The geological history and evolution of West Antarctica

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Abstract | West Antarctica has formed the tectonically active margin between East Antarctica and the Pacific Ocean for almost half a billion years, where it has recorded a dynamic history of magmatism, continental growth and fragmentation. Despite the scale and importance of West Antarctica, there has not been an integrated view of the geology and tectonic evolution of the region as a whole. In this Review, we identify three broad physiographic provinces and present their overlapping and interconnected tectonic, magmatic and sedimentary history. The Weddell Sea region, which lays furthest from the subducting margin, was most impacted by the Jurassic initiation of Gondwana break-up. Marie Byrd Land and the West Antarctic rift system developed as a broad Cretaceous to Cenozoic continental rift system, reworking a former convergent margin. Finally, the Antarctic Peninsula and Thurston Island preserve an almost complete magmatic arc system. We conclude by briefly summarizing the geologic history of the West Antarctic system as a whole, how it provides insight into continental margin evolution and what key topics must be addressed by future research.

Nunataks
An isolated rock outcrop standing proud of the surrounding ice sheet, often used as a descriptive Antarctic place name.

As a result of its long tectonic and magmatic history, complex topography and distinct geological provinces, West Antarctica defies simple classification as a convergent margin, magmatic arc or rifted continental margin[1,2]. This region, which is ~4,700 km long and up to 1,600 km wide (FIG. 1a), consists of crustal blocks of disparate tectonic origins, all of which have been affected by complex convergent margin processes[3,4]. Compared with East Antarctica, West Antarctica is younger, less tectonically stable and has a lower average elevation. The majority of West Antarctic crust developed between ~500 and 90 million years ago (Ma) along the active ocean–continent convergence zone that borders the ancient Pacific margin of Gondwana, which has left a lasting impact on the geology of the region.

Due to the complex tectonic setting, sparse rock exposure (FIG. 1b) and lack of detailed exploration, the fundamental structures and evolution of West Antarctica are actively debated. However, the integration of geological and geophysical techniques (BOX 1), together with tectonic frameworks from well-studied once-conjugate continents, has advanced our understanding of the region in recent decades[5–8]. In return, improved knowledge of the geology of West Antarctica has provided key geological evidence of the processes that lead to continental growth[9–11], as well as insight into the evolution of the overlying West Antarctic ice sheet[12–15]. These advances motivate continued study of West Antarctica and highlight the importance of understanding its geological evolution.

In this Review, we give an overview of the West Antarctic region. We divide West Antarctica into three broad physiographic provinces (FIG. 1) with differing, but often overlapping, geological histories: the Weddell Sea sector, which includes the elevated Ellsworth–Whitmore Mountains, Haag Nunataks and the low-lying Weddell Sea rift system; the low-lying Ross Embayment and West Antarctic rift system (WARS), and the elevated Marie Byrd Land (MBL) dome; and the arcuate, elevated spine of the Antarctic Peninsula and adjacent Thurston Island crustal block. For each of these provinces, we describe regional-scale physical characteristics, geological history and the current understanding of the area's tectonic evolution. Finally, we consider what makes West Antarctica a unique and important system.

The Weddell Sea sector

The Weddell Sea sector, which includes the shallow marine Weddell Sea rift system and onshore highlands of the Haag Nunataks and Ellsworth–Whitmore Mountains block (FIG. 1a), is the oldest and most enigmatic part of West Antarctica. It is bounded to the north by the Jurassic and younger oceanic crust of the southern Weddell Sea and to the south by the abrupt topographic step between the Ellsworth–Whitmore Mountains and the low-lying WARS. The Weddell Sea sector is flanked by the generally younger Antarctic Peninsula to the west and by the ancient cratonic East Antarctic continent and overlying Jurassic Ferrar magmatic province to the east.

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Key points

- West Antarctica is a geologically complex region that developed along the margin of Gondwana between the subducting Paleo-Pacific oceanic plate and the cratonic East Antarctic continent.
- West Antarctica can be broken into three broad geological and physiographic provinces: the Weddell Sea sector; the West Antarctic rift system and Marie Byrd Land; and the Antarctic Peninsula and Thurston Island.
- The Weddell Sea sector includes the oldest rocks in West Antarctica, was least affected by the marginal subduction system and its movement to its current position during the Jurassic initiation of Gondwana break-up was associated with back-arc extension in the Weddell Sea rift system.
- The West Antarctic rift system and Marie Byrd Land region followed as an active subducting margin and magmatic arc outboard from the East Antarctic Ross orogen. Subduction ceased during the Cretaceous, associated with extreme crustal extension and resulting in a broad rift basin and, ultimately, New Zealand rifting away.
- The Antarctic Peninsula and Thurston Island exemplify a continental margin magmatic arc, preserving a record of the flare-ups in magmatism. Arc magmatism ceased from south to north between 90 and 20 million years ago as the Phoenix oceanic spreading centre reached the continental margin trench.

Grenvillian
The mountain-building event ~1,000 million years ago, seen in continents around the world, which led to the assembly of the supercontinent of Rodinia.

Hf
(Hafnium). A geologically useful isotope, as its value is strongly controlled by its magmatic source, which is linked to tectonic setting.

Zircons
Highly resistant silicate minerals formed by igneous and metamorphic processes; the isotopes they contain and/or exclude make them ideal for radiometric dating and geochemical analysis.

Mantle extraction ages
Isotopically determined ages when the minerals making up a crustal rock were first extracted from the underlying mantle.

Laurentian
Referring to a large continental craton, which, today, forms the core of North America, but which was likely positioned close to Antarctica within the supercontinent of Rodinia.

Paleomagnetic data
The preserved orientation of magnetic minerals in rocks, which can be used to reconstruct where the rock was formed.

Precambrian evolution. The oldest rocks exposed in West Antarctica form a ~2-km^2 outcrop at Haag Nunataks, providing a unique window into the basement geology of the region (FIG. 1b). The rocks at Haag Nunataks formed in a magmatic arc during the Mesoproterozoic at ~1,170 Ma and were subsequently deformed at ~1,060 Ma (REF.[16]), making them more than twice as old as any other rocks identified in West Antarctica (FIG. 2). The exposed rocks are juvenile, that is, they formed through the direct melting of the mantle, rather than through remelting of existing crustal rocks[17]. Although the rock outcrop is small, aeromagnetic data (BOX 2) indicate that this basement province extends beneath a region of at least 120,000 km^2, as marked by high-amplitude magnetic anomalies matching those at Haag Nunataks[18,19].

The age and petrology of the Haag Nunataks block is distinct from the adjacent, younger Antarctic Peninsula but similar to the age and petrology of the Natal Embayment of Southern Africa[20] and the basement of East Antarctica. Therefore, the Haag Nunataks juvenile arc terrane might have developed on the accretionary margin of the proto-Kalahari Craton at ~1,200 Ma (REF.[21]) during the wider Grenvillian amalgamation of the Neoproterozoic supercontinent of Rodinia[22]. The absence of subsequent deformation events in the rocks of Haag Nunataks[16] suggests that these rocks acted as an undeforming microcontinental block from Grenvillian time onwards[23].

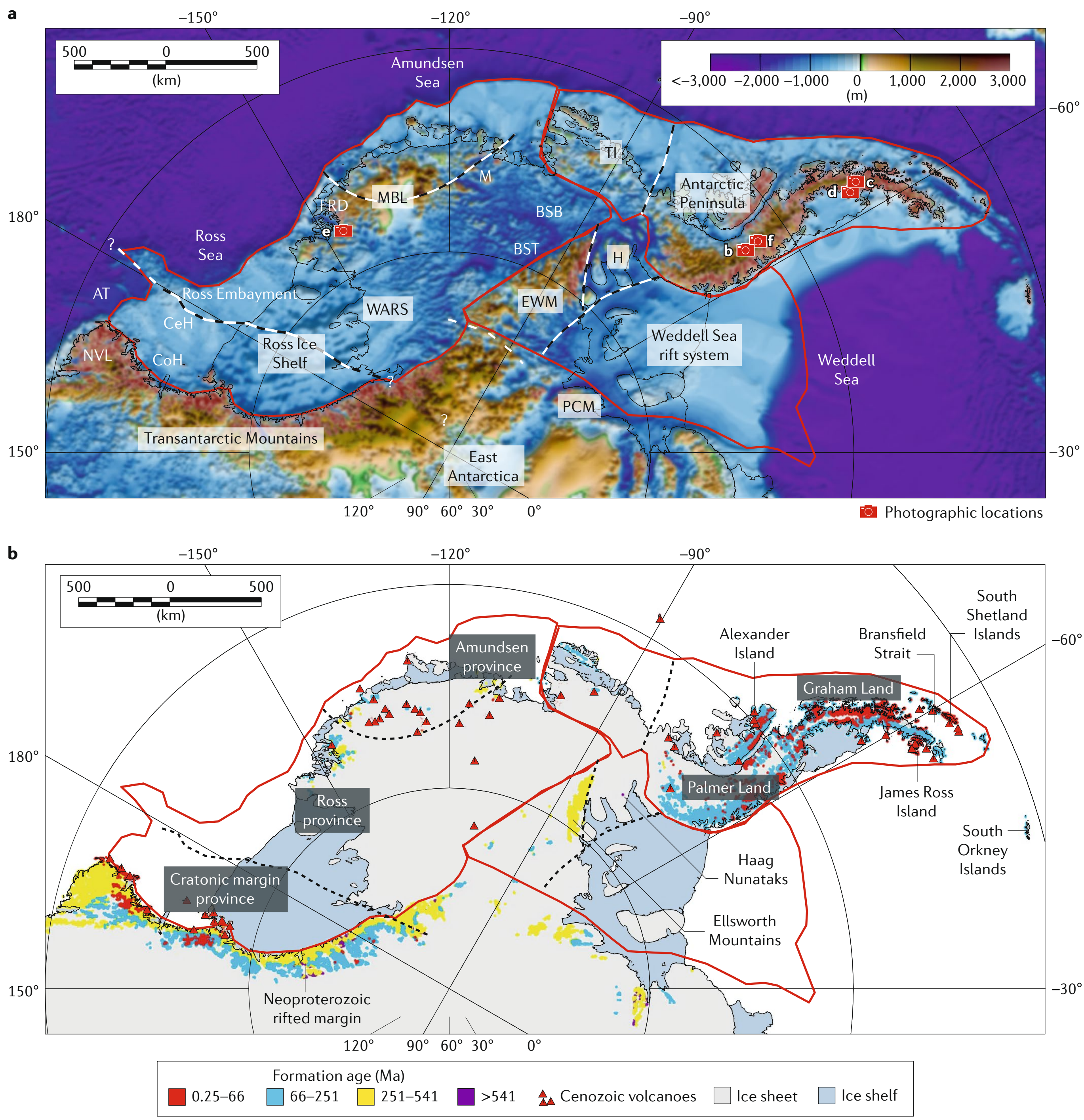
Paleozoic development. Adjacent to the Haag Nunataks province are the Ellsworth Mountains (FIG. 1b), a ~350-km-long mountain range that includes Mount Vinson (4,892 m), the highest peak in Antarctica. A succession over 13 km thick of conformable Cambrian to Permian sedimentary rocks are exposed along these mountains and likely extend across the wider Ellsworth–Whitmore Mountains region[5,24], as indicated by exposures in sparse nunataks. The basement geology of this region is not exposed; however, Hf (Hafnium) isotopic signatures from detrital zircons[25], along with mantle extraction ages (estimated to be 1,370 to 1,600 Ma) from Jurassic granites[17], indicate that Proterozoic-age basement is present across the region, meaning that the Ellsworth–Whitmore Mountains basement is similar in age to the exposed Haag Nunataks. Although of similar age, aeromagnetic data show that the weakly magnetized Ellsworth–Whitmore Mountains basement is distinct from the highly magnetic Haag Nunataks basement[2,18] (BOX 2). It is proposed that the Ellsworth–Whitmore Mountains were thrust over the margin of the Haag Nunataks block in the Permo-Triassic (~250 Ma)[26], indicating that the boundary between these two regions has been a long-standing geological discontinuity.

The oldest exposed rocks in the Ellsworth Mountains are the Cambrian Heritage Group (FIG. 2), which includes ~7.5 km of clastic, basaltic volcaniclastic and fossiliferous carbonate sediments[27] formed between ~532 and ~505 Ma (REF.[28]). Unlike the Paleo-Pacific continental margin magmatic arc along the Transantarctic Mountains in East Antarctica at this time[29], the Ellsworth–Whitmore Mountains region was dominated by a rapidly subsiding continental rift basin associated with extension either in a back-arc or embayment setting[5]. The precise location of the Ellsworth–Whitmore Mountains at this time is under debate (FIG. 3). Provenance data based on Heritage Group zircon ages suggest an East Antarctic or Australian source for these sediments[30], but a combined Laurentian and South African sediment source has also been proposed[28]. Other geochemical proxies (such as Hf isotopes) suggest that the sediments were from Southern Africa or locally derived basement[25]. Paleomagnetic data from the Cambrian Heritage Group

Fig. 1 | **West Antarctic setting. a** | Complex West Antarctic subglacial topography from Bedmap2, derived from airborne ice-penetrating radar[157], with bathymetry beneath the Ross Ice Shelf derived from gravity data[77]. The thick red lines demarcate the three main geotectonic provinces and the dashed black lines mark sub-provinces. The main provinces include the Weddell Sea sector, which includes the shallow marine Weddell Sea rift system and onshore highlands of the Haag Nunataks and Ellsworth–Whitmore Mountains (EWM) block; Marie Byrd Land (MBL) and the West Antarctic rift system (WARS), which are underlain by highly extended crust; and the Antarctic Peninsula and Thurston Island (TI), which expose a well-preserved continental marginal arc. Note the broad variety of distinct topographic provinces, which reflect the complex and contrasting geology that developed along the convergent margin. The camera symbols locate photographs in BOX 1. **b** | Outcrop geological age from SCAR GeoMAP and GNS Science 2019 (REF.[162]). Sparse outcrop data means that much of the sub-ice geology is interpolated from these outcrops based on geophysical data. The oldest province is the Weddell Sea sector, with rocks in places over a billion years old. The MBL and WARS region is dominated by rocks between 500 and 66 Ma, while the Antarctic Peninsula is dominated by younger rocks formed from 251 Ma to present day. Also shown are the locations of known Cenozoic volcanoes[68]. AT, Adare Trough; BSB, Byrd Subglacial Basin; BST, Bentley Subglacial Trench; CeH, Central High; CoH, Coulman High; FRD, Ford Ranges; H, Haag Nunataks sub-province; M, Mount Murphy; NVL, northern Victoria Land; PCM, Pensacola Mountains.

indicate a location towards the Natal Embayment during this time, and that the region was rotated by 90° after deposition of the sediments during the Cambrian[6,31]. Despite the controversy over sediment sources, there is general consensus that the Ellsworth–Whitmore Mountains lay to the north of their current location in Cambrian times, and were receiving sediments from the interior of the Gondwana supercontinent.

Between the Late Cambrian and Devonian, a period of relative tectonic quiescence was marked by the deposition of ~3 km of shallow marine sandstone in the Ellsworth–Whitmore Mountains, forming the extensive Crashsite Group[32]. This formation is overlain by the Whiteout Conglomerate, ~1 km of unsorted sediment deposited during the Upper Carboniferous–Permian Gondwanan glaciation[33]. Ice streams flowing outward from East Antarctica transported glacial sediments from the Transantarctic Mountains to the Ellsworth Mountains area, as suggested by ice-flow markers and limestone clasts with distinctive Cambrian fossils[33,34]. Similar Permo-Carboniferous glacial tills in the Pensacola Mountains (FIG. 1a) have been used to constrain the position of the Ellsworth–Whitmore Mountains at this time to a region north of the present-day Pensacola Mountains[33,35]. The Whiteout Conglomerate glacial unit is overlain by the Permian Polarstar Formation,

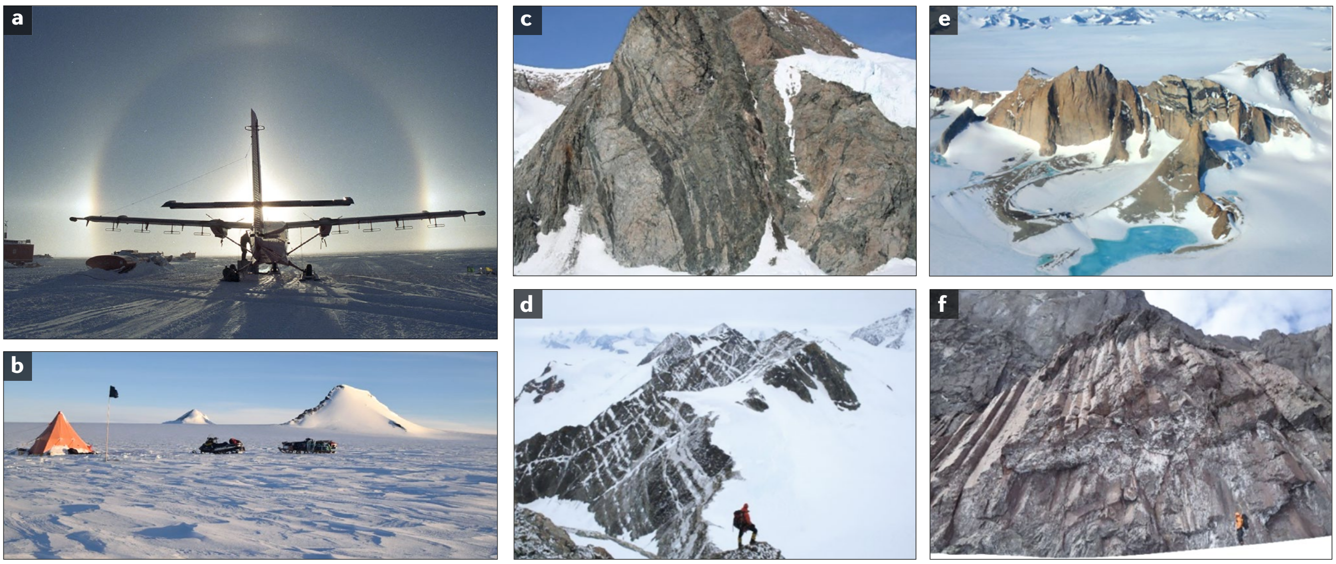


Box 1 | Key techniques for exploring West Antarctica

Geophysical techniques image or sense the rocks beneath the icy surface and include both airborne and ground-based surveys. Airborne surveys often include ice-penetrating radar to reveal the mountains and valleys buried beneath up to 5 km of ice[157] (FIG. 1). Aeromagnetic sensors, such as wing-tip pods that house magnetometers (see the figure, part **a**), are used to map the pattern of sub-surface faults, intrusions and geological provinces based on the varying magnetic properties of the different rocks involved[19]. Aerogravity data can be used to map sub-surface density variations that, when combined with topography and magnetic data, reveal large intrusions, thick sedimentary basins and regional-scale variations in crustal thickness.

Seismic data use sound waves travelling through the Earth's crust to map sub-surface structures. Reflection seismic data using a man-made source typically image shallower structures, such as stacks of sediments. Refraction seismic or passive seismic observations using man-made or natural sources, respectively, image the structure of the entire crust and mantle beneath[54] (BOX 2).

Other aspects of geological exploration in West Antarctica include ground-based fieldwork (see an example of a field camp in the figure, part **b**). Fieldwork can include, for example, sampling basement material, silicic ignimbrites, carboniferous granites and arc columnar jointed rhyolitic tuff (see the figure, parts **c**, **d**, **e** and **f**, respectively).



a ~1-km-thick unit dominated by shallow marine sandstones, with increasing amounts of siltstone and coals in the upper levels, marking a transition from marine delta to onshore coastal plain[36]. Detrital zircons and stratigraphic analysis both suggest that the youngest sediments in the Ellsworth Mountains were deposited in a basin with sediments sourced from the Transantarctic Mountains[37], rather than from Southern Africa. Volcanic tuff units interbedded in the Polarstar formation are dominated by mid-Permian to late-Permian prismatic zircons, indicating a link between the tuffs and a major magmatic flare-up event along the Paleo-Pacific margin[28,37] (BOX 3; FIG. 2).

The entire Paleozoic sedimentary succession was deformed into a series of closed-to-tight folds by a major dextral transpressive Permo-Triassic orogenic event[38]. This event is inferred to be part of the wider Andean-style Gondwanide orogeny, extending from South America through the Cape Fold Belt of South Africa and the Falkland Islands to the Pensacola Mountains on the edge of East Antarctica[39] (FIG. 1a). The assumption that this orogen was originally a linear structure is consistent with the hypothesis that the Ellsworth–Whitmore Mountains rotated through 90° in post-Permian times, as, today, the Ellsworth Mountains' structural trends are orthogonal to many other parts of the orogen[40,41]. However, as other parts of this orogen are not straight[42], the paleomagnetically observed rotation might have occurred during Gondwanide deformation[43]. An isolated Triassic granite (~208 Ma) intruded into the Ellsworth–Whitmore Mountains[44] indicates that subduction along the Paleo-Pacific margin continued after the Gondwanide orogen, although the location of the subduction zone is not clear.

Jurassic magmatism and microcontinental movement. The Early Jurassic is marked by a major pulse of large igneous province (LIP) magmatism that includes emplacement of both the Karoo and Ferrar mafic igneous provinces around 183–182 Ma in South Africa and East Antarctica[45,46] (FIG. 3a). The formation of these LIPs is considered a precursor of Jurassic continental break-up and magmatism in the Weddell Sea region[47], but the origin of the Ferrar magmas is debated. It has been proposed that melting and magmatism was driven by an upwelling mantle plume[48,49], which triggered the break-up of the Gondwana supercontinent in the Weddell Sea region[47,49]. However, geochemical analysis of the isotopic signatures indicates that the more extensive Ferrar magmas are distinct from typical plume-derived magmas[50,51]. This evidence favours the conclusion that the Ferrar LIP resulted from extension and decompressional melting in response to changes in subduction along the Paleo-Pacific margin[50,51].

Though magmatic rocks directly attributed to the Ferrar or Karoo LIPs are not seen anywhere in West Antarctica, the Ellsworth–Whitmore Mountains do contain at least four granites from the Middle Jurassic

(177–174 Ma)[44,52]. These granites are geochemically defined as being syn-collisional to within-plate (back-arc and/or continental rift), and, hence, distinct from typical volcanic arc granites[44]. The Middle Jurassic granites are thought to be derived from a combination of crustal melting due to upwelling of hot mantle and direct fractionation of the mantle-derived Ferrar magmas[2,44]. If the latter contribution was dominant, a relatively long crustal residence is required, as the granites post-date the Ferrar magmatism by at least 5 Ma (REFS[44,46,52]). Aeromagnetic data show that, in contrast to the three approximately circular Middle-Jurassic granites, the 174.6 ± 0.2 Ma Pagano Nunatak granite at the western edge of the Ellsworth–Whitmore Mountains province is highly elongated[53]. It is suggested that this granite was emplaced within a major shear zone that facilitated left lateral movement of the Ellsworth–Whitmore Mountains block along the margin of East Antarctica[43] (FIG. 3a).

Offshore, the thin continental crust of the southern Weddell Sea rift system[54] (BOX 2) is thought to have developed as a broad back-arc[55] in response to south-westerly movement of the Ellsworth–Whitmore Mountains and Haag Nunataks block[43,56] (FIG. 3a). However, the extent of Jurassic movement of the Ellsworth–Whitmore Mountains and Haag Nunataks block is controversial (FIG. 3a). Movement from a position in the Natal Embayment is suggested based on geological, stratigraphic and paleomagnetic data[5,6,40,57,58]. However, geophysical analysis and resulting interpretation of the Weddell Sea rift system as a region of stretched continental crust challenges the concept of microcontinental movement from further north[43,59–62]. Most significantly, seismic refraction data crossing the Weddell Sea rift system along the ice shelf front (FIG. 1b) reveal ~12-km-thick sediments with low modelled seismic velocities, which overlay lower crust with unusually fast modelled seismic velocities[60,63,64]. The high-seismic-velocity layer was originally interpreted as stretched continental crust[63], but interpretations based on reprocessing of the seismic data suggest the presence of unusually thick oceanic (~20 km) or transitional continental margin crust in this region[60].

In light of the proposed origin of this crust as a transitional continental margin, the magnetic anomalies in the northern Weddell Sea rift system (BOX 2) may reflect continental fragmentation between Southern Africa and East Antarctica[43,60,63,65] (FIG. 3b). In contrast, magnetic anomalies in the southern Weddell Sea rift system reflect the more limited movement of the Ellsworth–Whitmore Mountains prior to Gondwana break-up (BOX 2; FIG. 3a). The oldest oceanic magnetic anomalies offshore from the Weddell Sea sector are 145–160 Ma (REF.[60]), suggesting that all major tectonic movements were complete by this time.

MBL, WARS and the Ross Embayment

MBL comprises a Paleozoic–Mesozoic-age archipelago of islands and submerged continental crust (FIG. 1). Rock exposures forming the Ford Ranges in western MBL (BOX 1) exemplify the geological framework of the region. The oldest rocks here are immature sediments deposited in slope or trench settings that host subsequent mid-Paleozoic continental margin arc and late Mesozoic back-arc plutons. In contrast, central and eastern MBL host sparse coastal exposures that reflect mid-Paleozoic and Permo-Triassic convergent margin arcs[3,66,67]. The youngest rocks in MBL are basaltic scoria and lava flows exposed on the slopes of quiescent alkaline volcanoes (up to 4,285 m elevation), which are distributed along the crest and north flank of an elongate elevated region of disputed origin known as the MBL dome[68] (FIG. 1a).

The WARS is a ~600-km-wide region of thinned, subsided continental crust that borders the prominent Transantarctic Mountains (FIG. 1a). The rift topography here narrows and deepens southward from the shallow marine Ross Embayment, which spans the Ross Sea and Ross Ice Shelf, into the rugged, lineated subglacial troughs surrounding the Bentley Subglacial Trench (−2,555 m) and Byrd Subglacial Basin (−2,870 m). The narrow troughs and ridges imply fault-control and young or active tectonism upon new or inherited structures beneath the West Antarctic ice sheet.

Metamorphic basement and a concealed Precambrian element. The oldest known rocks of MBL form the gneissic crystalline basement beneath a late Miocene stratovolcano, Mount Murphy. A crystallization age of 505 ± 5 Ma for granodiorite[66] (based on U-Pb dating in zircons) implies that this basement originated in close proximity to the Transantarctic Mountains' Ross orogen[69]. Isotopic signatures from mantle xenoliths and later-emplaced granites indicate that Precambrian lithosphere underpins MBL[66,70]. Together with bedrock ages and geophysical contrasts, Nd isotopic data delineate two tectonic sub-provinces: an older, inboard Ross province and a younger, outboard Amundsen province[66] (FIG. 1b). Ultramafic xenoliths sampling the lithospheric mantle were erupted from Miocene volcanoes in this region. These xenoliths show diverse mineralogy, geochemical properties and equilibration temperatures[70,71], substantiating the presence of heterogeneous Precambrian lithosphere beneath MBL.

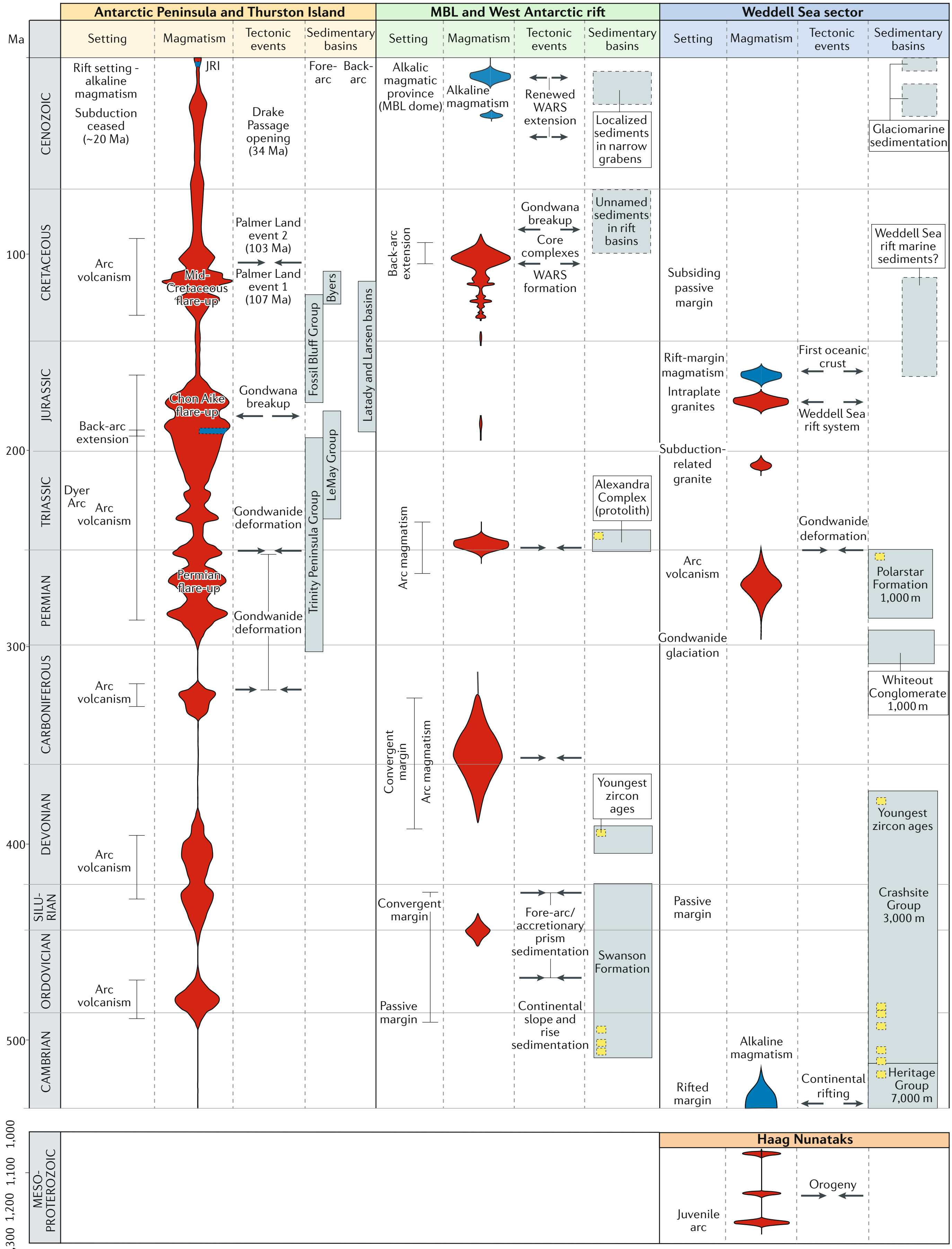
Paleozoic development of a convergent margin. The extensive Cambrian–Ordovician turbidites and flysch[72], which form the Swanson Formation in western MBL (FIG. 2), are part of a voluminous, immature sedimentary sequence deposited in a series of slope aprons and submarine fans along the Gondwanide margin (FIG. 3a). The oldest sediments in this formation are derived from the final stages of the Ross–Delamerian orogen, which formed along the Australian–East Antarctic continental margin of Gondwana between 514 and 490 Ma (REF.[73]) during the Neoproterozoic and Cambrian. Subsequently, in West Antarctica, these sediments were deformed into strongly cleaved, km-scale upright folds by coeval and subsequent contractional tectonics[74].

Pulses of granitoid magmatism and metamorphism occurred in MBL during the Ordovician–Silurian, Devonian–Carboniferous and Permo-Triassic[3,66,74] (FIGS 2,4a). Permian volcanic ash falls deposited in the adjacent Transantarctic Mountains are interpreted to have come from volcanoes along that convergent margin[75]. These ash falls and the formation of leucogranites by crustal melting of immature sediments reflect arc magmatism due to plate convergence and the incremental

U-Pb dating
Use of the relative abundances of isotopes of uranium (U) and lead (Pb) to determine the age that crystals formed within a magma or metamorphic rock.

Nd isotopic data
The use of samarium–neodymium (Sm–Nd) isotope decay system to determine the age of formation and evolution of the continental crust.

Leucogranites
Granites with a high proportion of light-coloured minerals compared with darker-coloured minerals; they are typically formed in continental collision settings.



Antarctic Peninsula and Thurston Island
MBL and West Antarctic rift
Weddell Sea sector
Ma
Setting
Magmatism
Tectonic events
Sedimentary basins
CENOZOIC
CRETACEOUS
JURASSIC
TRIASSIC
PERMIAN
CARBONIFEROUS
DEVONIAN
SILU-RIAN
ORDOVICIAN
CAMBRIAN
MESO-PROTEROZOIC
100
200
300
400
500
1,000
1,100
1,200
1,300
Rift setting - alkaline magmatism
Subduction ceased (~20 Ma)
JRI
Drake Passage opening (34 Ma)
Fore-arc
Back-arc
Arc volcanism
Mid-Cretaceous flare-up
Palmer Land event 2 (103 Ma)
Palmer Land event 1 (107 Ma)
Byers
Fossil Bluff Group
Latady and Larsen basins
Chon Aike flare-up
Gondwana breakup
Back-arc extension
LeMay Group
Dyer Arc
Arc volcanism
Gondwanide deformation
Trinity Peninsula Group
Permian flare-up
Gondwanide deformation
Arc volcanism
Arc volcanism
Arc volcanism
Alkalic magmatic province (MBL dome)
Alkaline magmatism
Renewed WARS extension
Localized sediments in narrow grabens
Gondwana breakup
Core complexes
WARS formation
Unnamed sediments in rift basins
Back-arc extension
Arc magmatism
Alexandra Complex (protolith)
Convergent margin
Arc magmatism
Youngest zircon ages
Convergent margin
Fore-arc/ accretionary prism sedimentation
Swanson Formation
Passive margin
Continental slope and rise sedimentation
Glaciomarine sedimentation
Weddell Sea rift marine sediments?
Subsiding passive margin
Rift-margin magmatism
Intraplate granites
First oceanic crust
Weddell Sea rift system
Subduction-related granite
Gondwanide deformation
Arc volcanism
Polarstar Formation 1,000 m
Gondwanide glaciation
Whiteout Conglomerate 1,000 m
Youngest zircon ages
Crashsite Group 3,000 m
Passive margin
Alkaline magmatism
Rifted margin
Continental rifting
Heritage Group 7,000 m
Haag Nunataks
Orogeny
Juvenile arc

Fig. 2 | **Timeline of key West Antarctic tectonic and magmatic events.** Tectonic and magmatic events evolved differently across the three provinces of West Antarctica (the Antarctic Peninsula and Thurston Island, Marie Byrd Land (MBL) and the West Antarctic rift system (WARS), and the Weddell Sea sector), as depicted in this timeline. The red and blue bands in the 'Magmatism' column show the relative magnitude of arc-related and rift-related magmatism, respectively. The arrows in the 'Tectonic events' columns indicate relative compression (inward-facing arrows) or extension (outward-facing arrows). Exposed (in grey text boxes with solid outlines) and inferred (in grey text boxes with dashed outlines) sedimentary successions are also shown in the 'Sedimentary basins' columns. The yellow squares are detrital zircon ages reflecting the minimum depositional ages. JRI, James Ross Island.

formation of new continental crust[76]. Over time, plutonism shifted outboard from the western Ross province of MBL to the eastern and central Amundsen province and Zealandia. Geochemical evidence suggests that the MBL and Zealandia subduction zone was retreating through Carboniferous to Permian times, which would favour crustal thinning and maximize the proportion of juvenile crustal material generated in this region[9]. Geochronological evidence suggests that successor basins containing Permo-Triassic sediments were deposited and subsequently metamorphosed. On the basis of coastal exposures and the geophysical characteristics of the concealed crust (BOX 2), this geological pattern is inferred to continue beneath the eastern half of the Ross Ice Shelf and Ross Sea[77].

In total, the ~400 million years of ocean–continent convergence described in this section resulted in an approximately threefold increase in the thickness of the continental crust in the MBL and WARS region. This increase might have resulted in lithospheric thickening and the development of a linear belt of elevated topography or an orogenic plateau[78] that was subsequently extended and thinned.

Cretaceous magmatism and intracontinental extension. The WARS and MBL contain no geological record of notable Jurassic or Early Cretaceous events. However, during this time, the thickened crust may have led to incipient partial melting of the lower crust that was important in subsequent events (FIG. 4b). Renewed subduction of oceanic crust and calc-alkaline plutonism occurred from 124 to 110 Ma, overlapping with the granulite-facies metamorphism and alkaline granite plus mafic plutonism that occurred between 115 to 96 Ma (FIG. 4b). Over the wide back-arc region, bimodal magmatism was accompanied by normal to oblique-normal slip upon low-angle to high-angle faults, resulting in crustal thinning and broad extension across the WARS (FIGS 3c,4b). In <20 million years (between ~105 and 85 Ma), central West Antarctica underwent ~600 km of extension and >1,000 km of stretching occurred across the Ross Sea through western MBL[79–81].

The large-scale extension and crustal thinning led to exhumation of mid-crustal migmatite gneiss–granite complexes along detachment faults[82], in both MBL and once-contiguous southern Zealandia. Isotopic and geochemical ties exist between these granites (which were formed by melting of the middle crust) and the upper crustal plutons[83]. The resulting crust beneath MBL and the Ross Embayment varies in thickness from 14 km beneath the basins up to 21–24 km beneath the Coulman and Central Highs[54,84] (BOX 2). The thinned crust attributed to West Antarctic extension and rifting continues to the foot of the Transantarctic Mountains[54]. However, recent airborne geophysical surveys indicate that the short-wavelength, high-amplitude magnetic anomalies that are characteristic of MBL and much of the WARS do not extend beneath the Ross Ice Shelf to the Transantarctic Mountain front[77] (BOX 2; FIG. 1b). Magnetically, the signatures of the 'cratonic margin province' of the WARS resemble the adjacent area of the Neoproterozoic (~670 Ma) passive margin and subsequent sequences of orogen-derived sediments exposed in the Transantarctic Mountains[85] and the turbidite-dominated Robertson Bay terrane of northern Victoria Land[86,87]. The cratonic margin province is, therefore, likely underlain by faulted Neoproterozoic crust of the pre-Ross rifted margin that is blanketed by sedimentary molasse eroded from the Ross orogen and younger strata[77], with limited Cretaceous or younger magmatic reworking (FIG. 4b). This province boundary intersects the Transantarctic Mountains at the junction of two East Antarctic basement provinces[88], but lack of aeromagnetic data coverage means continuation of this province boundary across the Transantarctic Mountains into East Antarctica is speculative (FIG. 1).

The Cretaceous events from 115 to 90 Ma reflect a dramatic change in the continental tectonic regime in MBL, Zealandia and the Antarctic Peninsula and the oceanic Phoenix and Pacific plates[89]. The regional importance of this change is demonstrated by the synchronicity of the pulses of magmatism seen along the Paleo-Pacific margin at this time (BOX 3). In MBL and the WARS, the subduction-related magmatism and wrench component of deformation was driven by the oblique subduction of young, hydrated oceanic lithosphere of the Phoenix plate[90,91] (FIG. 3c). As subduction waned, potentially due to the approach of the Phoenix spreading centre and Hikurangi Plateau to the continental margin trench ~100 Ma, extreme transtensional back-arc extension was distributed across MBL and the WARS[82,92].

Continental margin break-up and tectonic quiescence. The final stage of break-up in East Gondwana — leading to the eventual isolation of Antarctica over the South Pole — was driven by the rapid oblique subduction of young, hydrated oceanic lithosphere of the Phoenix plate[90,91], oceanic ridge–trench interaction[93,94] and encroachment of the Hikurangi LIP and oceanic plateau upon the trench[95] (FIG. 3c). The initial regional high-temperature metamorphism and extensive mid-crustal melting ~100 Ma weakened the crust of MBL, which was already scored by high-angle transcurrent faults due to oblique convergence. Plate separation between West Antarctica and Zealandia occurred along a narrow zone orthogonal to the rift basins of the Ross Sea[96] (FIG. 3c,d), suggesting that a pre-existing high-angle strike–slip fault system[97] was exploited for continental separation. The subsequent demise of the convergent boundary progressed from west to east. As the plate boundary shifted from convergent to divergent, seafloor spreading commenced between Zealandia and both West Antarctica and Australia by 83 Ma (REFS[7,98,99]) (FIG. 3d). Tectonic restoration of the

Plutonism
The formation of intrusive magmatic rocks beneath the Earth's surface, in contrast to volcanism, where magmas are erupted onto the Earth's surface.

Calc-alkaline
Magmas that are typically hydrous and oxidized, and are generally found in arcs above subduction zones.

Migmatite
A metamorphic rock where significant partial melting has begun.

Molasse
Poorly sorted terrestrial and shallow marine deposits associated with erosion from a nearby active orogenic belt.

Box 2 | **Geophysical features of West Antarctica**

Geophysical data play a key role in defining West Antarctica. Seismic data reveal the thickness of the continental crust, which reflects thickening by compression and addition of magma and thinning by extension and rifting. Aeromagnetic data can be used to determine which areas have rocks with similar amounts of magnetic minerals and how they have been subsequently juxtaposed and deformed. Here, crustal thickness derived from passive seismic observations[54] clearly separate the 35–45-km-thick cratonic crust in East Antarctica and the West Antarctic crust with a mean thickness of just 25 km. Together, crustal thickness[54] and aeromagnetic patterns[19,77] (see the figure, parts **a** and **b**, respectively) help to further refine understanding of West Antarctic provinces and the processes that formed them. The question marks indicate speculative extensions of province boundaries.

Weddell Sea

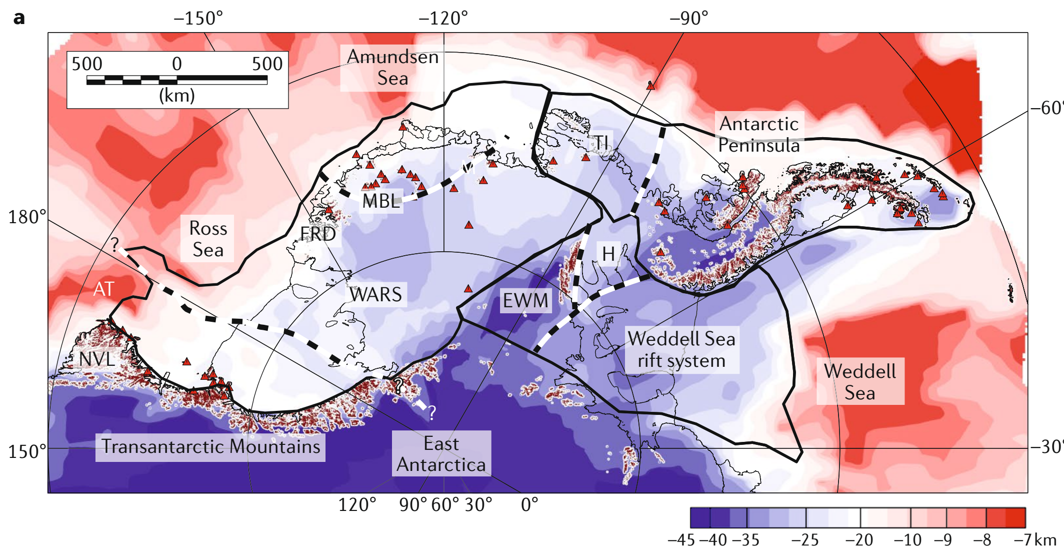
The Weddell Sea province reveals generally long-wavelength magnetic features. Offshore, the Northern Weddell Magnetic Province (NWMP) and Southern Weddell Magnetic Province (SWMP)[43], crust ~30 km thick[53,62], reflect the Jurassic rift fabric[43] and thick sedimentary cover[158] due to subsequent subsidence and sedimentation.

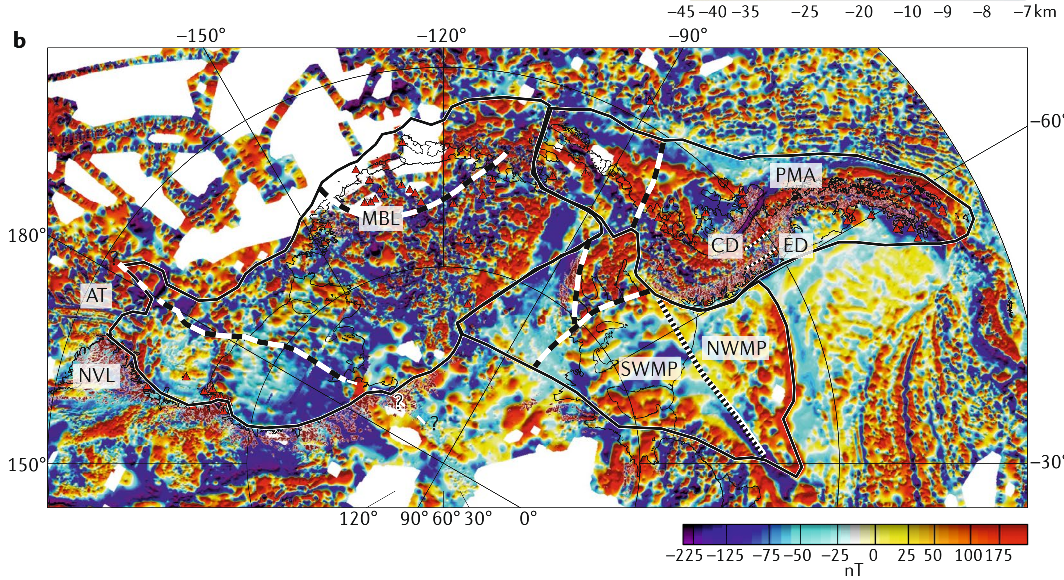
Antarctic Peninsula

The Antarctic Peninsula is marked by the ~2,600-km-long magnetic Pacific Margin Anomaly (PMA), attributed to a well-preserved magmatic arc[159]. Thicker crust and the detailed structures of the magnetic anomalies reflect periods of compression and tectonic thickening of the crust[11,149].

WARS

The West Antarctic rift system (WARS) is characterized by broad areas of crust 20–25 km thick attributed to Cretaceous to Cenozoic extension. The disordered high-amplitude magnetic patterns are attributed to wide-spread magmatism, including both intrusions and volcanoes[77,160].





AT, Adare Trough; CD, Central Domain; ED, Eastern Domains in the Antarctic Peninsula; EWM, Ellsworth–Whitmore Mountains; FRD, Ford Ranges; H, Haag Nunataks; M, Mount Murphy; MBL, Marie Byrd Land; NVL, northern Victoria Land; TI, Thurston Island.

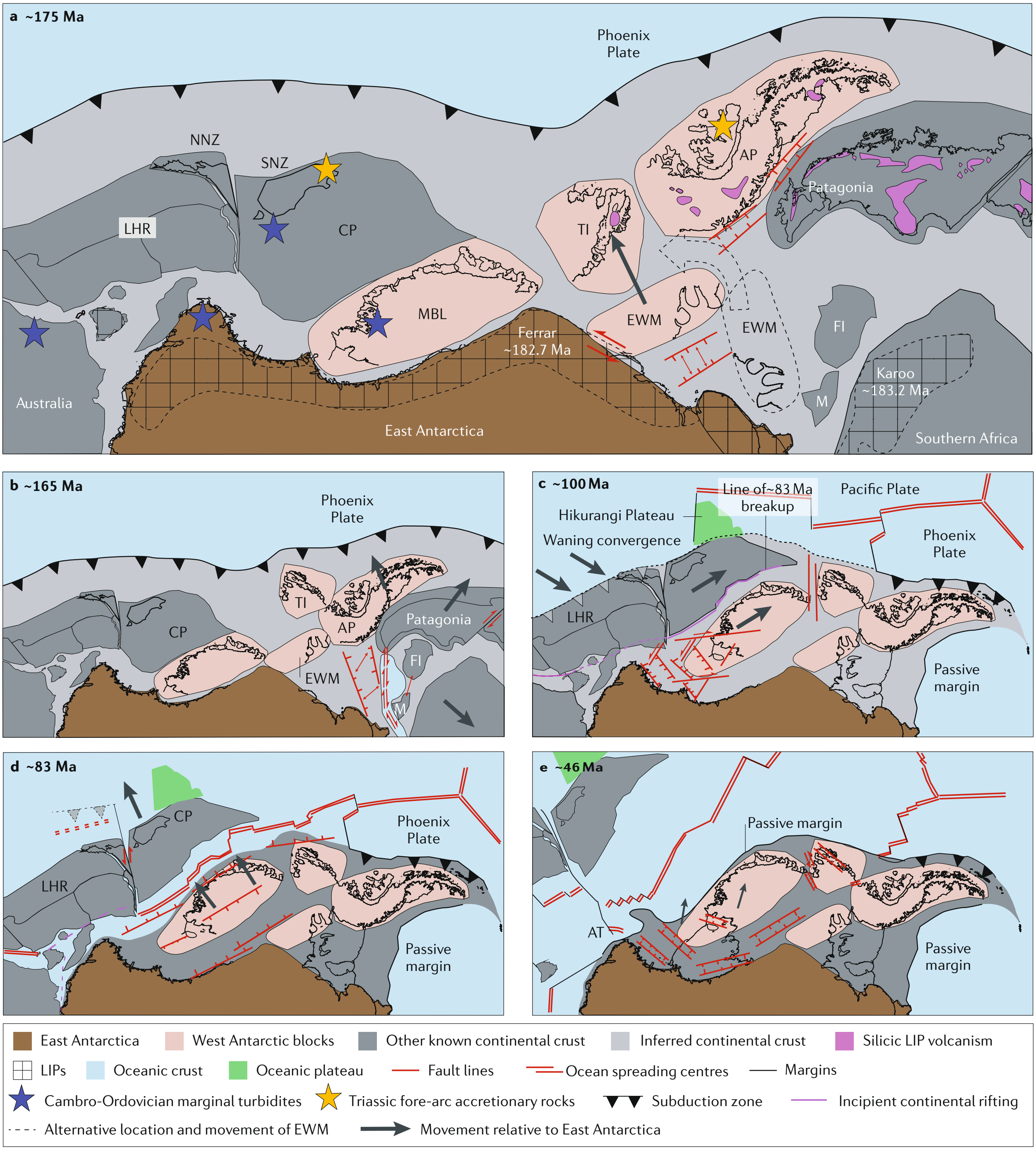
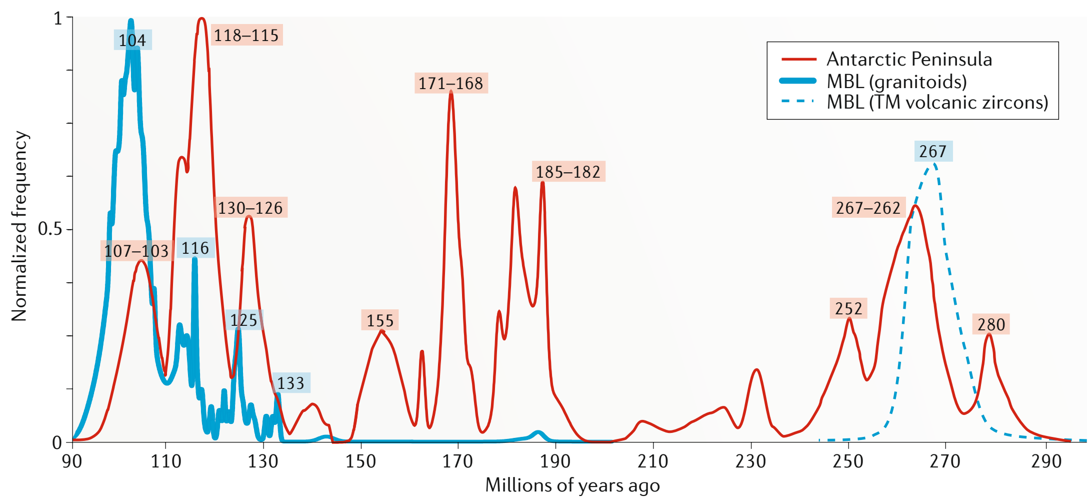


Fig. 3 | **Plate tectonic reconstruction from 175 to 45 Ma.** Plate tectonic reconstruction maps that show motion in an East Antarctica fixed reference frame. West Antarctic blocks[40], including Marie Byrd Land (MBL), Thurston Island (TI), the Antarctic Peninsula (AP) and the Ellsworth–Whitmore Mountains (EWM), are depicted as pale pink regions and modern coastlines are shown for reference. Other known present-day continental regions are shown in dark grey. Inferred intervening areas of continental crust are shown in light grey; such regions have been deformed and distorted to such an extent that they cannot be meaningfully be traced through time. **a** | Middle Jurassic initiation of Gondwana break-up is shown[37,43]; the hashed regions mark Jurassic mafic large igneous provinces (LIPs)[48] and the dark-pink regions mark silicic LIP volcanism[134]. Cambro-Ordovician marginal turbidites (blue stars) were widespread, whereas Triassic fore-arc accretionary rocks (orange stars) were rare. The dashed outline marks alternative location and rotation of the EWM. **b** | Separation of Southern Africa[163]. **c** | Initiation of MBL, Ross Sea and West Antarctic rift system extension[97]. **d** | Separation of Zealandia[7,8,97,98,164]. **e** | Final stages of West Antarctic rift development linked to extension in the Adare Trough (AT)[100,102,156]. CP, Campbell Plateau; FI, Falkland Island Plateau; LHR, Lord Howe Rise; M, Maurice Ewing Bank; NNZ, North Island New Zealand; SNZ, South Island New Zealand.

Box 3 | Magmatic flare-ups in West Antarctica

Magmatic 'flare-up' events characterize the geological history of the Paleo-Pacific margin (see the figure) and contributed substantially to the crustal growth along the accretionary continental margin. The solid red line shows the frequency curve for magmatic events on the Antarctic Peninsula[119,134,143,161]. The solid blue line shows the frequency curve for mid-Cretaceous granitoids from Marie Byrd Land (MBL)[143] and the dashed blue line shows the age frequency for volcanic zircons in the Transantarctic Mountains (TM) thought to be sourced from MBL[75]. High magma addition rates during the Cretaceous and Permian are evident along the entire proto-Pacific margin of West Gondwana. High rates of Antarctic Peninsula Jurassic magmatism correspond to a flare-up also seen in South America. Magmatic episodicity typically includes enhanced activity for ~4 million years and lulls of ~10 million years, with activity often enhanced by ~100–1,000 times compared with periods of quiescence.

The synchronicity of episodic flare-up magmatism along the Paleo-Pacific margin demonstrates that this process is controlled by complex tectono-magmatic relationships that are often external to the local arc, for example, plate reorganization or mantle-plume activity.



abrupt, steep, rifted margins of Zealandia and West Antarctica produces a tight fit of the already-extended crust, providing clear evidence that major extension across West Antarctica and Campbell Plateau occurred prior to break-up of this part of Gondwana[96] (FIG. 3c).

Neogene volcanism and landscape rejuvenation. The post-East Gondwana break-up period of quiescence was broken at ~45 Ma by renewed extension and basin sedimentation[100,101], spurred by a short-lived episode of spreading in Adare Trough[102] (FIG. 3e). Fault-controlled mafic dyking likely occurred during the ~45-Ma extensional phase. At ~34 Ma, mafic alkaline magmatism commenced in central MBL[103], although the construction of prominent large volcanoes and small monogenetic cones occurred from 13 Ma (REFS[104,105]). The presence of high-amplitude, short-wavelength magnetic anomalies (BOX 2) and peaks in subglacial topography (FIG. 1) suggests that such volcanic centres are spread over a vast region of MBL and the eastern Ross Embayment[106–108]. Cenozoic magmatism in MBL may have been driven by a mantle plume[105,109] or by the large quantities of hydrous sediments and oceanic lithosphere that were subducted into the mantle beneath MBL during the preceding ~400 million years[91]. In the latter explanation, subduction, in effect, fertilized the mantle with water and easily fusible minerals, leading to the development of a hydrous mantle wedge. Once subduction ceased, the hot, low-density material rose up from the lower mantle and supplied MBL magmatism[90,91,110].

The upwelling low-density mantle associated with Cenozoic volcanism likely provides dynamic support for the currently elevated MBL dome. This is suggested by the seismically imaged thin crust underlying the elevated MBL topography[54] (BOX 2), which would otherwise require a thick underlying crustal root. It has been proposed that the timing of uplift is constrained by a dissected low-relief planation surface overlain by Neogene volcanic rocks extending across MBL[103,111–113]. This planation surface is interpreted as a regional Cretaceous sea-level erosion surface formed after ~ 83-Ma break-up between West Antarctica and Zealandia[113]. Subsequent uplift to current elevations, peaking at ~2,700 m in the centre of MBL, were likely driven by buoyant mantle effects since ~34 Ma (REF.[113]). Although central MBL has been the site of uplift, coastal fjords in MBL where glaciers were once grounded but are now over 2 km below sea level and the presence of drowned wave-cut platforms in WARS are consistent with marked Neogene subsidence[114] in the regions flanking the MBL dome. The origin of this subsidence and the competing hypotheses of uplift driven by plume[14,108,115] versus hydrous mantle wedge[91] remain to be tested.

Antarctic Peninsula and Thurston Island

The Antarctic Peninsula is an arcuate mountainous belt that reaches heights of 3,200 m and preserves a complex geological and tectonic history from the Ordovician to the present day as a long-lived accretionary continental margin. This geological record has been shaped by

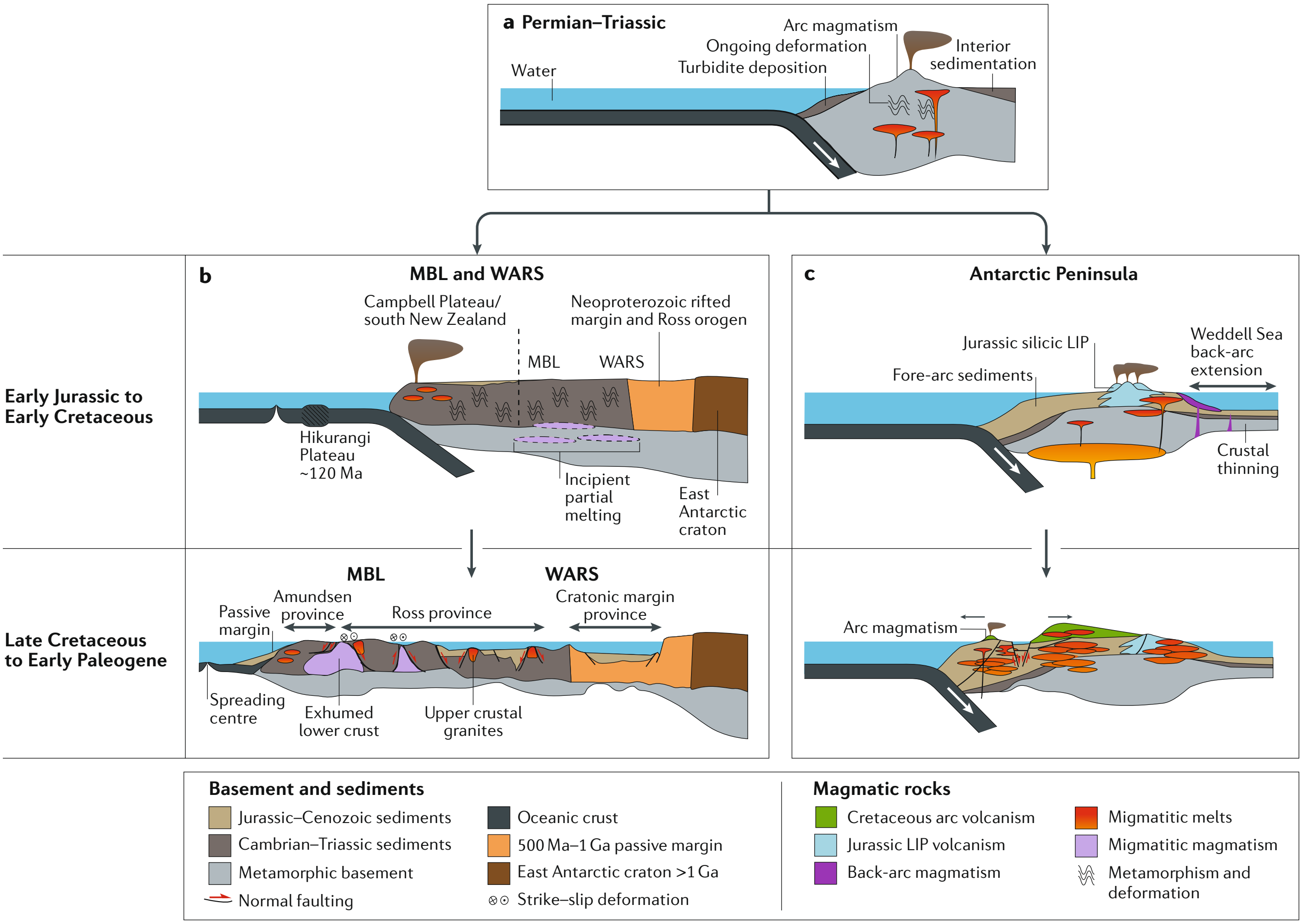


Fig. 4 | **Cross sections of the evolution of West Antarctica. a** | In Permo-Triassic times, an arc was present along the margin of West Antarctica. **b** | In the Jurassic, Marie Byrd Land (MBL), the West Antarctic rift system (WARS) and the Antarctic Peninsula had developed different tectonic settings. There was limited magmatism in MBL and the WARS, where thickened crust might have given rise to an elevated plateau and incipient melting of the lower crust. In the Late Cretaceous, MBL was characterized by broad extension exhuming lower crustal rocks, triggering melting and emplacement of upper crustal granites. **c** | Subduction and magmatism are ongoing in the Antarctic Peninsula in the Jurassic. In contrast to MBL and the WARS, the Antarctic Peninsula was marked by ongoing magmatism but limited extension. LIP, large igneous province. Cross sections based on information in REFS[11,77]. Parts **a** and **c** were adapted from REF.[11] CC BY 3.0 (https://creativecommons.org/licenses/by/3.0/). Part **b** was adapted from REF.[77], Springer Nature Limited.

subduction along the proto-Pacific margin and rifting in the Weddell Sea sector, with contrasting tectonic models proposed to explain the composite nature of the Antarctic Peninsula. Early models suggest that the Antarctic Peninsula is an amalgamation of relatively far-travelled terranes that accreted to the Gondwana margin, akin to the tectonic model for the formation of New Zealand[116]. However, a recent model proposes that, similar to the formation of Patagonia, the component provinces of the Antarctic Peninsula are not far travelled[11]. Today, the Antarctic Peninsula preserves a geological record through a continental margin arc, including well-preserved fore-arc, back-arc and magmatic successions.

Thurston Island exhibits close geological links to the Antarctic Peninsula[117,118], including the presence of a Devonian–Carboniferous basement, Mesozoic magmatism associated with the accretionary margin and a pulse of Early to mid-Cretaceous granitic magmatism. Many of these Mesozoic events correlate with those in MBL, highlighting the extent to which tectonic processes were coupled along the Paleo-Pacific margin.

Basement rocks. The oldest identified basement on the Antarctic Peninsula is early Ordovician (~485 Ma) diorite gneisses from the eastern Antarctic Peninsula[119], representing early arc magmatism (FIG. 2). Ordovician arc magmatism is recognized elsewhere along the proto-Pacific margin of Gondwana, particularly from the Famatinian complex in northwest Argentina and the North Patagonian Massif, and Silurian arc magmatism (~430 Ma) has been identified from western Palmer Land[120]. The Devonian–Carboniferous Target Hill metamorphic complex[121] is marked by magmatism at ~399 Ma and a metamorphic event at ~330 Ma (REF.[120]). Granodiorite basement gneiss dated at 349 ± 4 Ma outcrop on Thurston Island[117] and rare outcrops in South America have been dated to 346 ± 4 Ma (REF.[122]).

However, despite their lithological similarities to elsewhere on the Antarctic Peninsula, Devonian magmatism and Carboniferous metamorphism are now thought to be restricted events[119]. Together, these rocks form a long but discontinuous record of ongoing magmatism along the Antarctic Peninsula throughout the Paleozoic.

Carboniferous to Permian arc development. The >5-km-thick metasedimentary Trinity Peninsula Group (TPG) marks the onset of sedimentation on the Antarctic Peninsula (FIG. 2), beginning during the Late Carboniferous and continuing during the Permian[123]. The TPG was deposited in a supra-subduction setting during the early stages of subduction development and might result from debris flows and slides at the continental margin[123]. A potential correlative of the TPG is the Scotia metamorphic complex of the South Shetland Islands[124], which would indicate that subduction was ongoing along the Antarctic Peninsula at this time.

The Devonian FitzGerald Bluffs quartzite beds in southern Palmer Land are a stable margin sequence and, hence, distinct from the active continental margin sedimentary units elsewhere on the Antarctic Peninsula[125]. It has been suggested that, along with the younger (Permian) Erewhon Beds, these rocks are more comparable to the Ellsworth–Whitmore Mountains sequences and formed on a far-travelled block that originated inboard from the margin[125].

During the Permian, distinct episodes of granitoid magmatism and metamorphism at ~270 and ~255 Ma occurred across large parts of the Antarctic Peninsula[119]. A similar age distribution is also recorded from the North Patagonian Massif (280–250 Ma)[122], where Permian granitoid magmatism is extensive. Investigations of the detrital zircon population from the TPG of northern and eastern Graham Land show that it is dominated by Permian ages, with three prominent peaks between 285 and 260 Ma (REFS[75,126]) (BOX 3). The upper Permian Erewhon Beds of southern Palmer Land are thought to be derived from silicic volcanic rocks[127] and also to include peaks in zircon ages of 263 and 275 Ma, indicating that Permian arc volcanism (the Choiyoi province in Patagonia and the Antarctic Peninsula) extended into the southern Antarctic Peninsula and likely into MBL[125]. Analysis of detrital zircons from the Duque de York Complex of Patagonia[128] with a similar age profile to the TPG, and of Permian rocks in New Zealand with abundant ~250-Ma zircons[129], highlight the extensive nature of this magmatic event along the Gondwanide margin. However, although a Permian flare-up in magmatism is seen along the margin, geochemical analyses suggests that, in contrast to New Zealand and MBL, the South American and Antarctic Peninsula subduction zone was advancing in Permian times and led to magmatism dominated by continental crustal recycling[9].

Triassic magmatism is essentially absent in northern Graham Land but is prevalent in southern Graham Land[119], Palmer Land[120,130] and continues into the Thurston Island crustal block[117], with magmatism in the interval 240–220 Ma. The primary Triassic magmatic lithologies are granodiorite-tonalite gneisses and migmatites that have been attributed to emplacement in a convergent continental margin arc setting. Coincident with Triassic magmatism, the LeMay Group of Alexander Island was deposited in a deep-water fan setting as part of the outboard accretionary complex[123,131], similar to the Triassic Torlesse rocks in New Zealand[132] (FIG. 3a).

Supra-subduction
Being in a position overlying the subducting slab in a subduction zone system.

Jurassic to Cretaceous peak of arc magmatism. The Jurassic to Cretaceous period shaped the geological setting of the Antarctic Peninsula and reflects an episode of notable tectonic, magmatic and depositional evolution. Early Jurassic magmatism across the Antarctic Peninsula is represented by two contemporaneous but distinct magmatic events that developed in different tectonic settings. First, the felsic volcanism of the Chon Aike silicic LIP present across Patagonia and the eastern Antarctic Peninsula[133] (FIG. 3a). This LIP is characterized by three distinct volcanic episodes, or 'flare-ups' (BOX 3), at ~185, ~170 and ~155 Ma, and is associated with notable crustal melting[134]. The earliest episode of this silicic magmatism is coeval with the mafic Karoo–Ferrar LIP and is thought to result from intra-arc extension and heating by peripheral plume activity during the initial stages of West Gondwana break-up[135]. The later episodes of Jurassic silicic volcanism are linked to extension within a more typical destructive plate margin setting[134]. The second key magmatic event was coeval granitic magmatism recognized from multiple sites along the Antarctic Peninsula and Patagonia dated in the interval 188–180 Ma (REFS[136,137]). This magmatic event is represented along the Antarctic Peninsula by moderate to strongly foliated granitoids[136]. In contrast to the volcanic sequences, geochemical data from Patagonia suggest that the granitoid rocks were derived from subduction-related melting, confirming that subduction was ongoing at the time of extension-related silicic LIP volcanism[117,136,137].

The Early Jurassic saw the development of two distinct sedimentary depocentres to the east and west of the Antarctic Peninsula. East of the Antarctic Peninsula, the Larsen and Latady Basins developed as a result of continental rifting and back-arc extension during the early stages of Gondwana break-up and record sedimentation from Jurassic to Cretaceous times[138,139]. The more northerly Larsen Basin records a largely terrestrial syn-rift megasequence, correlated with the Magallanes Basin of southern South America and a marine-dominated post-rift megasequence. The Latady Basin to the south preserves a sedimentary succession several kilometres in thickness, recording sediment deposition from ~185 to ~150 Ma and a shift from a terrestrial to a shallow marine setting[139,140]. Broadly coeval with the early development of the Latady Basin is the emplacement of a ~1-km succession of 180–177-Ma basaltic lavas close to the east coast of the Antarctic Peninsula[55,141]. Geochemical signatures indicate that these basalts were emplaced in a back-arc setting likely associated with the development of the adjacent Weddell Sea rift system[43,141]. An extensional regime associated with ongoing subduction was, therefore, present during the Early Jurassic.

West of the Antarctic Peninsula, the Fossil Bluff Group preserves an Early Jurassic through to mid-Cretaceous volcanic-sedimentary sequence >8 km thick[142]. The sequence unconformably overlies the Triassic LeMay Group accretionary complex and is one of the most complete fore-arc successions in the world. Correlative volcaniclastic successions on Adelaide Island dated to 150–120 Ma (REF.[119]) indicate that the fore-arc continues north of Alexander Island. The volcaniclastic sediments and conglomerates of the upper parts of the Fossil Bluff Group eroded from the main volcanic arc, indicating coeval volcanic activity. This sedimentary source implies that Alexander Island was not far from the magmatic arc at this time[116], and a model of far-travelled terrane accretion for the Mesozoic Antarctic Peninsula may not be applicable here[11].

The Cretaceous represents the main phase of continental margin arc magmatism across the Antarctic Peninsula and Thurston Island (FIG. 4c). Mid-Cretaceous magmatism is widespread along the entire proto-Pacific margin of Gondwana at a time of global plate reorganization (BOX 3). The Lassiter Coast intrusive province along the eastern margin of Palmer Land shows voluminous intrusive magmatism demonstrated to have developed with three distinct flare-ups at ~125, ~115 and ~105 Ma (REF.[143]). A major magmatic episode in the Andean Cordillera, further along the margin from West Antarctica, also comprises three flare-up events in the interval 130–105 Ma (REF.[144]). Cretaceous magmatism on Thurston Island[117,145] and in MBL[82,83] also occurred around 110–95 Ma, but Cretaceous magmatism on Thurston Island is not as extensive as on the Antarctic Peninsula[143]. The arc volcanic record during the Cretaceous is less well documented than the plutonic record, but mid-Cretaceous volcanism is recorded from central and western Palmer Land[146,147].

One of the main tectonic events to affect the geology of the Antarctic Peninsula was the two-phase mid-Cretaceous Palmer Land event[116,148]. Phase 1 at ~107 Ma was a sinistral transpressional event that is well developed in southern Palmer Land, whereas phase 2 at ~103 Ma was a dextral transpressional event. Aeromagnetic data confirm that distinct central and eastern domains are present in Palmer Land[149] (BOX 2b). While geological evidence of deformation suggest that these domains collided[116], these provinces were likely not far travelled[11].

The Cretaceous sequences also include records of magmatism and sedimentation in the northern Antarctic Peninsula, particularly the South Shetland Islands and James Ross Island (FIG. 1b). The South Shetland Islands' Lower Cretaceous is dominated by the 2.7-km-thick intra-arc succession of the Byers Group[150], which consists of basaltic to silicic volcanic and volcaniclastic rocks. The Upper Cretaceous successions of James Ross Island, collectively referred to as the Gustav Group, form a >2-km succession of coarse-grained, marine siliciclastic sediments and volcanic rocks reflecting deposition on slope aprons and deep-water fans.

Transpressional
Having undergone simultaneous strike–slip and compressive deformation.

Hyaloclastite
Volcaniclastic breccia emplaced in a submarine or subglacial setting.

Decline of Cenozoic arc magmatism. From the Late Cretaceous to the Neogene, the collision of spreading ridge segments at the continental ocean boundary triggered the progressive shutdown of subduction along the Antarctic Peninsula margin from south to north[151]. Arc magmatism finally ceased on the Antarctic Peninsula at ~20 Ma on the South Shetland Islands, even though subduction still continues today. This ongoing subduction has led to rifting along the Bransfield Strait at ~10 Ma, which split the Pacific margin magnetic anomaly (BOX 2) and is associated with ongoing alkaline magmatism on the South Shetland Islands[152]. Contemporaneous with Cenozoic magmatism, extension between South America and the Antarctic Peninsula, coupled with back-arc extension of the Scotia subduction zone, led to the opening of the Drake Passage at ~34 Ma (REF.[153]), which permitted the development of the Antarctic Circumpolar Current.

Neogene magmatism on James Ross Island and neighbouring islands is characterized by lava-fed deltas, basaltic lavas, tuffs, and hyaloclastite breccias emplaced in a primarily subglacial setting[154]. The James Ross Island volcanic group, which forms the largest Neogene volcanic field on the Antarctic Peninsula and extends over 7,000 km^2, comprises a major shield volcano on James Ross Island and multiple satellite volcanoes. This late-stage volcanism has been associated with a deep thermal anomaly attributed to a slab window generated by the cessation of subduction[155]. Although post-subduction magmatism occurred, the extent of tectonic reactivation is limited, especially in comparison with the hyper-extended MBL and WARS region. This means that the Antarctic Peninsula remains as one of the best-preserved magmatic arcs on the planet.

Conclusions

This Review highlights the diverse nature of the West Antarctic region. Its different provinces reflect the impact of distinct tectonic processes, but all relate to the ongoing evolution of the Paleo-Pacific margin. The thin crust and extensive magmatism attest to the repeated tectonic reworking that has created, moved and overprinted every part of the system over the last ~500 million years. Today, most of the region is blanketed by ice, but, together, geological analysis of the exposed rocks and geophysical observations are revealing the complex history of the region.

West Antarctic tectonic evolution summary. In summarizing the evolution of West Antarctica, we consider it as an evolving tectonically active margin from ~500 Ma. The earliest rocks in West Antarctica are sedimentary sequences laid down ~500 Ma along an active margin facing the Pacific Ocean[72]. Subduction along the entire margin of West Antarctica had commenced by the Ordovician (488–444 Ma) and continued to the Permo-Triassic (~250 Ma)[3,66,74,119] (FIG. 4a). From Ordovician times, the Antarctic Peninsula was closest to the trench and marked by almost continuous magmatism[119,120]. MBL and the proto-WARS lay inboard of New Zealand and the Campbell Plateau; hence, arc magmatism appears to have been less prevalent than on the Antarctic Peninsula. A retreating subduction zone in the MBL sector, rather than an advancing subduction system as in the Antarctic Peninsula, may have favoured the development of more juvenile magmatism in MBL[9] relative to the Antarctic Peninsula. The Ellsworth–Whitmore

Mountains province (the most inboard province) only received notable magmatic input of ash-fall sediments in the Permian, during a major flare-up in magmatism along the margin[125]. The Permian to Triassic also saw deformation of the Ellsworth–Whitmore Mountains province, which was potentially driven by changes in the outboard subduction system[5].

The Jurassic marks the point where the tectonic setting of different provinces began to clearly diverge (FIG. 4b,c). Extensive magmatism in the Antarctic Peninsula has a variety of drivers, including ongoing subduction, potential interaction with a mantle plume and back-arc extension in the Weddell Sea rift system[55,134]. In the Ellsworth–Whitmore Mountains[44], intra-plate granites, some of which are localized along the boundary with East Antarctica[53], show that this block was being translated along the edge of the East Antarctic Craton, which facilitated back-arc extension in the Weddell Sea rift system[43]. Although MBL is associated with limited magmatism at this time, a major flare-up in magmatism occurred[82,83,143] by the mid-Cretaceous. Initially, the Cretaceous magmatic events appear synchronous along the margin and are attributed to arc magmatism along a common and extensive subduction system. However, cessation of subduction outboard of MBL from ~100 Ma, potentially due to jamming of the subduction zone by a spreading ridge or the Hikurangi Plateau, dramatically changed the tectonic regime in this part of West Antarctica[7,94]. Extensive magmatism occurred and was associated with 600 to 1,000 km of extension across MBL and the WARS, leading to crustal thinning and exhumation of lower crustal rocks[79,80,97].

From the Late Cretaceous, MBL and the WARS evolved as a passive margin, reactivated by renewed continental rifting 43–26 Ma (REF.[156]) and by upwelling hot mantle that triggered sparse but widespread mafic volcanism[91,105]. In contrast, arc magmatism progressively ceased beginning ~90 Ma from south to north along the Antarctic Peninsula due to collision of the Phoenix spreading centre with the trench[151]. The main phase of Phoenix plate subduction ceased by ~20 Ma, with localized subduction and limited back-arc spreading confined to the tip of the Antarctic Peninsula today[152]. Unlike MBL and the WARS, post-subduction magmatism on the Antarctic Peninsula was limited to a few volcanic centres, and post-subduction extension also appears to have been limited[155].

Broader implications. The tectonic and geological evolution of West Antarctica illustrates the complexity of convergent continental margins, with the hyper-extended MBL and WARS region standing in contrast to the well-preserved magmatic arc along the Antarctic Peninsula. The long-lived nature of subduction in the West Antarctic region resulted in multiple magmatic and tectonic events that provide rich insights into the metamorphic and tectonic processes that contribute to the geological evolution of marginal systems. For example, West Antarctica reveals the episodic nature of magmatic events in these convergent systems and demonstrates that these events appear to be synchronous along large parts of the entire margin. These observations highlight the fact that processes acting on a global-plate-tectonic scale can have a direct local influence.

Future challenges in West Antarctica. West Antarctica preserves a diverse record of the ~500-million-year evolution of a tectonically active continental margin and could, thus, provide key insights into how tectonic processes operate along this type of margin, in the geological record and today. Despite substantial advances in our understanding of how the West Antarctic evolved, large gaps in knowledge remain. The most fundamental gap is whether West Antarctica is best conceived as an accreted collection of rigid microcontinental blocks (as commonly depicted)[40] or as a plastically deforming and constantly growing melange of continental fragments and juvenile magmatic regions. This is essential to how we understand and describe the tectonic evolution of young continental lithosphere. New modelling techniques, such as finite-element modelling, have the potential to better describe the evolution of this system. For these models to be robust, more detailed geophysical and geological studies are required. Geophysical data can provide new constraints on the extent of magmatism and the areal extent and geometry of the underlying provinces, and geological observations and dating provide information about how and when the different components of the system were active. Going forward, defining the underlying geological template of West Antarctica and constraining its linkages to the dynamics of the overlying ice sheet, which is vulnerable to change due to human activity, are more important than ever.

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