

Geological evolution of the Prydz Bay-Prince Charles Mountains region, East Antarctica: advances and prospects

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Abstract The Prydz Bay-Prince Charles Mountains region in East Antarctica constitutes an exceptional geological transect for investigating continental evolution from the Archean to the Phanerozoic and its relationship with supercontinent cycles. This region preserves a complex record of magmatism, metamorphism, and tectonic reworking. Studies by the Chinese National Antarctic Research Expeditions in this region have yielded critical insights into the geological evolution of Antarctica. Key advances over the past decades encompass the elucidation of the Pan-African and Grenvillian tectono-metamorphic history, the delineation of the continent's crustal and lithospheric architecture, and the identification of extensive ultrahigh-temperature metamorphism and rare mineral assemblages. Despite these advances, many fundamental questions remain unresolved. The spatial and temporal extents of ancient orogenesis are poorly constrained across different crustal blocks, and the tectonic drivers of extreme metamorphism continue to be debated. The role of deep lithospheric architecture in controlling both past orogenic processes and present-day glacial isostatic adjustment remains underexplored. Furthermore, the origins of ancient cratonic nuclei and their constraints on early Earth geodynamics warrant further investigation. Future research should prioritize integrated, multi-disciplinary approaches that combine geological and geophysical analyses. Key objectives include delineating the architecture and evolution of subglacial basement, reconstructing the Phanerozoic uplift and erosion history of the orogens, and evaluating feedback mechanisms among lithospheric evolution, ice-sheet dynamics, and long-term climate. Holistic cross-disciplinary investigations will be essential to unravel the connections between deep Earth processes and surface systems in one of the planet's most enigmatic and geologically significant regions.

Keywords Antarctica, geology, orogen, subglacial basement, lithospheric architecture

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1 Geology of the Prydz Bay-Prince Charles Mountains region: coast and hinterland

Antarctica preserves Earth's ancient continental records, archiving critical evidence of fundamental planetary evolution events. The Transantarctic Mountains (TAM) are one of Earth's great mountain belts and a fundamental physiographic feature of Antarctica, dividing the thick cratonic lithosphere of East Antarctica from the thinned crust and warm upper mantle of an extensional province referred to as the West Antarctic Rift System (WARS) (Goodge, 2020; Figure 1). The modern TAM experienced significant uplift during the Late Mesozoic to Early Cenozoic, broadly synchronous with extension in the WARS, suggesting a genetic relationship between mountain

uplift and rift development. The WARS has undergone a prolonged history of extension, initiating with Jurassic rifting between East and West Gondwana, followed by Cretaceous stretching between East and West Antarctica (~150–100 Ma) (McFadden et al., 2010), then Late Cretaceous opening of the Ross Sea and separation of New Zealand crustal blocks (~83 Ma) (Eagles et al., 2004; McAdoo and Laxon, 1997; Mortimer et al., 2019), and finally culminating in focused Cenozoic extension and associated volcanism in the western Ross Sea (Artemieva and Thybo, 2020; Behrendt, 2013; Jordan et al., 2020). The Prydz Bay-Prince Charles Mountains region in the East Antarctica is composed of diverse terranes and crustal units with distinct formation and evolution histories. These geological records provide opportunities to decipher the formation of Antarctica and its correlations with key global events.

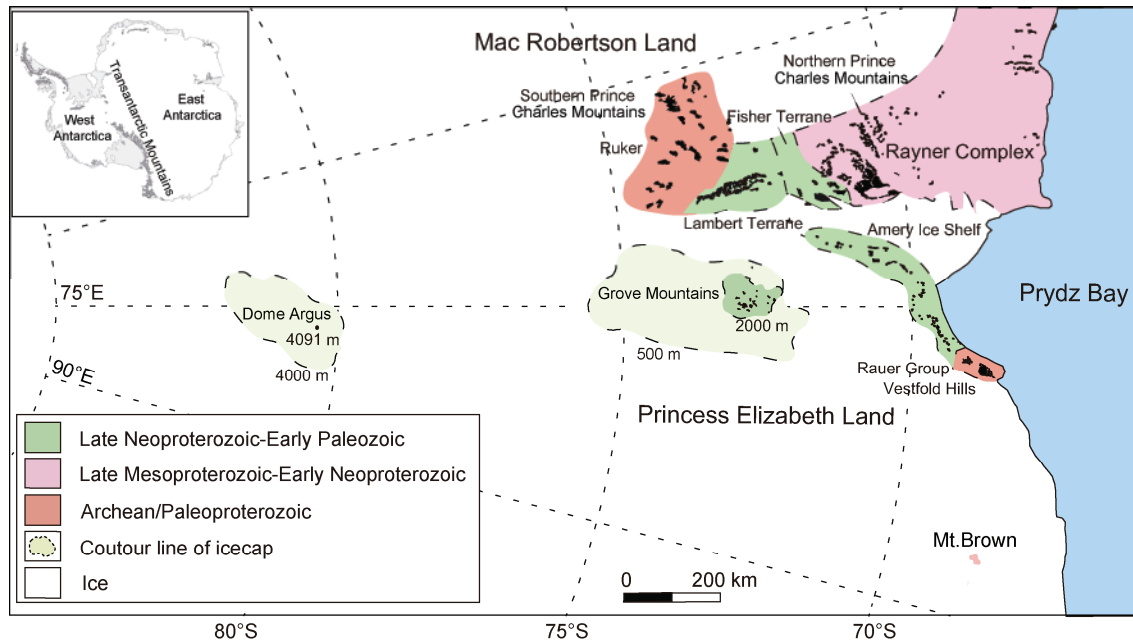


Figure 1 Geological sketch of the Prydz Bay-Prince Charles Mountains region (modified after Fitzsimons, 2003; Kamenev et al., 1993; Liu et al., 2014; Wang et al., 2022).

1.1 Geological units in the Princess Elizabeth Land

1.1.1 Major geological units in the coastal region of the Prydz Bay

In the Princess Elizabeth Land, the major bedrocks exposures along the coast of the Prydz Bay involve the Vestfold Hills, the Rauer Islands, the Larsemann Hills, the Bølingen Islands, the Søstrene Islands, and the islands and nunataks in eastern Amery Ice Shelf region (Carson et al., 1996; Dirks et al., 1994; Harley, 1987; Zhao et al., 2003). The Vestfold Hills represent a predominantly Archean terrain composed mainly of orthogneisses, with minor paragneisses and mafic dykes (Clark et al., 2012; Liu X C et al., 2013, 2023; Liu Z et al., 2024; Mikhalsky et al., 2019).

To the southwest of the Vestfold Hills, the Rauer Islands comprise both Archean (outcropping in the east and south) and Proterozoic rocks (Kinny et al., 1993; Tong and Wilson, 2006). The Archean component consists primarily of felsic orthogneisses accompanied by minor metapelites, quartzites, and marbles. The Larsemann Hills feature high-grade metamorphic rocks (amphibolite to granulite facies) (Carson et al., 1996; Grew et al., 2012; Tong et al., 2014, 2017; Wang et al., 2022; Zhao et al., 1993). Its northern basement is dominated by mafic and felsic orthogneiss, overlain by cover sequences of extensively migmatized paragneiss that underwent significant partial melting. The region also includes distinctive boron- and phosphate-rich rock units (Carson et al., 1995; Grew et al., 2013; Ren et al.,

1992). In the eastern Amery Ice Shelf region, the basement outcrops are limited within the nunataks. The rock types in this region include high-grade metamorphic rocks, charnockites, and granites. The high-grade metamorphic rocks consist mainly of orthopyroxene-bearing orthogneisses, with subordinate paragneisses, quartzite, and mafic granulite (Sheraton et al., 1984).

1.1.2 The Grove Mountains in the hinterland

The Grove Mountains, located >300 km inland from Prydz Bay and ~200 km eastwards from the southern Prince Charles Mountains (PCM), are among the few exposed outcrops in East Antarctica's interior. The Grove Mountains comprise 64 nunataks exposed across a 3,200 km² ice-covered area (Zhao et al., 2000). The region is dominated by high-grade metamorphic rocks and granitoids, with felsic gneiss as the predominant rock type, intercalated with minor mafic and pelitic granulites, paragneiss, and scapolite-bearing calc-silicate rock (Liu et al., 2002, 2006, 2007, 2009). In the eastern nunataks (e.g., Mount Harding and Zakharoff Ridge), the outcrops are mainly composed of leucocratic granulites and charnockites, interlayered with minor dark bands of plagioclase-amphibolitic gneiss. The western nunataks (e.g., Melvold Nunataks, Mason Peaks, Truman Peaks, and Black Peaks) are dominated by medium- to coarse-grained gneisses, with minor leucocratic granulite bands and thin, melanocratic layers or lenses of mafic or pelitic granulites. The basement of the Grove Mountains formed in the early Neoproterozoic (~920–910 Ma) (Harley et al., 2013; Hensen and Zhou, 1995; Liu et al., 2006, 2007) and underwent a single-period metamorphic event at ~570–500 Ma (e.g., Liu et al., 2009; Mikhalsky et al., 2001). Several mafic and pelitic granulites from glacial moraines in the Grove Mountains reached high-pressure granulite facies conditions (770–840 °C, 1.18–1.40 GPa), following a clockwise P–T evolution (Chen et al., 2018; Liu et al., 2009). A-type charnockite and granite sheets, emplaced during the syn- to post-orogenic stages, have been interpreted as products of partial melting (Liu et al., 2006, 2007).

1.1.3 The Gamburtsev Subglacial Mountains (GSM)

The GSM form a high-relief alpine mountain range (Cui et al., 2010; Lea et al., 2024; Rose et al., 2013; Sun et al., 2009) that is entirely buried beneath Dome A, the summit of the Antarctic Ice Sheet. Bounded by the Lambert Graben to the north and the South Pole Province to the south (Ferraccioli et al., 2011), the GSM represents a major mountain range in central East Antarctica. Despite its size, the deep structure and geological history of the range remains poorly understood (Daczko and Halpin, 2025; Fitzgerald and Goodge, 2022; Veevers, 2018). Divergent mechanisms have been proposed to explain the formation of the GSM. These mechanisms involve geologically recent thermal uplift associated with mantle hot spot activity (Sleep, 2006), ancient orogeny in a continental collision

zone (Fitzsimons, 2000, 2003), crustal shortening in response to long-distance stress transmission (Veevers, 1994), and uplift associated with rifting during continental breakup (Ferraccioli et al., 2011). Coastal and offshore sediments of GSM provenance from the PCM and Prydz Bay likely have been used to date the formation, yielding ages primarily of ~1,200–800 Ma and ~620–460 Ma (Van De Flierdt et al., 2008; Veevers and Saeed, 2008; Veevers et al., 2008), with a potential additional period at ~700 Ma (Gupta et al., 2022). More recently, dates from rock clasts in the TAM, which may have been transported there subglacially from the GSM, indicate crustal formation spanning the period of ~2,000–1,100 Ma (Goodge et al., 2017) and a period of rapid cooling at ~500 Ma, pointing to exhumation and thus East Antarctic orogeny around this time (Fitzgerald and Goodge, 2022).

1.2 The PCM in the Mac Robertson Land

In the Mac Robertson Land to the southwest of the Prydz Bay, the major exposure involves the PCM. From north to south, PCM can be divided into the Neoproterozoic-Mesoproterozoic Rayner Complex, the Mesoproterozoic Fisher Terrane, the Paleoproterozoic Lambert Terrane, and the Archean Ruker Terrane (Gupta et al., 2022; Liu et al., 2013, 2017; Mikhalsky et al., 1996; Morrissey et al., 2016; Zhang et al., 2025). These tectonic units record multiple stages of tectono-metamorphic and magmatic events from the Archean to the Neoproterozoic, which are linked to the formation of the Antarctic basement and the evolution of supercontinents and even early Earth's crust. The Rayner Complex is mainly composed of felsic-mafic orthogneisses interlayered with paragneisses, as well as granites and charnockites that have Nd model ages of ~2.2–1.6 Ga (e.g., Halpin et al., 2013). In the Mac Robertson Land region, regional granulite-facies metamorphism and extensive granite emplacement occurred at 1,000–970 Ma, followed by deformation and minor magmatic activity between 940–900 Ma (Boger et al., 2000; Halpin et al., 2007, 2013; Kinny et al., 1997). Locally, some mylonite zones and pegmatite dikes preserve evidence of Pan-African event (Boger et al., 2001). The Fisher Terrane is mainly composed of orthogneisses, calc-alkaline volcanic rocks and metasedimentary rocks that underwent amphibolite facies metamorphism at 1,020–940 Ma, which is attributed to the Grenvillian orogeny (Boger et al., 2000; Mikhalsky et al., 1999, 2001). In addition, a Pan-African overprint has been separately identified in the metapelitic rocks (De Vries Van Leeuwen et al., 2019). The Lambert Terrane is composed of Paleoproterozoic orthogneisses, metasedimentary rocks, and minor granite dikes, which preserve records of Grenvillian magmatic-metamorphic events. The peak metamorphic conditions of these events are constrained to 0.5–0.7 GPa and 750–810 °C (Corvino et al., 2011; Phillips et al., 2009). Pan-African period overprinting metamorphism and granite intrusion has been identified in the southern orthogneisses, with peak

conditions of 0.6–0.7 GPa and 630–700 °C accompanied by a clockwise retrograde decompression path (Boger and Wilson, 2005; Phillips et al., 2009). The Ruker Terrane comprises the Archean Ruker Complex and Proterozoic metasedimentary sequences. The Archean Ruker Complex mainly consists of 3,390–3,370 Ma tonalitic-trondhjemitic orthogneisses, 3,190–3,150 Ma granitic orthogneisses, and post-3,150 Ma metasupracrustals (Mikhalsky et al., 2010; Phillips et al., 2006, 2007). The basement of Ruker Complex underwent an orogenic event at ca. 2,800 Ma (Boger et al., 2006; Mikhalsky et al., 2006; Phillips et al., 2006). The diverse Archean to Paleozoic metamorphic and magmatic record of the PCM holds the key to addressing major unresolved scientific issues.

2 Key geological issues in the region

2.1 Antarctica's role in the supercontinent reconstruction

Research into supercontinent cycles is essential to advancing our understanding of plate tectonic evolution, mantle convection patterns, and global resource distribution (Goodge et al., 2008; Zhao et al., 2018). Supercontinents provide the essential framework for reconstructing Earth history (paleogeography and stratigraphic correlation) and deciphering the large-scale backdrop for climate-biota co-evolution (Jordan et al., 2020; Rogers and Santosh, 2009). Antarctica's geological record (rock assemblages, structures, paleomagnetic data, etc.), spanning from the Archean to the Cenozoic, holds a key to understanding the evolution of supercontinents, including the Paleoproterozoic Kenorland, the Early Neoproterozoic Rodinia and Late Neoproterozoic Gondwana (sub-) supercontinent. Particularly, as the core component of the Gondwana (sub-) supercontinent, the East Antarctica offering a unique perspective on testing and refining the reconstruction models (Boger, 2011; Mulder et al., 2019).

2.2 Orogenic evolution and environmental effects

The evolution of ancient orogenic belts, the fossilized roots of long-vanished mountain ranges, represents a fundamental archive of Earth's dynamic crustal processes. These orogenic belts record profound crustal thickening, high-grade metamorphism, and extensive magmatism. Their evolution profoundly influences the crustal architecture, resource distribution, environmental evolution, regional to global climate patterns, geomorphology, and geohazard distribution, making them key areas for studying deep-seated to surficial process coupling (Huang et al., 2023). In the Prydz Bay region, the geological records reveal multiple orogenic processes, though the tectonic nature of each orogenesis remains controversial (Black et al., 1987; Fitzsimons, 2000; Harley, 1987; Sheraton et al., 1984; Tong et al., 2019; Zhao et al., 1993, 1995, 2003). The uplift and erosional unroofing of these orogenic belts (i.e.

mountain chains) had a transformative impact on the planet's environment. The immense chemical weathering of freshly exposed silicate rocks in these orogenic highlands is hypothesized to be a primary driver of global cooling events, such as the Neoproterozoic Snowball Earth episodes, through the drawdown of atmospheric CO₂ (Huang et al., 2016). Concurrently, the erosion transported vast quantities of nutrients such as phosphorus and iron into the oceans, potentially triggering biotic radiations by enhancing primary productivity (Spencer et al., 2022). Investigating the exposed and subglacial orogenic belts of East Antarctica offers new insight into global orogenesis, crustal evolution and maturation, and paleoenvironmental evolution (Fitzgerald and Goodge, 2022).

2.3 Crustal uplift and cooling history

Quantitative investigation of crustal uplift and cooling history, as well as its geomorphic response, using low-temperature (<300 °C) thermochronology, is critical to unraveling complex feedback mechanisms between tectonics, surface processes, and climate (Fitzgerald and Goodge, 2022; Thomson et al., 2013). In Antarctica, reconstructing bedrock uplift histories (e.g., through thermochronology of exposed bedrocks) is essential for understanding ice sheet stability, ice-tectonic interactions, and long-term climate evolution. The continent's unique cryosphere-dominated erosion regime provides an exceptional natural laboratory for studying tectonic-climatic-geomorphic feedback systems. Limited low-temperature thermochronology data from the East Antarctic basement suggest significant Paleozoic-Mesozoic cooling (Maritati et al., 2020). Despite containing East Antarctica's largest ice stream, the long-term landscape evolution of the Prydz Bay-Prince Charles Mountains region remains poorly understood (Siegert, 2008; Taylor et al., 2004), hindering our understanding of the formation and evolution of the East Antarctic Ice Sheet.

2.4 Archean cratons and early Earth crustal formation

Archean cratonic nuclei constitute the sole archive for investigating the origin, non-uniformitarian formation mechanisms, and stabilization processes of Earth's earliest continental crust (Foley et al., 2003; Pearson et al., 2021). East Antarctica preserves globally significant, minimally modified Archean crustal nuclei. The Napier Complex, the most ancient cratonic nucleus in East Antarctica, preserves some of Earth's oldest rocks, dating back to 3.8 Ga (Harley, 1985; Harley and Black, 1997; Kelly and Harley, 2005). The Archean nuclei in the Prydz Bay-Prince Charles Mountains region, including the Vestfold Hills, the Rauer Group, and the Ruker Terrane, preserve Archean rock records (>3.0 Ga), make it a critical area for investigating: (1) incipient continental growth dynamics; (2) primordial crustal composition and thermal regimes; and (3) emergence of early habitable environments (e.g., Phillips et al., 2006; Stagg et al., 2004).

2.5 Deep lithospheric architecture

The deep lithospheric architecture records the long-term formation, stabilization, and modification of continents, providing a key record of Earth's geological history. A better understanding of deep lithospheric architecture relies on advancements in geophysical approaches, including seismic, aeromagnetic, gravity, and radar investigations. High-resolution regional geophysical surveys play a critical role in resolving high-precision crustal and lithospheric structure beneath the icecap (An et al., 2015a), ancient terrane boundaries and sutures (Artemieva and Thybo, 2020), and deep-seated controls on magmatism and mineralization (Jordan et al., 2020).

2.6 Lithospheric contributions to glacial isostatic adjustment

As Earth's largest freshwater reservoir, the Antarctic Ice Sheet directly influences global climate systems and coastal security through its evolution. Research into cryosphere-lithosphere coupling represents a critical scientific imperative for evaluating future ice mass changes and their cascading environmental consequences worldwide (Taylor et al., 2004). The Antarctic Ice Sheet has experienced a negative mass balance, losing an average of $\sim 127 \text{ Gt}\cdot\text{a}^{-1}$ from 2002 to 2022 (Diener et al., 2021; Hanna et al., 2024). This mass loss and its environmental impacts are central to polar research. Glacial isostatic adjustment provides critical insights into ice sheet evolution, constrains mantle viscosity structure, and supports robust assessments of global sea-level change (Peltier, 2004). Short-term ice mass fluctuations (decades to centuries) reflect rapid solid Earth responses, directly affecting estimates of ice-sheet mass balance and sea-level rise. In Greenland and the Arctic area, significant progress in ice-sheet research benefits from basic geological constraints involving the evaluation of shorelines, sedimentary archives, ice-marginal landforms and mantle dynamics (Larsen et al., 2014; Lecavalier et al., 2014; Steinberger et al., 2019). Progress in Antarctic Ice Sheet research is limited by fundamental geological constraints, including those related to sedimentary sequences, lithospheric characteristics, and mantle processes.

2.7 Subglacial geomorphology and geological process

While limited outcrops can be used for studying of geological evolution in Antarctica, subglacial geomorphology derived from ice-penetrating radar survey provides valuable clues to infer ice sheet evolution and geological processes of the continent. Based on the detailed subglacial topography and classic alpine glacial geomorphology observed beneath Dome A, it is suggested that the landscape of the GSM originated during the initial phases of Antarctic glaciation (at least 34 Ma ago), and that the high elevation of the GSM provided the initial cold conditions for ice

accumulation (Sun et al., 2009). In the Aurora Subglacial Basin of East Antarctica, the fjord landscapes under the ice sheet with well-defined topographic channels and mountain block show a dynamic early East Antarctic Ice Sheet (Young et al., 2011). In Dronning Maud Land, a pre-existing fluvial landscape of high escarpment and branching network of valleys beneath the ice sheet was revealed and used to reconstruct the glacial erosion history (Eagles et al., 2018). Recently, SCAR Bedmap 3 Action Group has released the newly interpolated subglacial topography DEM of Antarctica, and previous data gaps in Princess Elizabeth Land and Recovery Glacier have been filled by ice-penetrating radar surveys (Cui et al., 2010; Pritchard et al., 2025). The Bedmap 3 gridded datasets, which characterize the subglacial geomorphology, will greatly advance research on the evolution of the Antarctic Ice Sheet and the continent's geology. However, large portions of the ice sheet still have overly coarse terrain details and significant uncertainties in bedrock elevation due to a lack of radar measurements.

3 Representative advances based on Chinese Antarctic expeditions

Over recent decades, investigations during Chinese expeditions to the Prydz Bay region have driven substantial advances in understanding the geological evolution of East Antarctica. Progress spans disciplines from mineralogy and metamorphism to structural geology and geophysics. In this section, we synthesize key representative achievements.

3.1 Identification of Pan-African high grade tectono-thermal event

Like many regions of the East Antarctic Continent, the Larsemann Hills and the broader Prydz Bay area have experienced granulite-facies metamorphism. Conventional wisdom has widely interpreted this high-grade metamorphic event as occurring during the Grenvillian period (1,100–1,000 Ma) (Fitzsimons and Harley, 1991; Grew et al., 2012; Sheraton et al., 1984; Stüwe and Powell, 1989; Stüwe et al., 1989). Based on Sm-Nd, zircon Pb/Pb, and biotite Ar/Ar geochronology, the high-grade granulite-facies metamorphism and associated anatexis and granites were attributed to a Pan-African tectono-thermal event, and thus establishing the first link to the final assembly of the Gondwana supercontinent (Zhao et al., 1992, 1993, 1995). As East Antarctica was a pivotal component of the Rodinia and Gondwana supercontinents, the findings fundamentally advance the understanding of the formation of the Antarctic continent and the paleogeographic reconstruction of the supercontinents (Boger, 2011; Mulder et al., 2015). Subsequent research in the Grove Mountains supports the extensive occurrence and significant influence of the Pan-African tectono-thermal event in this region (e.g., Hu et al., 2016; Liu et al., 2009; Zhao et al., 2000). The

identification of Pan-African high grade tectono-thermal event and its correlation with the Gondwana assembly, serve as one of the landmark achievements in the region since the Chinese expedition. However, the Grenvillian metamorphism was interpreted to be important in some localities in the Prydz Bay region (Clark et al., 2012; Kelsey et al., 2007; Tong et al., 2019, 2021; Wang et al., 2008; Zong et al., 2021). The nature and extent of the Grenvillian and Pan-African events across different terranes require further investigation.

3.2 Grenvillian orogenesis in the Rayner Complex

The Grenvillian Rayner orogen, comprising the Rayner Complex and the Eastern Ghats Belt, is considered to represent the collision of East Antarctica and India, based on metamorphic petrology and isotopic geochronology (Halpin et al., 2013; Kelly et al., 2002; Liu et al., 2020). However, the evolution history prior to continental collision, and the collision patterns remain controversial (Mikhalsky and Sheraton, 2011; Nasipuri et al., 2018). The geochemical characteristics of mafic granulites sampled from the eastern part of the Rayner Complex, extending from the margin of the Amery Ice Shelf to Prydz Bay, resemble those of Nd-enriched or typical island arc basalts (Liu et al., 2014). In contrast, felsic orthogneiss samples from the same region exhibit geochemical signatures consistent with continental volcanic arc granites (Liu et al., 2016, 2017).

The Rayner orogen exhibited two distinct metamorphic patterns in the Grenvillian period. Metamorphism during 1,000–970 Ma reached medium- to low-pressure granulite facies (~850 °C at ~0.7 GPa) and exhibited a near-isobaric cooling P–T path (e.g., Fitzsimons and Harley, 1994; Hand et al., 1994). In contrast, metamorphism during 960–900 Ma reached higher peak conditions (~870–990 °C, ~0.74–1.00 GPa) accompanied by a near-isothermal decompression path (Halpin et al., 2005; Kelly et al., 2002). Based on these findings, a long-lived Mesoproterozoic continental island arc system and a two-stage collision model between India and the East Antarctica from arc-continent collision to continent-continent collision have been established, enhancing the understanding of Grenville-aged tectono-thermal events in Antarctica and the evolution of the Rodinia supercontinent (Liu et al., 2021).

3.3 Identification of rare mineral assemblages

Located in the center of coastal region of the Prydz Bay, the Larsemann Hills contain a basinal sedimentary sequence, now largely represented by upper amphibolite to granulite facies pelitic, psammitic and felsic paragneisses (Carson et al., 1997). A rare assemblage of boron-bearing grandierite-kornerupine-tourmaline was first recognized in Stornes Peninsula of the Larsemann Hills (Ren et al., 1992; Wang et al., 2004). In addition, the special phosphate wagnerite (Ren et al., 2004) and related mineral assemblage (Grew et al., 2013) were successively identified. The composition and boron isotope data for those borosilicates

were reported, and the enrichment in boron and phosphorus of the granulite-facies paragneisses is attributed to premetamorphic hydrothermal alteration, either in a rifted, most likely marine basin, or in a mud volcanic system located inboard of a continental arc that was active along the leading edge of the Indo-Antarctic craton (Grew et al., 2013; Wang et al., 2004).

3.4 Crustal and lithospheric architecture of the Antarctic continent

Antarctica preserves critical records of fundamental Earth evolution events, yet its extreme environment has historically relegated key formation processes to speculative models. Recently, researchers have produced the first high-resolution models of the 3D velocity structure, crustal thickness, thermal architecture, and lithospheric thickness for the entire Antarctic Plate, including both the continent and surrounding oceans (An et al., 2015b). These results suggest that the thick-crustal subglacial mountains of East Antarctica represent a Pan-African orogen that marks the collision between the Australo-Antarctic and Indo-Antarctic blocks during Gondwana amalgamation (An et al., 2015a, 2015b, 2015c, 2016). Integrated geophysical modeling reveals that the GSM are supported by a dense lower crustal root and represent a Pan-African accretionary orogen thrust onto the Precambrian basement, providing a new mechanism for their uplift (Wu et al., 2023a, 2023b). Moreover, Fu et al. (2024) provide geophysical evidence for a sharp Moho offset and a conductive mantle channel in the Larsemann Hills, which was used to infer the collisional nature of the Prydz Belt in East Antarctica.

3.5 The progress in extreme metamorphism and tectono-thermal evolution in the Prydz Bay region.

Since the initial documentation of ultrahigh-temperature (UHT) metamorphism in Antarctica (Dallwitz, 1968), subsequent work has identified its occurrence in the Napier Complex, the Rauer Group in the Prydz Bay region, and other localities (Harley, 1998; Harley and Motoyoshi, 2000; Kelsey et al., 2003; Tong and Wilson, 2006). In the Rauer Group, however, UHT metamorphism has been documented primarily in local pelitic granulites (Harley, 1994, 1998; Tong et al., 2021). As a result, its full spatial extent and underlying tectonic driver are poorly constrained. Some studies attribute it to the Grenvillian period (~1,000 Ma), linking it to collisional orogenesis and arc magmatism; others, however, argue for a Pan-African age (~590 Ma or ~530 Ma), associating it with the Prydz Orogeny and the final assembly of Gondwana (Clark et al., 2019; Dirks and Wilson, 1995; Harley, 1998; Hokada et al., 2016; Kelsey et al., 2007; Sims et al., 1994; Tong and Wilson, 2006; Wilson et al., 2007). Based on detailed petrological, thermodynamic and geochronological analyses, Pan-African UHT metamorphism was confirmed and identified in the

Larsemann Hills to the southwest of the Rauer Group (Wang et al., 2022). The confirmation of new occurrences of UHT metamorphism in the Prydz Bay region implies that this phenomenon may be regional in extent, rather than being limited to a specific lithology at a single locality. This was supported by subsequent study in the Rauer Group which reported the UHT conditions of mafic granulites (Chen et al., 2023). Additionally, Liu Z et al. (2023) constrained the composition of anatectic melts generated under UHT conditions through the investigation of melt and fluid inclusions in Mg-rich pelitic granulites from the Mather Peninsula of the Rauer Islands, East Antarctica. These findings collectively suggest a much wider distribution of high heat flow and provide critical constraints on the thermal evolution of the hot crust of ancient orogenic belt.

3.6 Archean crustal components in the glacial moraines in the Vestfold Hills

Archean continental nuclei represent fragments of Earth's earliest continental crust. Previous studies reveal a few distinct Archean nuclei in the Prydz region, in which the Vestfold Hills is a unique Neoproterozoic/Paleoproterozoic terrane composed primarily of 2.52–2.48 Ga tonalitic gneiss and Neoproterozoic metamorphic supracrustal rocks (Black et al., 1991; Clark et al., 2012; Oliver et al., 1982). Inherited or detrital zircons of Early Archean Age were reported in the Neoproterozoic orthogneiss and metasedimentary rocks (Clark et al., 2012). In the southeastern Vestfold Hills, a series of glacial moraines are present along the margin of the ice sheet. Lithologies involving orthogneiss, high-grade metamorphic rocks, and low-grade metamorphic volcanic rocks and sedimentary rocks were recognized from the moraines. LA-ICP-MS detrital zircon U-Pb age analyses of representative sedimentary gravel samples demonstrate that the U-Pb ages of the detrital zircons are predominantly in between 2,410 Ma and 2,600 Ma, and 3,340 Ma and 3,500 Ma, without the apparent metamorphic ages of 1,000 Ma or 500 Ma (Liu et al., 2011; Zhao et al., 2007). Further analyses reveal some magnetite also yielded Archean ages (Zhao et al., 2019). Recently, two types of magnetite quartzite (banded iron formation, BIF) were identified from the glacial moraines and the ages of the BIF were inferred to be Archean (Wang et al., 2023). The findings imply that to the southeast of the Vestfold Hills there may exist an Archean continental nucleus.

4 Future research prospects

The Prydz Bay-Prince Charles Mountains region encompasses diverse terranes and crustal units with distinct magmatic and metamorphic histories. These well-preserved geological records provide a critical foundation for investigating the tectonic evolution of Antarctica and its connections to key global events. Nevertheless, despite

considerable advances, many key geological terranes/units have not been well investigated due to logistical and analytical limitations. Consequently, the related fundamental geological issues remain unresolved, underscoring the need for renewed research efforts. Future investigations should prioritize the following aspects: (1) elucidating the nature and extent of orogenesis across different geological periods and constraining its correlation with the supercontinent cycle; (2) deciphering the evolution of giant orogenic belts and their resource and environmental effects; (3) refining the deep lithospheric architecture through integrated geological and geophysical analyses; (4) investigating landscape evolution and its potential climate feedbacks; (5) decoding the origins of Archean cratonic nuclei and early Earth geodynamic regimes; and (6) unraveling lithospheric controls on glacial evolution. Substantial advances will require an Earth system perspective that accounts for the complex feedbacks among the solid Earth, surface environment, ice sheets, and climate. Achieving this goal relies on multidisciplinary data that integrate geology, geophysics, remote sensing, and other disciplines.

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