laminated and cross-laminated sandstone and coarser massive conglomerate beds of uncertain age is conformably overlain by dacitic volcanic tuffs, which have been dated at 181.9 + 2.4 Ma (BAS unpublished data) and overlap in age with the likely correlative Mount Poster Formation, dated at ~183 Ma (Pankhurst et al., 2000; Hunter et al., 2006). New detrital zircon is presented here from Mount Peterson (Tables S4, S5) to determine if the succession shares a depositional history with the sandstones of Erewhon Nunatak (Elliot et al., 2016).

Three samples from the Mount Peterson beds (R.8009.4, R.8009.6, R.8010.1) yielded a prominent detrital zircon age peak at 265 ± 3 Ma (Fig. 13b), identical to the primary age population (265 ± 3 Ma; Fig. 13a) determined from Erewhon Nunatak (Elliot et al., 2016; this study). The age is also consistent with the main volcanic peak of the Choiyoi Province (~265 Ma, Rocha-Campos et al., 2011) and one of the two Permian age peaks identified from the Trinity Peninsula Group (~280 Ma and ~265 Ma: Barbeau et al., 2010; Castillo et al., 2016; Nelson and Cottle, 2019; Fig. 4a).

The principal detrital zircon age population (265 ± 3 Ma) from the Mount Peterson sandstones may also represent the likely depositional age; a Late Permian depositional age would indicate the sandstone succession is a probable continuation of the Late Permian, *Glossopteris*-bearing sandstones at Erewhon Nunatak. Other much less abundant age peaks identified from the Mount Peterson beds occur at 475 ± 4 Ma and ~620 Ma (Fig. 13b), which are also characteristics of detrital zircon age populations from the Trinity Peninsula Group and Duque de York Complex (Castillo et al., 2016). The Late Permian zircon population from Mount Peterson yield εHf values in the range -9.3 to +3.4, but with a significant concentration a at -2.6 ± 1.3 (BAS unpublished data). These values overlap with the mean values reported from the Permian accretionary complexes of the northern Antarctic Peninsula and west Patagonia investigated by Fanning et al. (2011) and Castillo et al. (2016). They reported similar ranges in εHf (-15 to +4), but with a concentration in the range -5 to -1, which in turn overlaps with reported εHf values of the Choiyoi volcanic provinces (Castillo et al., 2016; Falco et al., 2022).

Conformably overlying the Mount Peterson sandstone beds are a succession of clast-supported, poorly sorted conglomerates with a well-rounded, long-axis oriented polymict clast assemblage. The most abundant clasts are grey and green sandstone, amygdaloidal basalt, gabbro, felsic volcanic lithologies and quartzite. Clasts are typically 5-10 cm in diameter, but boulders reaching 80 cm are present, suggesting proximal sources. Cross bedding and clast imbrication suggest sediment transport from north to south. Two sandstone clasts from the Mount Peterson conglomerate beds are examined here for their detrital zircon age profiles (Fig. 13c; Table S5). They have a similar petrology to the underlying sandstones but have a subtly different provenance; the green clast (R.8009.3) shows a dominant, but younger Permo-Triassic population at 250 ± 5 Ma (Fig. 13c), and the grey clast (R.8008.2) exhibits a greater proportion of pre-Permian grains, but with a primary population at 265 ± 4 Ma, indistinguishable from the underlying Mount Peterson sandstones beds.

Elliot et al. (2016) considered that the Erewhon Nunatak-FitzGerald Bluffs (Fig. 2) region represents an allochthonous crustal block from the Permian West Gondwana margin and was likely to have been located adjacent to the Thurston Island crustal block (Fig. 12) and translated during plate reorganisation in the Early Jurassic. However, although the Devonian FitzGerald Bluff beds are consistent with a sediment source more closely related to the Ellsworth-Whitmore Mountains, the Permian sedimentary successions share a greater affinity to the accretionary complexes of Patagonia and the Antarctic Peninsula. The absence of any Permian magmatism or sedimentary units in Thurston Island (Riley et al., 2017) also suggests an adjacent paleo-location for the FitzGerald Bluff-Erewhon Nunatak microcontinental block may not be appropriate.

Although primary evidence for Permian volcanic rocks in the Antarctic Peninsula is lacking, the major accretionary complexes of northern Graham Land and southern Patagonia indicate a major volcaniclastic source deposited into developing fore-arc basins. Primary volcanic successions crop out in central Patagonia (e.g. Gianni and Navarrete, 2022; Falco et al., 2022) and subvolcanic equivalents are preserved across large parts of Patagonia, into Tierra del Fuego and sectors of the Antarctic Peninsula (eastern Graham Land and western Palmer Land; Fig. 11).

A broader extent of Permian volcaniclastic lithologies have been identified from back-arc basin settings in the Paraná, Karoo, Transantarctic Mountains and Sydney-Bowen (Australia) indicating the considerable extent of the Permian arc from South America to West Antarctica and Zealandia (Fig. 12; Nelson and Cottle, 2019). Detrital zircon ages and Lu-Hf isotopic data have been used by Elliot et al. (2016, 2017) to suggest that the distal volcaniclastic successions from the Paraná, Karoo and Transantarctic basins are derived from the extensive Permian magmatic arc. Elliot et al. (2017) concluded that volcaniclastic material from the Permian arc did not become the primary source for the Victoria Group sediments of the central Transantarctic Mountains until the Late Permian (c. 250 Ma) when Permian arc magmatism was most intense. Prior to the Late Permian, a significant topographic barrier separated the Victoria Group basin from the Gondwana margin. Subsequent arc uplift permitted volcaniclastic material to be transported further from the arc front.

4.7.1 Tectonic setting

Multiple investigations from the Antarctic Peninsula and Patagonia indicate the prominence of Permian magmatism defined by flare-up events at ~280, ~265 and ~250 Ma, recorded in the plutonic record, the Choiyoi volcanic province and the detrital zircon record of accretionary complexes (e.g. Trinity Peninsula Group, Duque de York Complex) and back-arc successions in the Transantarctic Mountains.

Nelson and Cottle (2019) examined the Hf isotope record of Permian magmatism along large sections of the proto-Pacific margin of Gondwana and identified a distinction between the lithospheric-crustal chemistry from South America and the Antarctic Peninsula, in comparison to elsewhere in West Antarctica, Zealandia and Australia characterised by more mantle-like compositions. The tectonic regimes along the margin may reflect this geochemical difference, with compression (slab advance) in Patagonia-Antarctic Peninsula and extension (slab retreat) elsewhere in West Antarctica-Zealandia-Australia. Alternatively, the geochemical and tectonic differences could be associated with slab angle (Castillo et al. 2020) and also there is local geological evidence that no consistent tectonic regime was applicable (e.g. extension in La Golondrina basin, Patagonia; Giacosa et al., 2012). A comprehensive analysis of Permian Choiyoi magmatism (Gianni and Navarrete, 2022) integrated plate-kinematic reconstructions and the lower mantle slab record beneath southwestern Pangea to understand Late Paleozoic – Mesozoic subducting slab dynamics. They demonstrated that the Choiyoi magmatic event was the result of large-scale slab loss, recoded by a 2800 – 3000 km slab gap. This study lends support to previous analysis arguing for interrupted subduction from northern Patagonia to northern Chile (e.g. Pankhurst et al., 2006; Fanning et al., 2011; García-Sansegundo et al., 2014).

Any consideration of the tectonic setting of West Gondwana during the Permian requires understanding of the development of the Carboniferous/Permian Gondwanide Fold Belt extending from the Sierra de la Ventana through to East Antarctica (Fig. 12). Permian deformation occurred ~1500 km inboard of the proto-Pacific continental margin and has been attributed to flat-slab subduction (e.g. Dalziel et al., 2000) or collision of an exotic terrane (e.g. Pankhurst et al., 2006). The tectonic model proposed by Pankhurst et al. (2006) involves the mid-Carboniferous – Early Permian collision of the Deseado Massif/Antarctic Peninsula terrane with the North Patagonian Massif, which was the consequence of ocean closure by subduction towards the northeast, beneath an autochthonous Gondwana that includes the North Patagonian Massif (Fig. 11). Pankhurst et al. (2006) addressed the issue that the Deseado Massif may not be a large enough colliding block to be the primary cause of deformation across the Gondwanide Fold Belt, and indicated its subsurface extent is significant, including an offshore extension. Following collision and initial compressive deformation along the Gondwanide Fold Belt, Early Permian slab break off resulted in significant granitoid magmatism and post-tectonic ignimbrite complexes. An interrupted, slab loss model (Gianni and Navarrete, 2022) may have been triggered by continental terrane collisions during the assembly of Patagonia (e.g. Pankhurst et al., 2006) and the accretion of buoyant oceanic highs, which would have lead to the large-scale destruction of the subducting slabs. Slab break-off processes would have developed along the margin between 285 – 250 Ma. Gianni and Navarrete

(2022) considered that the reduction in plate margin tectonic stresses caused by the widespread slab loss event combined with the upper mantle warming produced by supercontinent thermal insulation, and the first-order global tensional stresses associated with the incipient breakup of Pangea may have jointly promoted extension, orogenic collapse, and protracted magmatism. The extent of the slab-loss event into West Antarctica is uncertain, but the extent of Permian detrital material in the Antarctic Peninsula and Transantarctic Mountains certainly supports an extension of Permian magmatism along the margin.

A para-autochthonous model is preferred here (Fig. 11), in broad agreement with the recent model presented by Falco et al. (2022) based on Lu-Hf isotope geochemistry, for the development of the Permian continental margin, with deformation and magmatism associated with slab dynamics and slab loss. Crustal block translation (e.g. Deseado Massif) may have been the trigger for slab dynamic changes and lead to the Choiyoi silicic LIP. Sediment deposition would have been largely sourced from the Choiyoi volcanic successions of the North Patagonian Massif (Fig. 11) and their likely unexposed equivalents in the Antarctic Peninsula.

4.8 Triassic (252 – 201 Ma)

Several authors (Vaughan et al., 1999; Millar et al., 2002; Flowerdew et al., 2006; Riley et al., 2012, 2020c; Bastias et al., 2020; Castillo et al., 2020) have investigated the age and extent of Triassic magmatism and metamorphism in the Antarctic Peninsula. The greatest concentration of Triassic age crystalline rocks in the Antarctic Peninsula crop out in northwest Palmer Land (Fig. 2) and have been dated in the interval 237 – 202 Ma (e.g. Bastias et al., 2020; Castillo et al., 2020; Riley et al., 2020c). Millar et al. (2002) investigated the chronology of gneiss complexes from several sites in northwest Palmer Land; a leucosome from a banded migmatite orthogneiss at Mount Eissinger (Fig. 1) yielded a Triassic age of 228 ± 3 Ma, dating the age of migmatisation. A melanosome from a grey gneiss, also from Mount Eissinger gave ages with maxima at ~227 Ma and ~202 Ma, which were interpreted to record separate magmatic/metamorphic events (Millar et al., 2002). Castillo et al. (2020) re-examined the orthogneiss from Mount Eissinger and established a metamorphic rim age of 222 ± 2 Ma with inherited cores of ~250 Ma and also ~450 Ma. Mid-Triassic ages have also been reported (Millar et al., 2002) from Campbell Ridges (227 ± 1 Ma), Fomalhaut Nunatak (~233 Ma), Sirius Cliffs (234 – 232 Ma; Fig. 14) and Pegasus Mountains (228 ± 6 Ma). Riley et al. (2020c) dated an isolated metamorphic complex from the Gutenko Mountains region (Fig. 1) and identified a granitoid protolith emplaced in the interval 227 – 224 Ma, with two phases of metamorphism recorded at ~221 Ma and ~210 Ma.

Bastias et al. (2020) examined orthogneiss lithologies from northern Palmer Land, which they termed the Rymill Granite Complex (Fig. 2) and identified Late Triassic magmatism and metamorphism in the interval 217 – 203 Ma, recording marginally younger ages than Millar et al. (2002), but akin to the granodiorite age (206 ± 3 Ma) from Auriga Nunataks (Fig. 1; Vaughan et al., 1999). Riley et al. (2020c) also investigated metamorphic rocks from across northern Palmer Land to understand their deformation and metamorphic history. They constrained two distinct episodes of metamorphism during the Late Triassic at ~221 Ma and ~207 Ma, which they interpreted as dating the multiphase Peninsula Orogeny (Fig. 11). Riley et al. (2020c) correlated the timing of the Peninsula Orogeny with the well documented Chonide Event of central Patagonia (Suárez et al., 2019), which is related to a period of extension/transtension (mid-Triassic) and a potential compressional regime in the Late Triassic.

Elsewhere in the Antarctic Peninsula, Triassic magmatism and metamorphism is also recognised from eastern Graham Land (Flowerdew, 2008; Riley et al., 2012; Bastias et al., 2019; Castillo et al., 2020). Flowerdew (2008) defined the metamorphic rocks of the Joerg Peninsula and Stubbs Pass area (Fig. 1) as the Bowman Metamorphic Complex (Fig. 2). The oldest rocks of this region are metasedimentary units (paragneiss, schist, marble), which may correlate with the Trinity Peninsula Group succession and are intruded by extensive granite to gabbro sheets. The entire assembly has been deformed, metamorphosed and migmatised under at least amphibolite facies conditions and then cut by a later suite of weakly deformed granitoids. Riley et al. (2012) dated the episode of granite to gabbro sheets at 236 ± 2 Ma and the age of deformation and metamorphism at 224 ± 4 Ma; ages which correspond to the magmatic/metamorphic events of northwest Palmer Land.

Bastias et al. (2020) also examined the Bowman Metamorphic Complex (Fig. 2) of south eastern Graham Land and recorded ages in the range 223 – 215 Ma from orthogneiss of the Joerg Peninsula region (Fig. 1), consistent with the ages presented by Riley et al. (2012). Bastias et al. (2020) considered a distinct shift in Triassic magmatism from east (223 – 215 Ma) to west (217 – 203 Ma) across the Antarctic Peninsula, although the broader age determinations of Millar et al. (2002) do not support this temporal shift.

The metasedimentary Trinity Peninsula Group succession (Fig. 2) of the northern Antarctic Peninsula was primarily deposited during the Permian, but deposition continued into the Late Triassic/Early Jurassic (Bradshaw et al., 2012). The View Point Formation is the only succession of the Trinity Peninsula Group where deposition did not extend into the Triassic, but all other sequences exhibit detrital zircon or fossil evidence for Triassic deposition (Thomson, 1975; Hervé et al., 2005; Barbeau et al., 2010; Castillo et al., 2016). Both Barbeau et al. (2010) and Castillo et al. (2016) interpreted the youngest age of deposition as Early Triassic (~240 Ma), with O and Hf isotope evidence indicating no discernible difference between the prominent Permian arc source and that of the Early Triassic. A similar depositional history is also suggested for the Duque de York Complex of southern Patagonia (Castillo et al., 2016). Across the Antarctic Peninsula and Patagonia there is a clearly defined hiatus in magmatism during the Early Triassic (~250 – 230 Ma) with only rare examples of intrusive rocks and detrital zircons of this age.

Mid- to Late Triassic calc-alkaline magmatism, deformation and metamorphism forms part of a broad zone of activity that extends from the North Patagonian Massif to the Deseado Massif and Magallanes Basin in Patagonia (Fig. 6), and from southeast Graham Land to northwest Palmer Land in the Antarctic Peninsula (Fig. 11). Navarrete et al. (2019) referred to mid- to Late Triassic magmatism and deformation as the South Gondwanian flat-slab event (Fig. 11) that was responsible for the inland migration of the arc front. This episode of mid- to Late Triassic magmatism was accompanied and followed by an episode of Late Triassic deformation and metamorphism, the Peninsula Orogeny-Chonide Event (Fig. 11; Riley et al., 2020c), which may also correlate to the Tabarin Orogeny identified in southern Patagonia and the northern Antarctic Peninsula (Heredia et al., 2018).

Distinct to other Triassic units in the Antarctic Peninsula and Patagonia is the Le May Group succession of Alexander Island (Fig. 2). The Le May Group is a thick (several km), variably deformed succession of trench-fill turbidites and trench-slope sequences interbedded with ocean floor and ocean island igneous and sedimentary rocks and has been correlated to the Miers Bluff Formation of Livingston Island (Fig. 2; Hervé et al., 2006b). The Le May Group has been interpreted as an accretionary complex that developed in a continental margin setting along the proto-Pacific margin (Fig. 11), or alternatively as part of an allochthonous terrane (Vaughan et al., 2002). The age of the Le May Group is poorly constrained; radiolaria suggests a Late Jurassic – Cretaceous age and a general younging direction to the west, consistent with an accretionary complex setting. However, there is stratigraphic evidence that parts of the Le May Group are older. In northern Alexander Island near Mount King (Fig. 1), Carboniferous and Permian macrofauna are described (Kelly et al., 2001) whilst in southern Alexander Island some units may be Triassic in age given their relationship to the Early Jurassic Fossil Bluff Group (Fig. 2; Doubleday et al., 1993).

4.8.1 Tectonic setting

Following a prolonged period of enhanced magmatic activity during the Permian, an episode of magmatic quiescence is evident during the Early Triassic. An absence of granitoid magmatism and an abrupt cessation in deposition of the Trinity Peninsula Group mark a shift in the tectonic framework at the end of the Permian. This shift has been interpreted to be a consequence of the abrupt shallowing of the subducting slab following renewed subduction, more oblique convergence or even the cessation of subduction linked to the accretion of allochthonous terranes (Navarrete et al., 2019). The Late Triassic is considered to represent a transitional phase between Gondwanide and Andean tectonic cycles (Zaffarana et al., 2017).

Magmatic activity resumed in the Antarctic Peninsula at ~230 Ma with granitoid emplacement in northwest Palmer Land and southeast Graham Land, referred to as the Rymill Granite Complex (Bastias et al., 2020) and the Bowman Metamorphic Complex (Flowerdew, 2008). Riley et al. (2020c) determined two distinct tectonic events during the Late Triassic at ~221 Ma and ~207 Ma which constrain the Peninsula Orogeny and correlate with the Chonide Event in Patagonia (Suárez et al., 2019) and may represent the final phases of the Gondwanide Orogeny (Fig. 11). The overwhelming evidence from the Antarctic Peninsula and sectors of Patagonia is that mid- to Late Triassic deformation and metamorphism developed in a compressional regime with an initial phase of transtension, in broad agreement with Zaffarana et al. (2017) who suggested switching between extensional and compressional regimes. Dalziel et al. (2013), Navarrete et al. (2019) and Riley et al. (2020c) all proposed a tectonic setting of flat slab subduction of highly buoyant oceanic crust, potentially linked to interaction with a mantle plume in the Antarctic/Kalahari Craton sector (Dalziel et al., 2000). The South Gondwanian flat slab event is interpreted to have led to the deformation and metamorphism at ~221 Ma and ~207 Ma and inland migration of the arc (Fig. 11), coupled with adakitic magmatism (Navarrete et al., 2019).

The relative positions of the Antarctic Peninsula and Patagonia are critical to understanding the tectonic setting during the Late Triassic; Suárez et al. (2019) adopted a 'tight-fit' model based on the model of Lawver et al. (1998) with the tip of the Antarctic Peninsula adjacent to Golfo de Penas (Fig. 6), consistent with the reconstruction of König and Jokat (2006). Calderon et al. (2016) also suggested the proto-Antarctic Peninsula terrane was accreted to the southwestern margin of Patagonia in the Late Paleozoic with subduction-related magmatism located along the Antarctic Peninsula. Late Paleozoic – Early Mesozoic granitoids along the Antarctic Peninsula are calc-alkaline in composition, and zircon $\delta^{18}O$ and Lu-Hf isotopes supporting the existence of a subduction-related, Late Paleozoic – Early Mesozoic magmatic arc along the Antarctic Peninsula (Bastias et al., 2020). In this Late Paleozoic paleogeographic context, southern Patagonia lies east of the Antarctic Peninsula, in a retroarc position. Suarez et al. (2021) suggested that the Gondwanide Orogeny in southern Patagonia could be related to the accretion of the proto-Antarctic Peninsula terrane, and the Palaeozoic units would be deformed as part of a retrowedge, fold-and-thrust belt.

This agrees with the recent reconstruction of van de Lagemaat et al.(2021) and the model presented here (Fig. 11), constrained by the global plate circuit of South America – Africa – Antarctica. A tectonic setting with the Antarctic Peninsula and Patagonia forming a single continental block have also been proposed (Hervé et al., 2006; Ghidella et al., 2007) with southward migration of the Antarctic Peninsula not initiated until after the Early Jurassic (Fig. 11).

5. Summary

Our review and analysis of the pre-Jurassic geological and tectonic history of the Antarctic Peninsula and Patagonia have allowed us to develop kinematic reconstructions (see supplementary files for full details) from the Cambrian to the Jurassic. We have attempted to correlate geological units from across southern South America with the developing Antarctic Peninsula. Broadly speaking, the continental margin of Gondwana/Pangea was a convergent setting from the Ediacaran, punctuated by crustal block/terrane translation, deformation, magmatic pulses and periods of quiescence, frequently linked to the dynamics of the subducting slab.

Our analysis through the Palaeozoic and Early Mesozoic is the first detailed examination of the Antarctic Peninsula and Patagonia within the same geodynamic framework. For completeness, we also show kinematic reconstructions from the Jurassic – present (Figs. 11, 15). The key geological and tectonic events from the Mesoproterozoic – Triassic are summarised below, along with the key findings from our detailed review and kinematic analysis.

5.1 Mesoproterozoic

The only recognised Mesoproterozoic basement in West Antarctica is identified from Haag Nunataks at the southern end of the Antarctic Peninsula (Fig. 1). Haag Nunataks forms part of a crustal block with a separate geological and tectonic history to that of the Antarctic Peninsula. It developed in the Natal Embayment as part of a sequence of juvenile arc terranes fringing the proto-Kalahari craton.

5.2 Cambrian

There is no recognised bedrock of Cambrian age in the Antarctic Peninsula, but the adjacent Ellsworth Mountains preserve shallow marine/fluvial sedimentary rocks up to 8 km in thickness. The sedimentary sequences are associated with MORB-like basaltic lava successions that were emplaced in a continental rift setting. We favour the interpretation that the basaltic rocks of the Ellsworth Mountains (and related sequences of the Maud and Pensacola mountains) developed in a back-arc setting. A close relationship between the sedimentary successions of the Ellsworth-Pensacola mountains and northern Patagonia is supported by paleontological evidence whereas detrital zircon provenance analysis doesn't favour a close relationship with the North Patagonian Massif. A Natal Embayment origin for the Ellsworth Mountains block is not fully supported by detrital zircon or paleomagnetic evidence.

5.3 Ordovician

The Early Ordovician is interpreted to represent the initial development of the basement of the proto Antarctic Peninsula. Diorite gneiss from eastern Graham Land (Eden Glacier) forms the oldest in situ rocks of the Antarctic Peninsula crustal block (c. 485 Ma) and are interpreted to form a distal segment of the Famatinian magmatic belt, primarily exposed in the North Patagonian Massif.

An Ordovician collisional event, referred to as the compressional Transpatagonian orogen may have developed as a result of the accretion of the North Patagonian Massif with southwest Gondwana, although this may have occurred later in the Palaeozoic. The North Patagonian Massif exhibits a distinct Proterozoic/Early Palaeozoic history relative to the southern Patagonia/Deseado terrane, which sutured in the mid-Palaeozoic.

5.4 Silurian

The Silurian period represents a lull in magmatic activity across the Antarctic Peninsula and Patagonia following the significant pulses of Famatinian arc magmatism during the Ordovician. The hiatus in magmatic activity is reflected in the metasedimentary successions of the northern Antarctic Peninsula and Tierra del Fuego, which demonstrate only minor Silurian input to the Late Palaeozoic sequences. A magmatic arc (Western magmatic belt) is interpreted to have developed during the Late Silurian that extended across the North Patagonian and Deseado massifs and potentially extended into northwest Palmer Land.

5.5 Devonian

Magmatism developed in two contemporaneous belts across northern Patagonia during the Devonian, but is only represented in the Antarctic Peninsula at a single isolated site in eastern Graham Land (Target Hill). In Patagonia, the spatial distribution of magmatism is likely to be related to slab dynamics and the para-autochthonous Chaitenia terrane. Devonian–Carboniferous magmatism is interpreted to be related to segmented tectonic subduction and a switch-off and switch-on geodynamic model (push-pull tectonics), including the transition from flat-slab to roll-back subduction. Some metasedimentary sequences exposed in the northern Antarctic Peninsula are characterised by significant (~10%) Devonian detrital zircon age populations, indicating that for some sedimentary basins, Devonian arc/recycled material was more proximal at the time of deposition.

Merdith et al. (2021) illustrates Patagonia as para-autochthonous, rifting from the Gondwanan margin at 390 Ma, before colliding back into the Gondwanan margin at approximately the same relative location at 310 Ma. Consequently, we show two reconstructions (Fig. 9) for 359 Ma (end Devonian): 1) autochthonous, with Patagonia remaining on the margin in the same relative location with the Antarctic Peninsula (e.g van de Lagemaat et al.,2021); and 2) para-autochthonous, with a rifted Patagonia, located as described by Merdith et al. (2021).

5.6 Carboniferous

Akin to the Silurian – Devonian, the Carboniferous also represents an episode of restricted arc magmatism in the Antarctic Peninsula, whereas Carboniferous magmatism has been identified from the Deseado Massif and central Chile. The metasedimentary successions of northern Graham Land and Tierra del Fuego show only a minor contribution from Carboniferous sources reflecting the paucity of arc magmatism of this period. The identification of Early Carboniferous magmatism in the North Patagonian Massif sector of South America, but not in the Deseado terrane may indicate that translation of the Deseado terrane did not occur until the mid-Carboniferous, with collision during the Late Carboniferous and associated development of arc magmatism in southern Patagonia and the northern Antarctic Peninsula. The mid-Carboniferous marks the initial phase of deformation associated with the Gondwanide Orogeny as a result of terrane translation and collision.

5.7 Permian

Permian continental margin magmatism was the defining event of the Late Palaeozoic, with volcanic, volcaniclastic and intrusive rocks exposed extensively across the proto-Pacific margin of

Gondwana. Permian magmatism is characterised by three distinct pulses (flare-ups) at ~280 Ma, ~265 Ma and ~250 Ma, which are recorded in the magmatic record (Choiyoi Province) and detrital zircon age populations in accretionary complexes of the Antarctic Peninsula and Tierra del Fuego (e.g. Trinity Peninsula Group). An interrupted subduction, slab loss model has been proposed for the development of the Choiyoi Province and may have been triggered by continental terrane collisions during the assembly of Patagonia. Slab break-off processes would have developed along the margin between 285 – 250 Ma and the widespread slab loss event combined with the upper mantle warming produced by supercontinent thermal insulation lead to the development of a silicic large igneous province. A para-autochthonous model is preferred for the development of the Permian continental margin, supported by Lu-Hf isotope geochemistry, with deformation and magmatism associated with slab dynamics, slab loss and minor crustal block translation. Subduction is likely to have resumed by 250 Ma and allowed the development of fore-arc deposition incoroporated into accretionary complexes by 230 Ma.

5.8 Triassic

The abrupt shallowing of the subducting slab at the end of the Permian is linked to the cessation of magmatism in the Early Triassic. Magmatism in the Antarctic Peninsula resumed at ~230 Ma and was accompanied by two phases of deformation that developed at ~221 Ma and ~207 Ma. This has been termed the Peninsula Orogeny and correlates with Chonide Event in Patagonia. The overwhelming evidence from the Antarctic Peninsula and sectors of Patagonia is that mid- to Late Triassic deformation and metamorphism developed in a compressional regime with an initial phase of transtension (e.g. Suarez et al., 2019a, b). Deformation has been linked to the Gondwanian flat slab event that is also responsible for the inland migration of the arc front coupled with adakitic magmatism (Navarrete et al., 2019). Calderon et al. (2016) suggested the Antarctic Peninsula terrane was accreted to the southwestern margin of Patagonia in the Late Paleozoic with subduction-related magmatism located along the Antarctic Peninsula. In this Late Paleozoic paleogeographic context, southern Patagonia lies to the east of the Antarctic Peninsula, in a retroarc position. Suarez et al. (2021) suggested that the Gondwanide Orogeny in southern Patagonia could be related to the accretion of the proto-Antarctic Peninsula terrane, and the Palaeozoic units would be deformed as part of a retro-wedge, fold-and-thrust belt.

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Declaration of 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.

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Figure 1: a) Bedmap of West Antarctica depicting the distinct crustal blocks and rift systems. MBL: Marie Byrd Land; EWM: Ellsworth-Whitmore Mountains; H: Haag Nunataks; location 1 is the Fowler Peninsula. b) Location map of sample sites the Antarctic Peninsula.

Figure 2: Geological map of the Antarctic Peninsula from Burton-Johnson and Riley (2015). The principal crystalline metamorphic basement and metasedimentary units are shown. The putative terrane boundaries of Vaughan and Storey (2000) are also depicted, WD: Western Domain; CD: Central Domain; ED: Eastern Domain.

Figure 3: a) Tectonic setting of the proto-Kalahari craton showing the juvenile arc terranes on the margins of the craton and the collision with Laurentia at ~1000 Ma resulting in the Grenville Belt and Namaqua-Natal-Maud belt (Riley et al., 2020b). HN (Haag Nunataks); FI-MEB (Falkland Islands-Maurice Ewing Bank), CL (Coats Land); Gru. (Grunehogna), TOAST: Tonian oceanic arc superterrane. b) Gondwana reconstruction at approximately 550 Ma (after Jacobs and Thomas, 2004) illustrating the location of the Haag Nunataks-Ellsworth Whitmore Mountains (H-EWM) crustal block relative to the juvenile island arcs of the Namaqua-Natal Belt and Maud Belt. FI: Falkland Islands; M: Madagascar; EAAO: East African Antarctic Orogen;; Da: Damara belt; F: Filchner block; G: Grunehogna; SR: Shackleton Range; TAM: Transantarctic Mountains; Z: Zambesi belt.

Figure 4: Kernel density estimation plots of detrital zircon ages (compiled from Barbeau et al., 2010 and Castillo et al., 2016) from a) Trinity Peninsula Group metasedimentary rocks of the northern Antarctic Peninsula; b) Duque de York Complex of Patagonia; c) Desolación Island adjacent to the Magallanes Fault Zone.

Figure 5: Kinematic GPlates reconstruction of the proto Antarctic Peninsula and Patagonia continental margin in the Cambrian (Castillo et al., 2017). The rift-related basaltic magmatism of the Ellsworth, Queen Maud and Pensacola mountains are depicted. Aus.: Australia; Ant.: Antarctica; Afr.: Africa; S.Am.: South America; PAT: Patagonia; NE: Natal Embayment; EAAO: East African Antarctic Orogen; H-EWM: Haag Nunataks-Ellsworth-Whitmore Mountains; FI/Mv: Falkland/Malvinas crustal block. PAT^2 position is from Gonzalez et al. (2018).

Figure 6. Location map of southern South America illustrating the key crustal blocks, geological terranes and key units. PAT: Patagonia.

Figure 7: Kinematic GPlates reconstruction for the Early Palaeozoic Gondwana margin illustrating the early development of the Antarctic Peninsula.

Figure 8: Diorite gneisses exposed on the Eden Glacier, eastern Graham Land. The vertical height of the section is approximately 60 m.

Figure 9: Kinematic GPlates reconstruction for the Mid Palaeozoic Gondwana margin illustrating the development of the Antarctic Peninsula, Deseado Massif and North Patagonian Massif. Global plate reconstructions of Merdith et al. (2021) shown for reference. An alternative reconstruction is provided for the end=Devonian to better illustrate the Patagonian excursion suggested by Merdith et al. (2021).

Figure 10: Detrital zircon data from the Devonian quartzites at FitzGerald Bluffs (Elliot et al., 2016; R.8002.2 - this study) in comparison to the Crashsite Group quartzites of the Ellsworth Mountains (Castillo et al., 2017).

Figure 11: Kinematic GPlates reconstruction for the Late Palaeozoic – Early Mesozoic Gondwana margin illustrating the accretionary complexes of the Trinity Peninsula Group and Duque de York, and the Triassic extent of the Peninsula Orogeny-Chonide Event.

Figure 12: Reconstruction of the Permian Gondwana continental margin highlighting the volcaniclastic sedimentary successions and magmatic arc front of Nelson and Cottle (2019). The extent of the Gondwanide fold belt is from Eagles and Eisermann (2020). AP: Antarctic Peninsula; CANT: Central Antarctica; TI: Thurston Island; MBL: Marie Byrd Land; EWM: Ellsworth-Whitmore Mountains; NPM: North Patagonian Massif; DM: Deseado Massif; DdYC: Duque de York Complex; TPG: Trinity Peninsula Group

Figure 13: Detrital zircon data from a) the sandstone beds at Erewhon Nunatak (Elliot et al., 2016; R.8006.1 - this study) in comparison to the sandstone beds from b) Mount Peterson (R.8009.4, R.8009.6, R.8010.1 - this study) and c) quartzite clasts (R.8002.2, R.8009.3 - this study) from the Mount Peterson conglomerate beds.

Figure 14: Field images of ortho- and paragneiss units from Sirius Cliffs, northwest Palmer Land. Ice axe is 65 cm in length.

Figure 15: Kinematic GPlates reconstruction for the Late Mesozoic – Cenozoic Gondwana margin illustrating the transition to the present day configuration.

Sample	Locality	Lithology	Latitude	Longitute	Event	Age	2s error	inheritance	Reference
H9.67.1	Adie Inlet	K fls megacrystic granodiorite	66.192500	62.756357	inherited			545	Riley et al. (2012)

H9.41.1	Adie Inlet	bt kfs paragneiss	66.200393	62.804803	youngest detrital grain			514	Riley et al. (2012)
H8.99.1B	West Eden Glacier	diorite gneiss	66.224580	63.234608	magmatism	487	3		Riley et al. (2012)
H8.100.1	East Eden Glacier	diorite gneiss	66.213757	63.191317	magmatism	485	3		Riley et al. (2012)
H8.100.1	East Eden Glacier	diorite gneiss	66.213757	63.191317	metamorphism	280			Riley et al. (2012)
H9.41.3	Adie Inlet	leucosome in bt kfs paragneiss	66.200393	62.804803	anatexis	276	3		Riley et al. (2012)
H9.41.2A	Adie Inlet	xenolithic diorite	66.200393	62.804803	inherited			275	Riley et al. (2012)
H9.504.1	North Eden Glacier	diorite gneiss	66.066582	63.309835	magmatism	272	2		Riley et al. (2012)
H9.67.1	Adie Inlet	K fls megacrystic granodiorite	66.192500	62.75635[illegible]	magmatism	259	3		Riley et al. (2012)
H8.99.1B	West Eden Glacier	diorite gneiss	66.224580	63.234608	metamorphism	258	5		Riley et al. (2012)
H9.42.2A	Adie Inlet	xenolithic diorite	66.200[illegible]7	62.804510	magmatism	257	3		Riley et al. (2012)
R.8187.1	Bastion Peak	granodiorite	66.164550	63.583380	magmatism	256	3		Riley et al. (2012)
H9.538.1	Bastion Peak	leucosome in diorite gneiss	66.098267	63.717633	anatexis	255	5		Riley et al. (2012)
K7.563.3	Stubbs Pass	folded and foliated granite sheet	68.171743	65.231155	inherited			460 - 480	Riley et al. (2012)
K7.526.2	Stubbs Pass	leucosome in mafic orthogneiss	68.200487	65.182303	inherited from host	239	8		Riley et al. (2012)
K7.563.3	Stubbs Pass	folded and foliated granite sheet	68.171743	65.231155	magmatism	236	2		Riley et al. (2012)
K7.526.2	Stubbs Pass	leucosome in mafic orthogneiss	68.200487	65.182303	anatexis	224	4		Riley et al. (2012)

H9.89.1	Cape Caey	banded diorite gneiss	66.338472	63.716558	magmatism	c. 212			Riley et al. (2012)
R.414.1	Cole Peninsula	granodiorite	66.783330	64.004170	magmatism	c. 200			Riley et al. (2012)
M17.37.2	Dyer Plateau	granodiorite gneiss	71.48261	65.09553	magmatism	228	7		Riley et al. (2021)
M17.37.2	Dyer Plateau	granodiorite gneiss	71.48261	65.09553	metamorphism	221	4		Riley et al. (2021)
M17.37.3	Dyer Plateau	Quartzo-feldspathic vein in granodiorite gneiss	71.48261	65.09553	magmatism	227.6	6.2		Riley et al. (2021)
M17.37.3	Dyer Plateau	Quartzo-feldspathic vein in granodiorite gneiss	71.48261	65.09553	metamorphism	209	3		Riley et al. (2021)
K7.557.1	Joerg Peninsula	hornblende orthogneiss	68.10842	65.02416	magmatism	223	2		Bastias et al. (2020)
K7.562	Stubbs Pass	hornblende orthogneiss	68.18704	65.30471	magmatism	217	1		Bastias et al. (2020)
K7.526.3	Stubbs Pass	hornblende orthogneiss	68.20049	65.1823	magmatism	215	2		Bastias et al. (2020)
R.6306.7	NW Palmer Land	hornblende orthogneiss	71.61314	66.34537	magmatism	212	2		Bastias et al. (2020)
R.5786.3	NW Palmer Land	hornblende orthogneiss	70.91583	66.91833	magmatism	203	1		Bastias et al. (2020)
R.5290.1	NW Palmer Land	hornblende orthogneiss	70.53333	66.8	magmatism	217	2		Bastias et al. (2020)
R.6067.8	NW Palmer Land	hornblende orthogneiss	70.69417	66.58389	magmatism	208	3		Bastias et al. (2020)
R.5511.1*B	Target Hill	Granitic orthogneiss	65.99167	63.05	magmatism	399	9	ca. 440	Castillo et al. (2021)

R.4007.7*B	Target Hill	Mafic banded gneiss	66.00833	63.06667	magmatism	327	9	ca. 400	Castillo et al. (2021)
H9.538.1†A	Bastion Peak	Leucosome in diorite gneiss	66.09827	63.71763	metamorphism	255	5		Castillo et al. (2021)
R.8187.1†A	Bastion Peak	Granodiorite	66.16455	63.58338	magmatism	256	3		Castillo et al. (2021)
R.8184.3B	Bastion Peak	Granodiorite	66.16455	63.58338	magmatism	252	2	ca. 260, 1110	Castillo et al. (2021)
H9.67.1A	Adie Inlet	Kfs megacrystic granodiorite	66.1925	62.75636	magmatism	246	2	ca. 270, 290, 580-550, 740, 780	Castillo et al. (2021)
H9.41.3	Adie Inlet	Leucosome in bt kfs paragneiss	66.20039	62.8048	metamorphism	276	3		Castillo et al. (2021)
H9.41.2A	Adie Inlet	Xenolithic diorite	66.20039	62.8048	magmatism	257	3	275 ± 3	Castillo et al. (2021)
H9.41.1	Adie Inlet	Bt kfs paragneiss	66.20039	62.8048	magmatism			514 ± 7 and 1082 ± 13	Castillo et al. (2021)
R.349.2B	Adie Inlet	Migmatite	66.21667	62.78333	magmatism	252	2	410-530, 700-780, 980-1040, 1930	Castillo et al. (2021)
H8.100.1	East Eden Glacier	Diorite gneiss	66.21376	63.19132	magmatism	280	2	485 ± 3	Castillo et al. (2021)
H8.99.1B	West Eden Glacier	Diorite gneiss	66.22458	63.23461	magmatism	258	5	487 ± 3	Castillo et al. (2021)
H9.89.1	Cape Casey	Banded diorite gneiss	66.33847	63.71656	magmatism	212	1		Castillo et al. (2021)
R.414.1	Cole Peninsula	Granodiorite	66.78333	64.00417	magmatism	200	1		Castillo et al. (2021)
K7.563.3	Stubbs Pass	Folded and foliated granite sheet	68.17174	65.23116	magmatism	236	2	425 ± 8 and 1061 ± 20	Castillo et al. (2021)
K7.563.1	Stubbs Pass	Cpx hbl paragneiss	68.17174	65.23116	magmatism			622 ± 12 and 1089 ± 17	Castillo et al. (2021)
K7.526.2	Stubbs Pass	Leucosome in mafic orthogneiss	68.20049	65.1823	metamorphism	224	4		Castillo et al. (2021)

R.5257.1B	Mount Eissenger	Migmatitic orthogneiss	70.0333	67.65	metamorphism	202		222 ± 2; ca. 250 and 440	Castillo et al. (2021)
R.5278.8	Campbell Ridges	Orthogneiss	70.3666	67.3833	magmatism	227	1	ca. 460, 530 and 1000	Castillo et al. (2021)
R.2730C	Campbell Ridges	Orthogneiss	70.36667	67.5333	magmatism			ca. 505	Castillo et al. (2021)
R.1907.3	Mount Charity	Pogphyritic granite	69.94166	64.42166	magmatism	259	5	ca. 470	Castillo et al. (2021)
R.3336.4G	Orion Massif	Grey gneiss	70.41667	66.6833	magmatism			258 ± 2	Castillo et al. (2021)
R.3336.4P	Orion Massif	Leucosome	70.4158	66.6886	metamorphism	206			Castillo et al. (2021)
R.751.52	View Point	Granitoid cobble			magmatism	463	5		Millar et al. (2002)
R.5257.1	Mount Eissenger	Orthogneiss	70.0333	67.65	magmatism	422	18		Millar et al. (2002)
R.5257.1	Mount Eissenger	Orthogneiss	70.0333	67.65	magmatism	435	8		Millar et al. (2002)
R.5511.1	Target Hill	Orthogneiss	65.99167	63.05	magmatism	393	1		Millar et al. (2002)
R.5511.1	Target Hill	Orthogneiss	65.99167	63.05	magmatism	397	8		Millar et al. (2002)
R.5511.1	Target Hill	Orthogneiss	65.99167	63.05	magmatism	327	9		Millar et al. (2002)
R.5511.1	Target Hill	Orthogneiss	65.99167	63.05	metamorphism	311	8		Millar et al. (2002)
R.349.2	Adie Inlet	Paragneiss	66.20039	62.8048	migmatisation	258	3		Millar et al. (2002)
R.1907.3	Mount Charity	Pogphyritic granite	69.94166	64.42166	magmatism	267	3		Millar et al. (2002)
R.1907.3	Mount Charity	Pogphyritic granite	69.94166	64.42166	magmatism	259	5		Millar et al. (2002)
R.3336.4	Orion Massif	Granitoid	70.41667	66.6833	magmatism	258	2		Millar et al. (2002)

R.5257.1	Mount Eissenger	Orthogneiss	70.0333	67.65	metamorphism	228	3	Millar et al. (2002)
R.5257.1	Mount Eissenger	Orthogneiss	70.0333	67.65	metamorphism	227		Millar et al. (2002)
R.5278.8	Campbell Ridges	Orthogneiss	70.3666	67.3833	magmatism	227	1	Millar et al. (2002)
R.5294.1	Sirius Cliffs	Granitic orthogneiss	70.55	66.8833	magmatism	233		Millar et al. (2002)
R.2535.6	Formalhaut Nunataks	migmatitic gneiss	70.9625	66.6667	metamorphism	233		Millar et al. (2002)
R.5294.1	Sirius Cliffs	Granitic orthogneiss	70.55	66.8833	magmatism	233		Millar et al. (2002)
R.5391.4	Pegasus Mountains	Orthogneiss	70.92194	67.01639	magmatism	228	6	Millar et al. (2002)

Highlights

- Analysis of the pre-Jurassic geological history of the Antarctic Peninsula and Patagonia within the same geodynamic framework.
- Developed kinematic reconstructions for time slices from the Cambrian to the Jurassic.
- Correlated geological units from across southern South America with the developing Antarctic Peninsula.
- Margin of Gondwana/Pangea was a convergent setting from the Ediacaran, punctuated by crustal block/terrane translation, deformation, magmatic pulses and periods of quiescence.
- A broadly autochthonous margin is indicated frequently linked to the dynamics of the subducting slab.