Abstract: The allochthonous terrane accretion model previously proposed for the geological development of the Antarctic Peninsula continental margin arc is reviewed in light of recent data and the geology is reinterpreted as having evolved as an in situ continental arc. This is based upon the following factors: (1) the presence of Early Palaeozoic basement and stratigraphic correlation of sequences between the autochthonous and previously proposed allochthonous terranes; (2) isotopic evidence for similar deep crustal structure across the different terranes; (3) ocean island basalt magmas and deep marine sedimentary rocks formed during continental margin extension within the previously proposed accretionary wedge sequence (i.e. not formed against an active oceanic arc); (4) the distribution of magnetic susceptibility measurements and aeromagnetic data locating the palaeo-subduction zone along the west of the Peninsula; (5) a lack of clear palaeomagnetic distinction between the terranes. The following alternative tectonic history is proposed: (1) amalgamation and persistence of Gondwana; (2) subsequent silicic large igneous province magmatism and extension; (3) development and history of Andean subduction until its cessation in the Cenozoic. A number of features in the Antarctic Peninsula correlate with those of other circum-Pacific margins, supporting a global evaluation of allochthonous v. autochthonous margin development to aid our understanding of crustal growth mechanisms.

Convergent continental margins are geologically complex, with the composite units interpreted as developing either in situ from autochthonous units (e.g. South China; Zhou et al. 2006) or through accretion of allochthonous terranes (e.g. New Zealand; Wandres & Bradhaw 2005). Continental margins represent the dominant sites of Phanerozoic continental crustal growth, therefore an understanding of whether or not this growth occurs dominantly in situ (e.g. Kemp et al. 2009) or through arc and terrane accretion (e.g. Reymer & Schubert 1984; Draut & Clift 2001) is integral to models of crustal development.

The Antarctic Peninsula was initially interpreted as an autochthonous continental arc of the Gondwanan margin, which developed during Mesozoic subduction beneath the supercontinent (Suárez 1976). However, following the identification of a major shear zone in the southern Antarctic Peninsula (the Eastern Palmer Land Shear Zone; Fig. 1) the composite geology of the Peninsula was reinterpreted as representing a series of allochthonous accreted terranes (Vaughan & Storey 2000). In this paper we evaluate the currently available dataset for the tectonic history of the Peninsula and propose a refined model for the in situ development of a geologically complex continental margin and correlate this tectonic history with major continental arcs elsewhere.

Principal geological units of the Antarctic Peninsula

Independent of the overall tectonic model, the geology of the Antarctic Peninsula can be divided into six broad units (Figs 1 and 2): the metamorphic basement; Palaeozoic to Triassic sedimentary rocks; Jurassic to Cenozoic sedimentary rocks; non-metamorphosed intrusive rocks; Jurassic to Palaeogene volcanic rocks; Neoogene to Recent alkaline volcanic rocks.

Metamorphic basement

Dominantly composed of orthogneisses and metabasites (Wendt et al. 2008), the metamorphic basement crops out in NW and NE Palmer Land and southern Graham Land, with sparser outcrops in eastern Graham Land. The metamorphic basement is most extensive in Palmer Land, with orthogneisses, paragneisses, amphibolites and metasediments recording amphibolite-to-granulite-facies metamorphism in NW Palmer Land, and lower grade amphibolite-facies metamorphism in NE Palmer Land (Wendt et al. 2008). Ordovician, Permian and Triassic metamorphism of Ordovician and younger protoliths produced amphibolite-grade orthogneisses, metabasites (amphibolites), migmatites and paragneisses in southern and eastern Graham Land (Wendt et al. 2008; Riley et al. 2012b). One small, irregular locality (the c. 10km long Target Hill) in eastern Graham Land records Carboniferous metamorphism of a Devonian igneous protolith with no evidence for later metamorphism (Millar et al. 2002; Riley et al. 2012b), despite being <15km from similar outcrops that do provide such evidence. This may be related to the Carboniferous metamorphism of the Deseado Massif in Patagonia (Pankhurst et al. 2006) and is often viewed as the ‘classic’ locality for the Peninsula’s basement (Milne & Millar 1989), although it is clearly anomalous and misrepresentative.

Although the metamorphic basement was originally assigned to the early Palaeozoic or Archaean (Adie 1954) and later to the early to mid-Palaeozoic (Singleton 1980), it is now clear that its mapped extent (Fig. 1) includes rocks of Ordovician to Jurassic outcrops (Weyer et al. 1994; Riley et al. 2012b) and consequently magmatic ages for the metamorphic basement overlap with those of non-metamophosed intrusive rocks (see below and Fig. 2).

Palaeozoic–Triassic sedimentary rocks

The oldest sedimentary sequence on the Antarctic Peninsula recording continental extension are limited outcrops of quartzite
Fig. 1. Geological map of the Antarctic Peninsula, showing the distribution of the principal geological units defined in the text (Fleming & Thomson 1979; Thomson & Harris 1979; Thomson 1981; Thomson et al. 1982; Storey et al. 1986; Rowley et al. 1992; Moyes et al. 1993; Riley et al. 2011a, b). EPLSZ, East Palmer Land Shear Zone; WD, Western Domain; CD, Central Domain; ED, Eastern Domain. Domain and Eastern Palmer Land Shear Zone distribution adapted from Vaughan & Storey (2000) and Vaughan et al. (2012a). Extents of the Larsen Basin and Lassiter Coast Intrusive Suite from Vennum & Rowley (1986), Hathway (2000) and Flowerdew et al. (2005).
sedimentary rocks of the Erehwon Beds also crop out only in a restricted area of SW Palmer Land, but were deposited in a Permian back-arc basin (Laudon 1991).

Latest Carboniferous to mid-Triassic sedimentary and low-grade metasedimentary rocks of the Trinity Peninsula Group are exposed extensively across northern Graham Land (Smellie & Millar 1995; Riley et al. 2011b; Bradshaw et al. 2012). They comprise mudstones and sandstones of turbiditic origin with a continental arc provenance (Smellie 1991), although the geographical origin of this source remains unclear. Similar lithologies occur on the South Shetland Islands (the Triassic or Jurassic Miers Bluff Formation and the Mesozoic to Cenozoic Scotia Metamorphic Complex metasediments; Willan et al. 1994; Trouw et al. 1997; Hervé et al. 2006; Barbeau et al. 2010) although proposed depositional ages for these units range from Triassic to Paleocene (Willan et al. 1994; Trouw et al. 1997; Hervé et al. 2006; Pimpirev et al. 2006).

Jurassic–Cenozoic sedimentary rocks

Lower Jurassic to Lower Cretaceous turbidite sandstones and conglomerates with minor volcanic rocks, chert and siliceous mudstones form the LeMay Group, the lowest stratigraphic strata on Alexander Island (Fig. 1; Thomson & Tranter 1986; Holdsworth & Nell 1992). This sequence is interpreted as representing an accretory trench-fill assemblage (Suárez 1976; Doubleday et al. 1993). East of the LeMay Group on Alexander Island, mainly separated by the LeMay Fault (Fig. 1), arc-derived fluvial, deltaic and submarine fan deposits forearc basin sediments form the Upper Jurassic to Lower Cretaceous Fossil Bluff Group (Storey & Garrett 1985; Butterworth et al. 1988). Although the Fossil Bluff Group unconformably overlies the LeMay Group, the two units are dominantly in faulted contact along the LeMay Fault and overlap temporally (Doubleday et al. 1993). Minor Late Jurassic ocean island basalt (OIB)-like sills and submarine lava flows are also found within the LeMay and Fossil Bluff groups (Doubleday et al. 1994; Macdonald et al. 1999).

Interbedded Jurassic volcanic and sedimentary back-arc basin sediments occur in eastern Palmer Land (the Mount Hill Formation; Meneilly et al. 1987) and southern Palmer Land (the Latady Group; Hunter & Cantrill 2006). These two formations are considered to be correlatives (Vaughan & Storey 2000) and record deposition in the Latady Basin during rifting of Gondwana. A thick sequence of Late Jurassic to Cenozoic sediments forms the Larsen Basin (exposed on James Ross Island, surrounding islands and northeastern Graham Land; Fig. 1) with initial sedimentation again occurring during the Jurassic break-up of Gondwana and continuing east of the contemporaneous volcanic arc (Macdonald et al. 1988; Hathway 2000). The Larsen Basin includes the dominantly conglomeratic Botany Bay Group alluvial fan sequence, deposited contemporaneously with Jurassic rifting and volcanism (Farquharson 1984; Hunter et al. 2005).

Non-metamorphosed intrusive rocks

Mafic to felsic plutonic rocks with dominantly calc-alkaline continental-margin affinities are prevalent on the Antarctic Peninsula (Leat et al. 1995). Granitic magmatism in Graham Land and Palmer Land peaked in the Middle Cretaceous (120–90 Ma, Leat et al. 1995) including the emplacement of the extensive Lassiter Coast Intrusive Suite in south Palmer Land (Fig. 1; Pankhurst & Rowley 1991).

Jurassic–Palaeogene volcanic rocks

With the exception of waning and post-subduction Cenozoic volcanic rocks (see next subsection), all volcanic rocks on the Antarctic...
Peninsula were assigned to the Antarctic Peninsula Volcanic Group (Thomson & Pankhurst 1983). However, this grouping ignored tectonic setting, eruption age or geochemistry and encompassed basalt–rhyolite compositions associated with fore-, intra- and back-arc settings. Subsequent work (Leat & Scarrow 1994; Riley & Leat 1999; Pankhurst et al. 2000; Riley et al. 2001; Hunter et al. 2006) suggests that the Antarctic Peninsula Volcanic Group may be divided into two main groups, as follows.

(1) Jurassic silicic volcanic rocks correlating with the Chon Aike silicic large igneous province (LIP) of South America and associated with the rifting and break-up of Gondwana (termed here the Chon Aike Volcanic Group). This group includes the Graham Land Volcanic Group (Riley et al. 2010) of eastern Graham Land and the Mount Postor (Rowley et al. 1982) and Brennecke formations (Wever & Storey 1992) in eastern Palmer Land.

(2) Intermediate–mafic composition volcanic rocks exposed along the Peninsula’s west coast with a fore- or intra-arc origin and characterized by thick volcanioclastic sequences (Riley et al. 2010). Geochronological data from the mainland of the Antarctic Peninsula are sparse (especially in Palmer Land), but existing data indicate that active margin arc magmatism is active subsequent to the Chon Aike Volcanic Group volcanism (Pankhurst et al. 2000), ends prior to the Late Neogene to Recent intraplate alkaline volcanism (Smellie 1987) and is most prevalent in the Cretaceous (Rex 1976; Fig. 2).

**Neogene–Recent alkaline volcanic rocks**

Scattered Neogene–Recent alkaline volcanic rocks along the Antarctic Peninsula record a change in eruptive setting from subduction to extensional regimes (Saunders 1982). Their main exposures are on the South Shetland Islands, around James Ross Island and on Alexander Island (Fig. 1), and indicate a widespread extensional volcanic regime as in the rest of West Antarctica (Gonzalez-Ferran 1982; Smellie 1987).

### The allochthonous terrane model and the Eastern Palmer Land Shear Zone

The Eastern Palmer Land Shear Zone (Fig. 1) is a major ductile to brittle–dextral shear zone. It is up to 20 km wide in places and is proposed to have a lateral extent of at least 1500 km, although it may continue for over 3000 km (Vaughan & Storey 2000; Vaughan et al. 2012a).

The course of the shear zone is interpreted from outcrops of breccia, mylonites and pseudotachylites showing reverse to dextral reverse deformation (Vaughan & Storey 2000). The shear zone has an overall westward dip and a NE–NNE transport direction of the hanging wall. \(^40\)Ar–\(^39\)Ar dating of a syn-deformation mylonite from eastern Palmer Land gave ages of 106.9±1.1 Ma and 102.8±3.3 Ma respectively, which were interpreted to date deformation along the Eastern Palmer Land Shear Zone (Vaughan et al. 2002a,b). This period of deformation is generally referred to as the Palmer Land Event and is interpreted as the timing of proposed terrane accretion (Vaughan et al. 2012b).

Vaughan & Storey (2000) interpreted the location of this shear zone to separate broad, geologically distinct regions within the Peninsula and drew similarities between them and the composite terranes of New Zealand, where distinct geological terranes representing an allochthonous continental margin and allochthonous arc sequences are separated by major fault zones (Bradshaw 1993). They noted that other regions of the circum-Pacific margin show evidence of allochthonous arc terranes in contact with cratonic or old mobile-belt basement across a deformation zone, similar to the Eastern Palmer Land Shear Zone. Based on these comparisons, Vaughan & Storey (2000) interpreted the Antarctic Peninsula to be composed of three domains of allochthonous and autochthonous accreted geological terranes: the Eastern Domain, Central Domain and Western Domain (Fig. 1). The relative timing of each domain’s principal units is summarized in Figure 2.

### The Eastern Domain

Located to the east of the Eastern Palmer Land Shear Zone in the east and north of Graham Land and in the east and south of Palmer Land (Fig. 1), this proposed terrane represents the former Gondwanan margin and preserves the autochthonous magmatism and sedimentation associated with subduction along this margin. The oldest outcrops in the domain are the metamorphic basement of eastern Graham Land and represent the Gondwanan basement of the Peninsula.

In Graham Land the Eastern Domain includes the metamorphic basement, Trinity Peninsula Group turbidites (interpreted by Vaughan & Storey 2000, to represent an accretionary complex), the Jurassic Botany Bay Group alluvial fan deposits, extensive Jurassic silicic volcanism of the Chon Aike Volcanic Group, and Neogene to recent alkaline volcanic rocks around James Ross Island (Rex 1976). The geology of eastern Graham Land has been closely correlated with the successions of Patagonia from the Ordovician at the time of the Famatinian arc (Riley et al. 2012b) to at least the Middle Jurassic during the extensive felsic volcanism associated with the Chon Aike silicic large igneous province (Riley et al. 2001) and subsequently from the Late Jurassic to the Early Cretaceous (Farquharson 1982).

In Palmer Land, pre-Mesozoic outcrops in the Eastern Domain are restricted to the limited outcrops of the Fitzgerald Beds and Erewhon Beds in the far south and west of the region (Fig. 1). The Eastern Domain of Palmer Land is dominated by Jurassic-aged shallow marine to terrestrial sandstones and mudstones of the Latady Group and extensive gabbrorocks to granitic intrusions of the Lassiter Coast Intrusive Suite (Fig. 1), as well as a continuation of the Chon Aike Volcanic Group and more minor Mesozoic mafic volcanic rocks and dykes (Wever & Storey 1992).

Vaughan & Storey (2000) correlated the Eastern Domain of the Antarctic Peninsula with the Western Province of New Zealand where Early Palaeozoic sedimentary rocks and Late Palaeozoic and Cretaceous granitoids represent the autochthonous Gondwanan margin (Wandres & Bradshaw 2005).

### The Central Domain

The Central Domain, lying west of the Eastern Palmer Land Shear Zone, is dominantly composed of Mesozoic and older igneous and meta-igneous units, and is interpreted (Vaughan & Storey 2000) as an allochthonous Mesozoic magmatic arc (the Triassic Dyer Arc; Vaughan et al. 2012b) underlain by older microcontinental basement, accreted to the Eastern Domain during the Palmer Land Event and sutured along the Eastern Palmer Land Shear Zone. The oldest units are orthogneisses of the metamorphic basement in NW Palmer Land (Millar et al. 2002), intruded by Jurassic–Cretaceous gabbrorocks to granitic bodies, associated metavolcanic rocks and dykes (Vaughan & Millar 1996; Scarrow et al. 1998; Vaughan et al. 2012b). Limited intrusive outcrops associated with the Lassiter Coast Intrusive Suite of the Eastern Domain and contemporaneous with the proposed age of terrane accretion also crop out on the SW coast of Palmer Land in the Central Domain (Flowerdew et al. 2005).

This domain was correlated by Vaughan & Storey (2000) with the Carboniferous to Cretaceous arc magmatism and sediments of the Median Tectonic Zone of New Zealand, interpreted to be at least partly allochthonous (Bradshaw 1993).
The Western Domain

The Western Domain of the Antarctic Peninsula is represented by Alexander Island, Adelaide Island (Fig. 1) and potentially by the metasedimentary rocks of the South Shetland and South Orkney islands (Meneilly & Storey 1986; Vaughan & Storey 2000; Vaughan et al. 2012a). The Western Domain on Alexander Island is separated from the Central Domain by the Late Cretaceous–Early Palaeogene rift of the George VI Sound (Fig. 1; Doubleday & Storey 1998). On Alexander Island the domain is composed of the LeMay Group turbidite deposits; the Fossil Bluff Group forearc sedimentary rocks; minor Late Jurassic lava flows and sills associated with both sedimentary formations (Doubleday et al. 1994; Macdonald et al. 1999); Late Cretaceous to Eocene forearc volcanic rocks and plutons (McCarron 1997); and Pleistocene alkaline volcanic rocks (Hole 1988). Vaughan & Storey (2000) interpreted the Western Domain as either a subduction–accretion complex to the Central Domain arc or a separate exotic crustal fragment sutured to the Central Domain. In the original terrane model (Vaughan & Storey 2000) Adelaide Island was included in the Central Domain but, because of stratigraphic correlations between the Adelaide Island sediments and the Fossil Bluff Group as well as correlation of the magmatic units of the two islands, Adelaide Island has been reassigned to the Western Domain (Riley et al. 2012a; Vaughan et al. 2012a).

Vaughan & Storey (2000) correlated this domain with the Eastern Province of New Zealand, where Pernian to Cretaceous igneous and sedimentary units are interpreted as allochthonous arc complexes accreted during plate convergence (Wandres & Bradshaw 2005).

Evaluation of the terrane accretion model

Following the Vaughan & Storey (2000) interpretation of the Antarctic Peninsula as a composite continental margin, numerous new datasets have emerged allowing fresh insight into the geological development of the Antarctic Peninsula such that the terrane accretion model has been further refined (e.g. Vaughan et al. 2012a,b). The aim of this paper is to present these key findings and discuss why an autochthonous model of margin development is preferable.

Palaeomagnetic evidence for differential terrane movement

The most direct method for testing the terrane hypothesis is through palaeomagnetic analysis. As noted by Vaughan et al. (2012a), palaeostream data from the Eastern Palmer Land Shear Zone and plate convergence models indicate that in a terrane accretion model the Central and Western domains originated from the modern-day north, at lower palaeolatitudes than the Eastern Domain. This should mean that Western and Central domain samples formed prior to terrane accretion will have higher palaeopole latitudes than for contemporaneous Eastern Domain samples. This is made more straightforward by the low degrees of rotation of the Peninsula since at least the Cretaceous (Kellogg & Reynolds 1978).

Unfortunately, existing palaeomagnetic data for the Antarctic Peninsula are limited and remagnetization is prevalent in pre-Cretaceous samples (Poblete et al. 2011). We have collated and calculated palaeopoles for the existing data in Figure 3. Following the data quality assessment procedure of Van der Voo (1990), we selected only samples that have been radiometrically or stratigraphically dated, that show no evidence for remagnetization, and where the number of samples (n) > 24, precision (k) ≥ 24 and the cone of confidence (α95) ≤ 16.

From Figure 3 it can be seen that for both domains little antithetical movement has occurred since the Mid-Cretaceous and a reduction in palaeopole latitude occurred during the Middle Jurassic to Early Cretaceous. However, data are limited to the Eastern and Western domains and very few data exist prior to the Mid-Cretaceous when the separate domains are proposed to have been distal. Although Figure 3 shows no distinction between the two domains, for this reason we will have to test alternative lines of evidence until a more robust palaeomagnetic dataset becomes available.

Lithological and sedimentary provenance correlations between terranes

As a number of lithological units from the different proposed terranes share broadly similar lithological descriptions it is critical to any tectonic model to determine whether or not they share a petrogenetic history.

Basement chronology

When Vaughan & Storey (2000) defined the terrane model for the Antarctic Peninsula, the oldest recognized in situ rocks from the Eastern Domain were Devonian (c. 393 Ma) and Carboniferous (c. 323 Ma) intensely deformed granitoid gneisses from Target Hill (Millar et al. 1999), whereas in the Central Domain they were pre-Late Triassic granitoid gneisses and marble breccias from the metamorphic basement in NW Palmer Land (Millar et al. 1999; Vaughan et al. 1999). However, subsequent studies (Millar et al. 2002; Riley et al. 2012b) have identified Silurian orthogneisses from the Central Domain in NW Palmer Land (422 ± 18 Ma) and Ordovician orthogneisses from eastern Graham Land (487 ± 3 Ma). If (as in the terrane model) the two domains represent a magmatic arc (the Central Domain) accreted to the Gondwanan margin (the Eastern Domain) then significantly different basement ages may
be expected for the two domains. However, as noted by Millar et al. (2002), the presence of old Gondwanan continental basement material in both domains (Fig. 2) does not support this hypothesis, and requires at least that the basement of the Central Domain suspect terrane be rifted from a Gondwana or a similarly old continental margin prior to arc development.

It could also be argued that the absence of any evidence for Carboniferous metamorphism on the Antarctic Peninsula except for at Target Hill where the later metamorphic events recorded elsewhere are absent (Millar et al. 2002) indicates different crustal histories on the Peninsula. However, Target Hill is clearly anomalous as extensive Permian and Triassic metamorphism is recorded in both the Central and Eastern domains (Millar et al. 2002; Riley et al. 2012a) and Permian metamorphism has been noted further along the Gondwanan margin in South America and West Antarctica (Pankhurst et al. 1998; Herve et al. 2010), supporting an autochthonous origin for the proposed domains.

**Stratigraphic correlations**

The terrane accretion model interprets the sedimentary sequences along the Antarctic Peninsula to be assigned to different domains: (1) the Trinity Peninsula Group and Botany Bay Group of Graham Land, and the Latady Group of Palmer Land to the Eastern Domain; (2) The LeMay and Fossil Bluff groups of Alexander Island, the clastic sedimentary rocks of Adelaide Island and the metasedimentary rocks of the South Shetland and South Orkney islands to the Western Domain. Consequently, provenance and stratigraphic correlations may help test the terrane hypothesis. Stratigraphic and radiometric dating correlations have previously been applied to the volcano-sedimentary sequences of Adelaide Island (Riley et al. 2012a) and have shown their affinity to the Fossil Bluff Group of the Western Domain rather than their original inclusion in the Central Domain.

In addition to correlating the strata of Adelaide Island with Alexander Island, Riley et al. (2012a) argued against the hypothesis that the Central and Western domains represent separate terranes prior to accretion (Vaughan & Storey 2000). They noted that the volcaniclastic and conglomeratic strata of these two Western Domain islands (Alexander and Adelaide islands) require provenance from a proximal active volcanic arc from the Late Jurassic to Albion. This correlates with the volcanic activity recorded in the Central Domain of NW Palmer Land from c. 153 to c. 107 Ma (Leat et al. 2009) and agrees with the easterly provenance of the Western Domain palaeo-flow directions and plutonic clast ages from Adelaide Island indicating a NW Palmer Land provenance (Griffiths & Oglethorpe 1998; Riley et al. 2012a). This supports a common history for the Central and Western domains.

Although it is principally included in the Eastern Domain, previous workers (Willan 2003; Wendt et al. 2008; Barbeau et al. 2010) have discussed whether the Trinity Peninsula Group is an autochthonous unit of the Eastern Domain or an allochthonous or parautochthonous unit of the Central Domain. The occurrence of Ordovician, Devonian (albeit a minor constituent) and Permian detrital zircon grains in the Trinity Peninsula Group, but the presumed absence or paucity of a similar aged source on the Antarctic Peninsula was used to imply derivation from a more distal source (i.e. the North Patagonian Massif; Willan 2003). The identification of Ordovician and Devonian to Jurassic magmatic and metamorpho-

**Geochemical evidence**

Geochemical investigations of magmatic rocks from the Antarctic Peninsula have revealed evidence of the deeper crustal structure and tectonic history of the proposed terranes.

**Evidence for the deep crustal structure**

Radiogenic isotopes are a sensitive measure for the involvement of old crustal material in younger magmatism, and can provide evidence for the deep crustal structure of continental margins. Most granitoids of the Antarctic Peninsula have radiogenic isotope compositions indicating a strong continental affinity with high Sr and low Nd isotope ratios. This requires the involvement of older continental material in their petrogenesis. Flowerdew et al. (2005) compiled isotopic data from the Cretaceous Lassiter Coast Intrusive Suite granitoids of the Central and Eastern domains in southern Palmer Land. This suite was dominantly emplaced in the Eastern Domain over a period spanning the proposed age of terrane amalgamation, but some intrusions were emplaced in the Central Domain after this date (Flowerdew et al. 2005). They concluded that the granitoids were derived through contamination of a juvenile mantle component by Proterozoic lower crustal material and observed no change in the isotopic signature between the two domains. The Central Domain data were more homogeneous than the Eastern Domain data (εNd(105) values of −1.3 to −3.2 for eight samples, compared with −1.2 to −4.0 for 10 samples, excluding two at −4.0 and +0.2) and were attributed to a subtle change in basement character. However, as the Eastern Domain samples came from a far larger area than the Central Domain samples (c. 400000 km distance between the farthest Eastern Domain samples compared with c. 200000 km for the Central Domain samples) and 11 rather than three separate plutons, it should be expected for the Eastern Domain samples to show greater heterogeneity.

The εNd(105) values of Flowerdew et al. (2005) for the Lassiter Coast Intrusive Suite in both domains ranged from +3 to −4, but 18 out of 20 values were between −1 and −4. This restricted range was attributed to homogenization of the lower crust prior to Cretaceous granitic magmatism (Flowerdew et al. 2005), a result of the extensive Jurassic silicic LIP magmatism in Palmer Land. During this Jurassic event, mantle-derived melts underplated, mixed, assimilated and homogenized with lower crustal partial melts prior to eruption, leaving an isotopically homogenized lower crust (Riley et al. 2001). Consequently, this homogeneous signature suggests an association of the Central Domain with the Jurassic magmatism associated with Gondwanan breakup and renders a distal origin unlikely.

The lack of any isotopic distinction between magmatism of the Eastern and Central domains (Flowerdew et al. 2005) is in agreement with the collated Nd isotopic data of Millar et al. (2001) for felsic and mafic intrusions, and volcanic rocks from the Peninsula (Fig. 4). Nd isotopes are particularly sensitive to the involvement of pre-Phanerozoic crust in Phanerozoic magmatism, and have been used to show the involvement of Archaean and Proterozoic crust in evolved Mesozoic and Cenozoic magmatism elsewhere on the circumpacific margin (e.g. Liew & McCulloch 1985; Cullen et al. 2013). Figure 4 shows that the εNd and geochronological data for igneous rocks from the Central and Eastern domains display similar isotopic signatures and model ages through time and similar trends in their evolution, and that both domains require involvement of Proterozoic crustal material (Millar et al. 2001). This implies that a similar Proterozoic component is present in the deep crust beneath the different domains and supports a common autochthonous history. However, it is important to note the distinct drop in εNd values for the Central Domain plutonic rocks at c. 140–130 Ma, recording emplacement of the high εNd magmatism of the Wiley Glacier Complex in NW Palmer Land. This intrusive
suite was emplaced in an extensional setting (Vaughan et al. 1997) and consequently assimilation of the extended overlying crust by the mantle-derived magmatism was reduced, producing more juvenile isotopic values relative to preceding and subsequent magmatism. Another increase in εNd, at 182–232 Ma for the Central Domain samples may indicate a similar extensional event in the Late Triassic.

Evidence for the underlying mantle chemistry and its tectonic implications

The chemistry of the mafic magmas can provide a more direct insight into the mantle sources beneath the terranes and their tectonic histories. Late Jurassic (Oxfordian–Kimmeridgian) OIB-like and arc-like pillow basalts and intrusions are recorded from the Fossil Bluff Group of Alexander Island (Macdonald et al. 1999), and similar Jurassic pillow basalts and sills of OIB, enriched mid-ocean ridge basalt (E-MORB), normal (N)-MORB and arc-like affinity crop out within the LeMay Group (Doubleday et al. 1994). The presence of OIB-like magmas within contemporaneous sedimentary rocks challenges an accretionary wedge model for the formation of the host sediments as petrogenesis of OIB-like magma requires low-degree melting of a fertile, non-metasomatized mantle. This requires subduction to not be locally active at the time of their emplacement and previous subduction cannot have metasomatized the mantle source. Their presence instead supports sedimentation in a back-arc or extensional margin setting (more likely the latter given the lack of a magmatic arc to the west of Alexander Island). The absence of an arc and active subduction zone to develop against supports a model of deposition for the Western Domain sediments against the Gondwanan margin instead of a distal oceanic arc. This is in agreement with the eastern palaeocurrent provenance of turbidite sequences (Edwards 1980) and the Cambrian to Cretaceous detrital zircon ages (Millar et al. 2001; Willan 2003).

The close spatial and temporal association of these OIB-like magmas from a non-metasomatized mantle source with E-MORB, N-MORB and arc-like magmas is comparable with the extensional magmatism found in suprasubduction-zone ophiolites produced during the initial period of subduction initiation (Stern et al. 2012). Similarly, on the Peninsula this magmatism records a period of lithospheric extension and consequent upwelling of fertile non-metasomatized mantle during the resumption of subduction after a Late Jurassic pause (Macdonald et al. 1999). This is supported stratigraphically by the presence of contemporaneous Oxfordian–Kimmeridgian radiolarian cherts associated with pillow basalts and volcanic tuffs within the oldest LeMay Group outcrops (Burn 1984; Holdsworth & Nell 1992), a typical feature of suprasubduction-zone ophiolite sequences (Metcalf & Shervais 2008), and the appearance of volcanolitic material higher up the LeMay Group stratigraphy indicating a proximal mafic arc source (Willan 2003). A similar association of Late Jurassic to Early Cretaceous OIB, E-MORB and arc-like mafic dykes are recorded in the Central Domain in NW Palmer Land (Scarrow et al. 1998) and the Eastern Domain in NE Palmer Land (Weyer & Storey 1992), further supporting a shared tectonic history of the three terranes.

In addition to the OIB and MORB dykes, tholeiitic and calc-alkaline arc-derived mafic dykes on the Peninsula have been used to infer its tectonic history. Vaughan et al. (2012b) interpreted incompatible element depleted Triassic tholeiitic mafic dykes (predating amphibolite-grade metamorphism at c. 200 Ma) in the eastern Central Domain of Palmer Land as representing shallow melting of a deformed mantle beneath an intra-oceanic arc, supporting the terrane hypothesis. However, similar tholeiitic mafic magmas were emplaced during the Cretaceous in NW Palmer Land (Central Domain) at c. 150 Ma and 84–72 Ma (Scarrow et al. 1998) and in eastern Graham Land (Eastern Domain) at 126–106 Ma (Leat et al. 2002). This Cretaceous magmatism represents melting during periods of high lithospheric extension of a subduction-modified asthenospheric mantle, previously depleted by Jurassic magmatism (Scarrow et al. 1998; Leat et al. 2002; Riley et al. 2003). As both the chemically similar Triassic and Cretaceous tholeiitic dykes were emplaced in both the Central and Eastern domains this argues against the requirement for an allochthonous island arc setting for the Triassic magmas, instead indicating a period of subduction-driven lithospheric extension of the Gondwana margin during the Triassic, supported by the increase in granitic εNd, during the Late Triassic (see above; Fig. 4). The restricted distribution of these dykes in the eastern Central Domain indicates a limited spatial extent of Triassic lithospheric extension.

Geophysical datasets

Multiple geophysical datasets have been collected that allow further insight into the geological characteristics and tectonic histories of the proposed domains and their relationship to each other.

Magnetic susceptibility of the magmatic suites

Analysing the magnetic susceptibility of rocks allows determination of their magnetic content and as such provides an indication of the magma’s redox state during emplacement and the degree of crustal contamination (Ishihara 1998). The distribution of magnetite-series (high fo2) and ilmenite-series (low fo2) granitoids on the East Pacific margin (Ishihara et al. 2000; Hart et al. 2004) has
shown a tectonic control on oxidation state, with dominantly mag- 
netite-series intrusions occurring closest to the convergent margin 
where crustal extension reduced the degree of crustal contamin-
ation and consequent reduction in oxidation state. In contrast, 
ilmenite-series granitoids dominantly crop out further inland 
where crustal contamination of the intruding melts was increased 
by crustal thickening.

Wendt et al. (2013) collected bulk magnetic susceptibility data 
for the Antarctic Peninsula to investigate the spatial and temporal 
patterns of the magnetite- and ilmenite-series granitoids so as to 
understand the magmatic redox states for the proposed terranes. 
They identified that the Triassic and Cretaceous plutonic rocks are 
overwhelmingly magnetite series (high fO2) in the west of the 
Peninsula (the Central Domain) and ilmenite series (low fO2) in 
the east (the Eastern Domain), although all Jurassic plutonic rocks are 
ilmenite series in both domains. This distribution is at odds with a 
tectonic model involving a palaeo-subduction zone along the line 
of the Eastern Palmer Land Shear Zone as this would produce 
suprasubduction extension and dominantly magnetite-series plut- 
ons in the overriding Eastern Domain as well as the volcanic arc 
of the Central Domain. Instead, the evidence for decreasing fO2 
from west to east supports a simpler model of a single subduction 
zone west of the Peninsula, placing the magnetite-series granitoids of 
the Central Domain closer to the convergent margin and the 
Eastern Domain plutonic rocks further landward, as seen in North 
and South America (Ishihara et al. 2000; Hart et al. 2004). This 
interpretation of crustal assimilation as the dominant control on 
-era susceptibility is supported by the εNd data (see above), 
which showed decreased crustal assimilation during formation of the 
Early Cretaceous extensional magnetite-series intrusions of the 
Central Domain.

Aeromagnetic and gravity data for distinct terranes

Aeromagnetic data also provide insight into the bulk magnetic sus-
cceptibility of the composite lithologies of the Peninsula, although 
specific lithologies and relative ages have to be inferred. These 
data (Fig. 5; Vaughan et al. 1998; Ferraccioli et al. 2006) broadly 
agree with those of Wendt et al. (2013), with the most extensive 
high magnetic susceptibilities being on the west of the Peninsula in 
the Central Domain. The highest magnetic anomalies are focused 
on a narrow linear feature (the Pacific Margin Anomaly, Fig. 5; 
Vaughan et al. 1998) along the Central Domain’s western margin. 
This anomaly also correlates with a Bouguer gravity high (Ferraccioli et al. 2006). Mapping and dating samples from this 
region indicates that the anomaly is largely caused by highly mag-
netically susceptible Early Cretaceous (141–129Ma) gabbroic and 
tonalitic–granodioritic extensional plutons produced during a peak 
in magmatic activity (Vaughan et al. 1998). Less extensive, shorter 
wavelength magnetic highs are found in the Eastern Domain of 
Palmer Land, but the Jurassic gabbroic intrusions producing them 
are clearly not as prevalent as the mafic bodies in the Central 
Domain and may be related to Gondwana rifting rather than arc 
magmatism (Storey et al. 1987; Wever & Storey 1992). Although 
the data of Ferraccioli et al. (2006) were presented in support of 
the terrane accretion model, no extensive linear magnetic feature 
follows the trace of the Eastern Palmer Land Shear Zone; this find-
ing argues against the presence of a major tectonic suture separat-
ing allochthonous or parautochthonous terranes. Instead, the 
most prominent linear feature abruptly bisects the Central Domain into 
a western zone of high magnetic susceptibility and an eastern zone 
of low susceptibility, reflecting the edge of the Pacific Margin 
Anomaly related mafic magmatism not a terrane boundary.

As with the Wendt et al. (2013) data, the aeromagnetic data do not 
show evidence for high fO2, magnetite magmatism along the 
Eastern Palmer Land Shear Zone and the Eastern Domain, as 
would be expected in a terrane accretion model, nor an expression 
of the Eastern Palmer Land Shear Zone itself. Again, the data are 
best explained by a simpler continental margin model with 
increased dominance of magnetite-series magmatism towards a 
single convergent margin to the west of the Peninsula.

Proposed tectonic history of the Antarctic Peninsula

From the data discussed above we conclude that the different com-
posite crustal units of the Antarctic Peninsula developed as autoch-
thonous sequences on the remnant Gondwanan margin, not 
through terrane accretion of allochthonous bodies. We do not, 
however, dispute the presence of an extensive zone of oblique 
reverse deformation marked by the Eastern Palmer Land Shear 
Zone. Thus, returning to the historical model of continental margin 
growth we propose the following genetic history for the Peninsula 
(illustrated in Fig. 6) and explain how the units previously pro-
posed as originating in separate terranes fit into a common history 
of a single, autochthonous arc.

**Proterozoic to Carboniferous: basement formation**

Although no Proterozoic material is exposed on the Antarctic Peninsula the evidence from Nd isotopes (see above) strongly sup-
ports the occurrence of either unexposed Proterozoic crust or sedi-
mentary rocks derived from Proterozoic crust in all three domains. 
Proterozoic detrital and inherited zircon grains indicate the pres-
ence of similarly aged crust within the Gondwanan margin on 
which the Peninsula developed (Millar et al. 2002; Barbeau et al. 
2010). Protracted periods of arc magmatism along the Gondwanan 
margin during the Palaeozoic formed the oldest metamorphic 
basement in Graham Land and north Palmer Land. The scattered 
distribution of these basement outcrops, their occurrence in both 
the Central and Eastern domains, and geochemical evidence for its 
existence in the basement of all domains indicate extension and 
incorporation of the basement units into the developing margin 
during subsequent events.

**Carboniferous to Triassic: Pangaean margin**

Continental margin magmatism continued along the Peninsula 
during the Carboniferous to Triassic period of final assembly and 
persistence of Pangaean. Contemporaneous dyke chemistries and 
the provenance of Central and Eastern Domain sedimentary rocks 
indicate active and proximal Permian to Triassic arc subduction 
(Laudon 1991; Vaughan et al. 2012b). Passive margin clastic sedi-
mentary rocks, back-arc basin sediments and continental margin 
turbidites were deposited forming the Fitzgerald and Erewhon 
Beds in SW Palmer Land (Eastern Domain) and the Trinity 
Peninsula Group in Graham Land (Eastern Domain).

**Early–Middle Jurassic: silicic LIP magmatism**

The c. 182Ma emplacement of the Karoo–Ferrar mafic large igne-
ous province in Antarctica and Africa (Encarnación et al. 1996; 
Duncan et al. 1997; Minor & Mukasa 1997; Riley & Knight 2001) 
is associated with the onset of Gondwana break-up and is in part 
contemporaneous with silicic magmatic activity in Patagonia and 
the Antarctic Peninsula (Riley et al. 2001), producing the Chon 
Aike Volcanic Group on the Peninsula between 188–178Ma and 
172–162Ma (Pankhurst et al. 2000). Magmatism is within the 
Eastern Domain, but homogenization of the Central and Eastern 
domains’ lower crust (see above) indicates the effect of LIP mag-
matism in both domains and indicates a close spatial distribution.

Contemporaneous Weddell Sea rifting associated with this 
magmatism separated South Africa from Antarctica and the 


Antarctic Peninsula from Patagonia (167–140 Ma, König & Jokat 2006). This thinned the crust on the eastern side of the Antarctic Peninsula, as revealed by a decrease in the Bouguer gravity anomaly relative to the Peninsula’s spine (Garrett 1990; Ferraccioli et al. 2006). The intraplate rifting resulted in the onset of Latady Group and Mount Hill Formation deposition (Eastern Domain) in back-arc basin settings at 188 Ma (Fanning & Laudon 1999; Willan 2003). Terrestrial sedimentation during this period also formed the
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Botany Bay Group in eastern Graham Land (Eastern Domain), and passive margin extension offshore led to the onset of deposition of the LeMay Group of Alexander Island (Western Domain); extension recorded across the Peninsula again illustrating the common tectonic history of the domains.

**Late Jurassic: magmatic quiescence and subsequent subduction resumption**

Subduction along the Peninsula ceased in the Late Jurassic, reflected by a low in magmatic activity at 156–142 Ma (Leat et al. 1995). During the recommencement of active subduction, extensional passive margin tectonics resulted in sedimentation on Alexander Island and Adelaide Island (Western Domain) and OIB- and MORB-like intrusive and volcanic magmatism on Alexander Island as fertile non-metasomatized mantle upwelled. A high isostatic residual gravity anomaly over Alexander Island reveals these mafic intrusions to be extensive at depth, forming up to 7.5 km of the vertical crustal stratigraphy (Garrett 1990; Ferraccioli et al. 2006). These events argue against formation of the Western Domain as an accretionary wedge to a distal oceanic arc (see above) and mark the resumption of subduction (see above) and subsequent increase in magmatic activity during the Cretaceous.

**Early Cretaceous**

Extensive arc and back-arc tectonics across the Peninsula in the Early Cretaceous produced a peak of Phanerozoic intrusive magmatism and crustal growth. Crustal extension followed the onset of subduction and thinned the crust in western Palmer Land, as revealed by the reduced Bouguer anomaly west of the Peninsula’s spine (Garrett 1990; Ferraccioli et al. 2006). Crustal thinning resulted in mantle melting and low εNd magnetite-series magmatism in the Central Domain (Fig. 4). This distinct chemistry marks reduced crustal contamination of juvenile mantle melts resulting from high degrees of crustal extension, not a distinction in the existing crustal structure (see above). The highly magnetic Pacific Margin Anomaly (Fig. 5) over western Palmer Land reveals that similar mafic to intermediate intrusions are far more prevalent in the lower to middle crust and isostasy modelling indicates that they may form about one-third of the crustal thickness beneath the Pacific Margin Anomaly (Garrett 1990; Vaughan et al. 1998).

**Late Cretaceous and Cenozoic**

Magmatic activity began to wane following the Palmer Land Event (Leat et al. 1995). Post-inversion extension associated with continuing subduction in the Late Cretaceous–Early Palaeogene

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*Fig. 6. Illustrative tectonic reconstruction for Palmer Land highlighting the key events in the autochthonous development of the Antarctic Peninsula.*
produced the rift of the George VI Sound (Doubleday & Storey 1998). Through the Late Cretaceous and Cenozoic magmatism migrated northwards (Leat et al. 1995), following the migration of active subduction. Peaks in volcanic activity occurred in the Latest Cretaceous–Eocene, particularly in Adelaide Island, Alexander Island and the South Shetland Islands, and may reflect collision of a spreading ridge with the subduction zone (McCarron 1997; McCarron & Millar 1997; Haase et al. 2012; Riley et al. 2012a). Extension between South America and Antarctica began at c. 50 Ma as the Drake Passage began opening, developing a deep-water connection between 34 and 30 Ma (Livermore et al. 2005, 2007). Subsequent magmatism on the Antarctic Peninsula waned until the production of scattered intra-plate alkaline volcanism from 6.5 to 0.1 Ma (Rex 1976; Ringe 1991).

Comparisons and correlations with other continental arcs

It is important to understand how globally representative these processes are and whether similar tectonic histories and characteristics can be observed along other continental margins, so here we compare our observations with other circum-Pacific continental margins.

South America

As the continuation of the Gondwanan margin recorded by the Antarctic Peninsula, the Andean chain is the obvious comparison for margin development. Like the Peninsula, the South American margin has had its tectonic history interpreted through autochthonous and allochthonous accretion models.

Arguments against the allochthonous arc models are similar to those employed here for the Antarctic Peninsula. Ramos et al. (1986) proposed a model of Palaeozoic accretion during the formation of Gondwana, constructing the central Andes from three major terranes that collided in two events during the Cambrian-Ordovician and the Devonian. This hypothesis was based on sharp changes in the stratigraphic units across proposed terrane boundaries. However, based largely on the similarity of the magmatic and metamorphic histories and isotopic signatures, as well as an absence of suture zones and large-scale stacking, Lucassen & Franz (2005) disputed this and proposed autochthonous Palaeozoic growth of the margin. An allochthonous origin has also been proposed for Patagonia (Ramos 1984), involving collision with South America in the Permian. However, correlation of sedimentary, igneous and metamorphic units across the proposed suture zone and the lack of geophysical evidence for the suture also support an autochthonous origin of Patagonia, with subduction-related transpression producing the deformation structures in situ (Kostadinoff et al. 2005; Gregori et al. 2008).

Baja California and the North American Pacific Coast

The geophysical similarity of distinct regions of magnetic susceptibilities separated by a proposed suture zone has led to previous comparison of the Antarctic Peninsula with the Mesozoic Peninsula Ranges Batholith of California (Ferraccioli et al. 2006). The proposed suture divides the magnetite-series, Early Cretaceous plutons and host crust of the Western Peninsula Ranges Batholith from the ilmenite-series mid-Cretaceous plutons and crust of the Eastern Peninsula Ranges Batholith. The significance of this suture (as with the Eastern Palmer Land Shear Zone) has been interpreted as representing exotive terrane accretion, accretion of a fringing arc or heterogeneities within a single arc (Sedlock 2003, and references therein). However, as with the Antarctic Peninsula granitoids, the similar pattern of ilmenite- and magnetite-series plutons may be related to suprasubduction-zone processes, with magmatite-series intrusions occurring in the extended crust close to the convergent margin and the ilmenite-series produced by increased crustal assimilation inland. This would support autochthonous, single arc development models of the Peninsula Ranges Batholith (e.g. Walawender et al. 1991; Ortega-Rivera 2003).

New Zealand

New Zealand is also a continuation of the proto-Pacific Gondwana margin and remains a classic example of terrane accretion during continental growth. It has traditionally been grouped as three distinct provinces (Wandres & Bradshaw 2005, and references therein): (1) the autochthonous Early Palaeozoic metasedimentary sequence and younger granitoids of the Western Province; (2) the multiple allochthonous arc, forearc and accretionary complexes of the Eastern Province; (3) the Carboniferous to Early Cretaceous batholith and volcanic and sedimentary sequences of the Median Tectonic Zone, separating the Western and Eastern provinces. However, on the basis of compiled geochronological, structural and petrogenetic evidence the Median Tectonic Zone has been reinterpreted as a magmatic arc complex that developed along the margin of the Western Province (Mortimer et al. 1999; Wandres & Bradshaw 2005), similar to the reinterpretation here of the Mesozoic magmatism in the Antarctic Peninsula’s Central and Eastern domains.

Conclusions

The identification of an extensive transpressional shear zone bisecting the Antarctic Peninsula led to a significant reinterpretation of the development of the region’s composite geological terranes as a series of two or three accreted terranes. However, in the light of the collated stratigraphic, geochronological, geochemical and geophysical datasets we support an alternative tectonic history of autochthonous continental margin development. This reinterpretation is based on the following evidence.

(1) *In situ* Early Palaeozoic meta-igneous basement is present in both the proposed autochthonous Eastern Domain and allochthonous Central Domain.

(2) There is stratigraphic correlation of multiple sedimentary and volcanic sequences between the domains.

(3) The Nd isotopes are similar for igneous units in each domain, indicating similar deep crustal structures.

(4) OIB-like magmas and deep marine extensional sedimentary sequences within the Western Domain stratigraphy support an extensional margin, not a forearc depositional setting.

(5) Magnetic susceptibility of the igneous units increases towards the west of the Peninsula, reflecting extensional suprasubduction magmatism in the Central Domain and a farther landward setting for the Eastern Domain.

(6) There is no distinction in palaeopole latitudes between the domains prior to the proposed accretion event in the current (albeit highly limited) data.

With these arguments for an autochthonous rather than allochthonous margin development a tectonic history is proposed by which the composite geological units of the Antarctic Peninsula can be produced *in situ*. The series of events can be summarized as follows.

(1) Continental margin magmatism and sedimentation occurred during amalgamation and persistence of the Gondwana and Pangaea supercontinents.

(2) Extensional tectonics and silicic LIP magmatism marked the onset of supercontinent break-up.

(3) Amagmatic extensional tectonics and associated sedimentation and low-volume OIB magmatism occurred during a pause and subsequent resumption of arc magmatism.
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(4) Large-scale arc and back-arc extensional magmatism developed, including the emplacement of voluminous mafic to intermediate intrusions above the subduction zone.

(5) Transpressional deformation formed laterally extensive faults and shear zones, with voluminous intermediate to felsic back-arc magmatism.

(6) Arc magmatism waned as subduction migrated from the margin.

(7) Intraplate alkaline magmatism followed subduction cessation.

Comparison with other circum-Pacific continental margins shows that similar features to those observed in the Antarctic Peninsula and presented as support for autochthonous development of the margin can be observed elsewhere, including the margins of South America, California and New Zealand where accreted terrane development has also been proposed. Consequently, this paper supports a careful re-evaluation of these margins to investigate whether they too developed in situ. These two competing hypotheses of accretional or autochthonous development imply very different processes for crustal growth, and so it is important to determine their relative dominance globally.

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