Preface of the special issue on 'ANTARCTICA'

Recent advances in mineralogy, petrology, geochemistry, and geochronology in East Antarctica

Tomokazu HOKADA[*,**], M. SATISH-KUMAR[***] and Tetsuo KAWAKAMI[†]

[*]*National Institute of Polar Research, Tokyo 190-8518, Japan*
[**]*Polar Science Program, Graduate Institute for Advanced Studies, SOKENDAI, Tokyo 190-8518, Japan*
[***]*Department of Geology, Faculty of Science, Niigata University, Niigata 950-2181, Japan*
[†]*Department of Geology and Mineralogy, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan*

A prolonged crustal history from Archean through Proterozoic to Cambrian, spanning more than half of the Earth's evolution through time is preserved in the rock record in East Antarctica. Geological field studies have been conducted in Dronning Maud Land and Enderby Land of East Antarctica as part of the scientific program of Japanese Antarctic Research Expedition (JARE). Late Neoproterozoic to Cambrian (>600-520 Ma) high-grade metamorphic terranes, developed as major orogenic belts during the Gondwana supercontinent formation, are recognized in central Dronning Maud Land, Sør Rondane Mountains, Belgica and Yamato Mountains (Yamato-Belgica Complex), Lützow-Holm Bay-Prince Olav Coast region (Lützow-Holm Complex) to western Enderby Land (Western Rayner Complex) over 2000 km from west to east along the coast-inland of the Antarctic continent. Relatively narrow and sporadic Meso-Neoproterozoic (1000-900 Ma) high-grade blocks (Hinode Block and Niban-nishi Rock - granulite-facies; Akebono Rock - amphibolite-facies) are identified in Prince Olav Coast geographically within the Lützow-Holm Complex. Archean high-grade-UHT granulites and gneisses of the Napier Complex represent the largest regional terrain covering 400 × 200 km^2 area in Enderby Land, along with widespread Meso-Neoproterozoic granulite-facies zone of Rayner Complex from Enderby Land through Kemp Land, McRobertson Land toward east to Prydz Bay region. Thus, the continental crustal domain investigated by the Japanese Antarctic expeditions is key in understanding the Archean-Proterozoic-Cambrian deep crustal history and processes. In this special issue we summarize the recent progress in the mineralogical, petrological, geochemical, and geochronological studies carried out in East Antarctica.

Keywords: Archean-Proterozoic-Cambrian, Gondwana, East Antarctica

INTRODUCTION

The Antarctic continent comprises 9% of the Earth's surface landmass. Nevertheless, because of its remoteness and inaccessibility due to thick ice cover, extensive geological studies are limited to the narrow coastal belts or high mountains standing out of the ice sheet. National scientific programs of Japanese Antarctic Research Expedition (JARE) under the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan have been rigorously conducting research in various fields including geological studies since 1957. For the past 10 years, JARE has strongly focused on geological studies on various crustal segments of early Archean to Neoproterozoic-Cambrian geological entities in East Antarctica. These recent activities of JARE expeditions cover ~ 1500 km along the coast and inland of East Antarctica (Fig. 1) from 10°E to 45°E in Dronning Maud Land and Enderby Land. A total of 19 geologists participated in expeditions between 2016 and 2022, signifying the importance of this region in elucidating the magmatic, metamorphic and crustal fluid processes during the formation of Gondwana and their lineage before the formation of the supercontinent (Figs. 2 and 3). The progress of geological studies in East Antarctica by JARE researchers have been recognized by the international community as exemplified by the dissemination of scientific results through thematic special publications (e.g., Satish-Kumar et al., 2008, 2013).

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T. Hokada, hokada@nipr.ac.jp Corresponding author

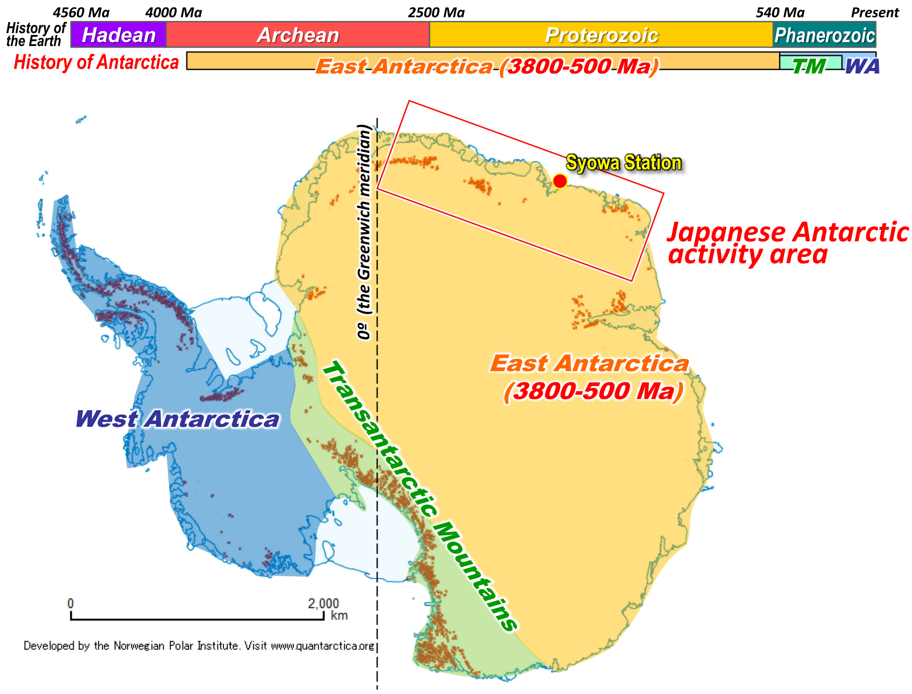

Figure 1. Geological overview of Antarctic continent.

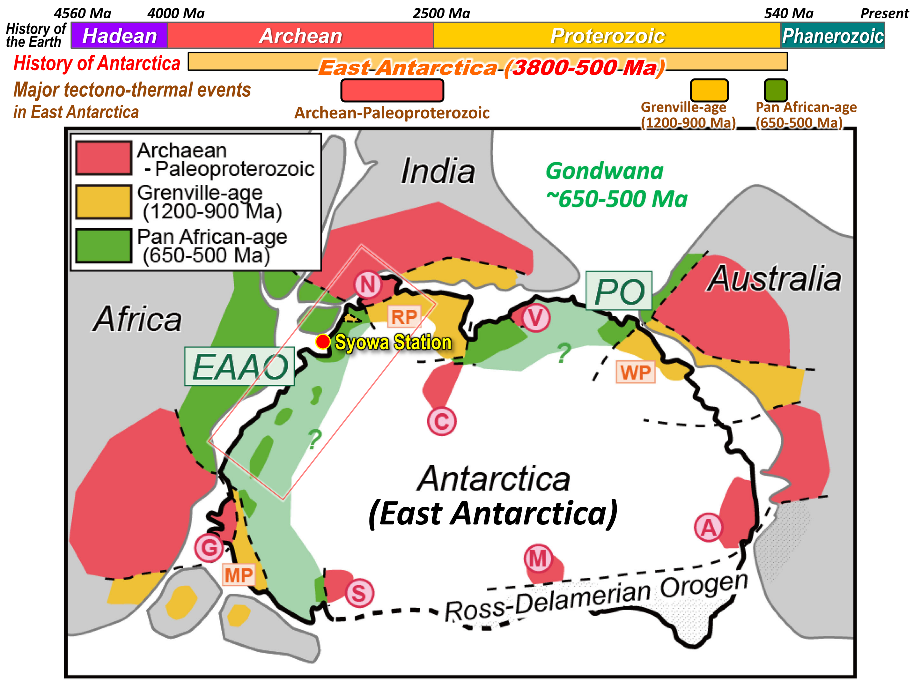

Figure 2. Configuration of Antarctica (East Antarctica) and the surrounding continents at Gondwana (~ 650–500 Ma) compiled after Fitzsimons (2000), Harley (2003), Jacobs et al. (2003), Shiraishi et al. (2003). A, Terre Adélie; C, southern Prince Charles Mountains; G, Grunehogna; M, Miller Range; N, Napier Complex; S, Shackleton Range; V, Vestford Hills; MD, Maud Province; RP, Rayner Province; WD, Wilkes Province; EAAO, East-African-Antarctic Orogen; PO, Pinjarra Orogen.

In this thematic issue, we present recent research advances in Antarctica employing multiple subjects including mineralogy, petrology, geochemistry, and geochronology, that contribute not only to fill in the voids of information between the orogenic zones within the amalgamated Gondwana fragments, but also to promote the understanding of the physical and chemical processes during the formation of continents and supercontinents. The prolonged crustal history preserved in the Archean through Proterozoic to Cambrian rock record in Dronning Maud Land and Enderby Land, forms the basis of the JARE geological field surveys, enduring the extremely difficult conditions prevailing in ice covered inland regions (Fig. 4). The scientific achievements are presented in 18 landmark papers, covering the area from western Dronning Maud Land to Enderby Land, which deal with various research subjects of miner-

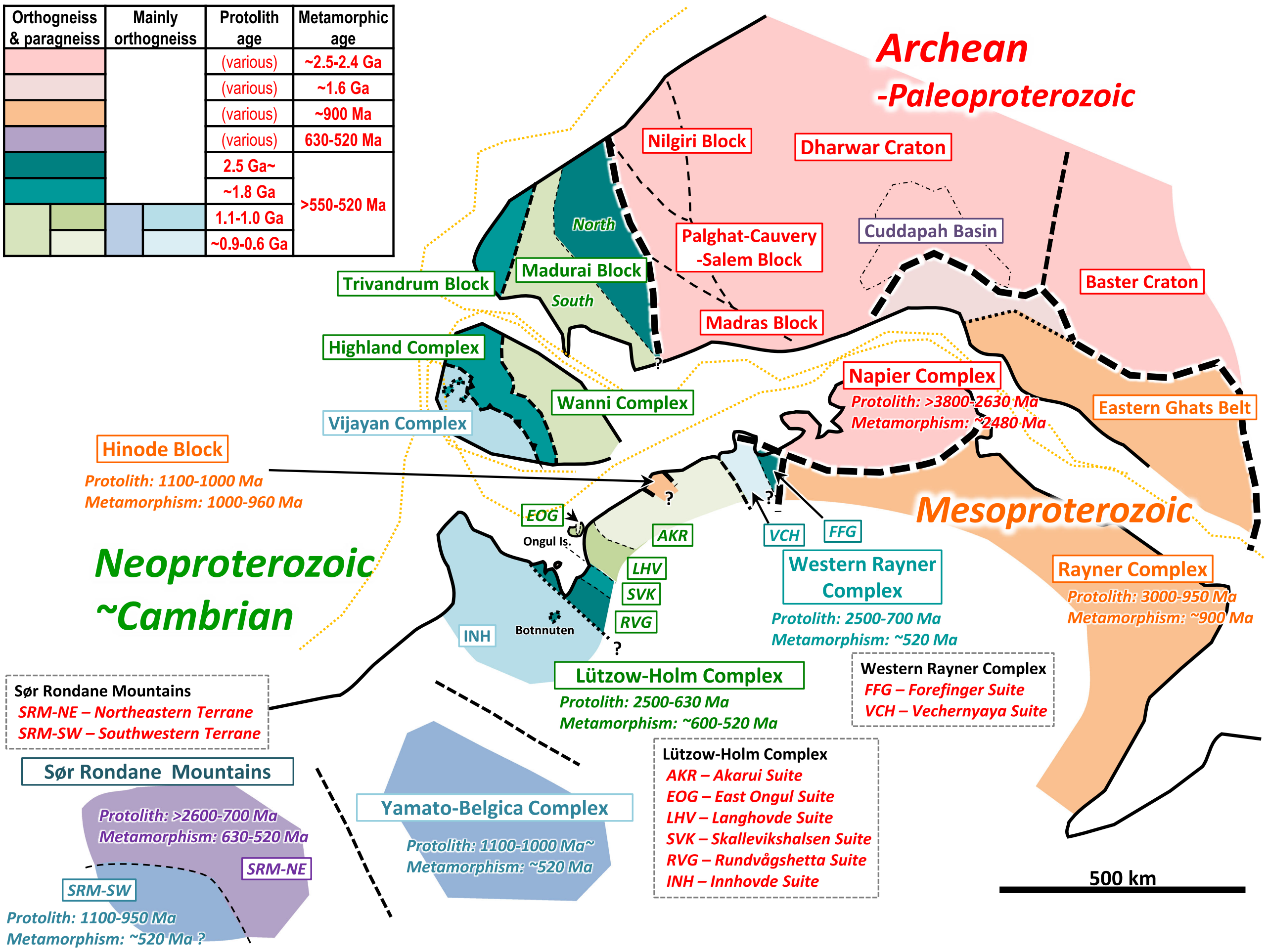

Figure 3. Geological correlation of Dronning Maud Land–Enderby Land of Antarctica and Sri Lanka–southern India modified after Dunkley et al. (2020).

alogy and petrology, mineral- and whole-rock geochemistry including stable and radioisotopes, geochronology, structural, and regional geology.

LATE NEOPROTEROZOIC-CAMBRIAN (>600–520 MA) GONDWANA SUTURE OROGENIC ZONES

As illustrated in Figure 4, the high-grade metamorphic terranes with ages spanning between 600 and 520 Ma are distributed over 200 km as coastal outcrops and nunataks in the Dronning Maud Land (Shiraishi et al., 2008). Formation of the Gondwana supercontinent in the late Neoproterozoic to Cambrian is one of the key issues in understanding the regional continental collision event and related deep crustal processes. High-grade metamorphic and magmatic events related to such widespread continental collision are recorded and preserved in this part of Antarctic continent.

Western-central Dronning Maud Land

Geological field surveys in western and central Dronning Maud Land have been conducted by each national Antarctic programs of Norway, Germany, South Africa, and Japan with substantial international collaborations between them (e.g., Owada et al., 2003; Baba et al., 2015; Jacobs et al., 2015; Hokada et al., 2019). Grantham et al. (2023 in this issue) report the combined field geological, structural, petrological, and geochronological studies on Sverdrupfjella and Gjelsvikfjella in western Dronning Maud Land, which forms the western end of Neoproterozoic–Cambrian (>600–520 Ma) Gondwana suture orogenic zones, and discuss its correlation with southern-eastern Africa.

Sør Rondane Mountains

The Sør Rondane Mountains (SRM) is a well-studied region that exposes the collision zone between a terrane dominated by granulite facies to ultrahigh-temperature

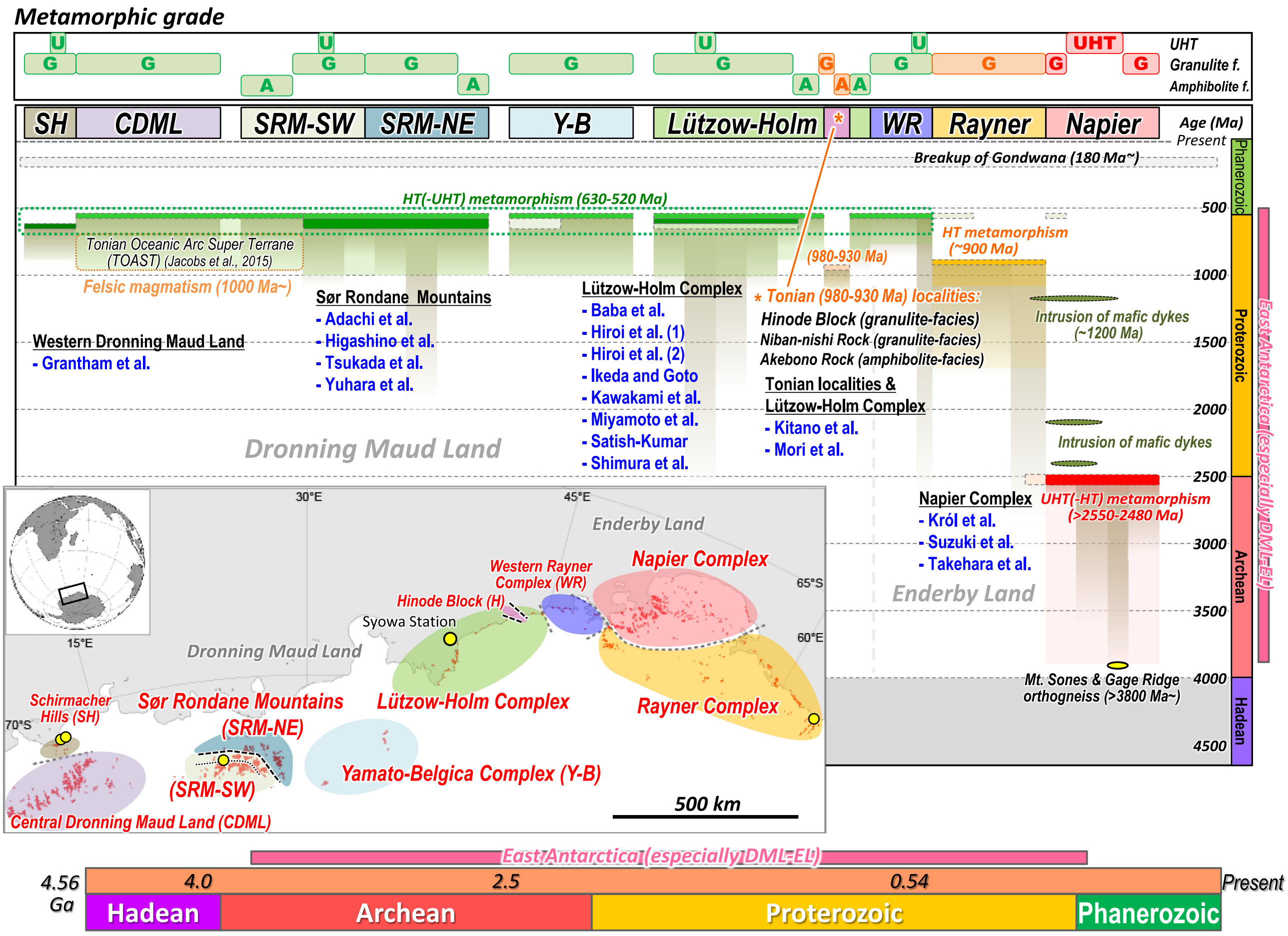

Figure 4. Detailed geological unit divisions, metamorphic grades, and time-scale of Dronning Maud Land and Enderby Land modified and updated from Shiraishi et al. (2008) (incorporating with Sheraton et al., 1987; Shiraishi et al., 1997; Jacobs et al., 2015).

(UHT) metamorphic rocks (Higashino and Kawakami, 2022) (NE-Terrane) with a clockwise pressure-temperature (*P*-*T*) path and a terrane composed of granulite-facies to amphibolite-facies rocks (SW-Terrane) that record a counter-clockwise *P*-*T* path (Osanai et al., 2013). The SRM records long-lived or multiple thermal episodes in the time frame of 630-520 Ma (Elburg et al., 2016; Higashino et al., 2023a). Adachi et al. (2023 in this issue) reports the discovery of contrasting metamorphic rocks with different *P*-*T*-*time* (*P*-*T*-*t*) paths bounded by a ductile shear zone from the SW-Terrane and propose the presence of two stages of collision in the SRM. Based on detailed structural mapping and geochronological constraints, Tsukada et al. (2023 in this issue) report the possible tectonic boundary, adding further supporting evidence for tectonic juxtaposition of contrasting rock units as described in Adachi et al. (2023). Yuhara et al. (2023 in this issue) discuss the geochemical signature of post-tectonic granites, providing further impetus to the regional magmatic activity reported in previous studies (e.g., Owada et al., 2013; Elburg et al., 2016).

The SRM is also known as a key area for understanding the fluid-rock interactions in collision settings (Higashino et al., 2013, 2015; Kawakami et al., 2017; Higashino et al., 2019a, 2019b; Mindaleva et al., 2020). Traces of saline fluids are found as Cl-rich minerals in the matrix or enclosed in garnet in the granulite facies rocks along the Main Tectonic Boundary bounding the NE and SW Terranes (Higashino et al., 2013, 2019a). Prograde to peak-metamorphic saline fluids probably had low $\delta^{18}O$ as constrained from O isotope zoning recorded in garnet enclosing Cl-rich biotite (Higashino et al., 2019b). Retrograde saline fluid infiltrations are recorded as cracks filled with Cl-rich biotite and/or hornblende (Higashino et al., 2015, 2019a). Higashino et al. (2023b in this issue) report an excellent case study of multiple retrograde saline fluid infiltrations. By careful textural observations combined with EPMA-Raman microanalyses, the authors are able to clarify the one-phase CO_2-Cl-H_2O fluid infiltration followed by saline fluid infiltration.

Lützow-Holm Complex

The Lützow-Holm Complex, where the Japanese base 'Syowa Station' is located, has been studied in detail ever since the first JARE expedition in 1957. The Lützow-Holm Complex is a late Neoproterozoic to Cambrian (>600–520 Ma) major orogenic beltrelated to the formation of Gondwana supercontinent (Shiraishi et al., 1994, 2003; Dunkley et al., 2014, 2020). The progressive metamorphism of amphibolite-facies zone through transitional-zone to granulite-facies (including UHT) zone along with clockwise *P*–*T* evolution is clearly demonstrated in several outcrops throughout the Lützow-Holm Bay-Prince Olav Coast region (Hiroi et al., 1991; Motoyoshi and Ishikawa, 1997). Recent study has revealed that transitional-zone rocks also attained higher-*T* granulite facies conditions at the pressures of ~ 1.1 GPa (Suzuki and Kawakami, 2019). Furthermore, many geological, petrological, and geochemical studies have been conducted recently, especially in the granulite-facies zone, that emphasize long-lived high temperature metamorphism with partial melting and possible magma generation at UHT conditions (e.g., Durgalakshmi et al., 2021; Carvalho et al., 2023). However, data from the amphibolite-facies zone are comparatively scarce. Baba et al. (2023 in this issue) report a counter-clockwise *P*–*T* path from Tenmondai Rock located in the transitional-zone for the first time. Contrary to this, Shimura et al. (2023 in this issue) discuss the clockwise *P*–*T* path for a sample from the same locality. Thus, further data and discussion are required for better understanding the *P*–*T* evolution of this locality. In the amphibolite-facies zone, Tonian-aged metamorphism is newly reported, adding to the previous report from Hinode Block (Dunkley et al., 2020), which is separately summarized in a subsequent section.

From the transitional to granulite facies zones, Ikeda and Goto (2023 in this issue) proposed some fundamental and important process of how chemical composition and zonation of garnet are formed, modified and preserved. Hiroi et al. (2023 in this issue) report for the first time the occurrence of borosilicate (grandidierite) within nanogranitoid inclusions. Their discovery of such a rare occurrence is the result of decade long careful observations of numerous felsite/nanogranitoid inclusions reported from multiple localities within the granulite-UHT zone of Lützow-Holm Complex (e.g., Hiroi et al., 2014, 2019). Kawakami and Harley (2023 in this issue) use their boron isotopic studies on coexisting borosilicates (kornerupine and tourmaline) to discuss the behavior of boron isotopes and crystallization processes of borosilicates in high-temperature conditions. The behavior of boron is, thus, one of the hot topics that provide vital clues on the evolution of deep crustal rocks. Hiroi et al. (2024 in this issue) report the mode of occurrence of Cl-rich calcic-amphibole and Cl-poor subcalcic amphibole in the granulite-facies rock. Carbon isotopic composition on various types of graphite occurrences are reported in Satish-Kumar (2023 in this issue), a contribution in which a case study is provided for exploring the possibility of carbon reservoirs in orogenic belts that might have implications on the long term carbon geodynamic cycle. Miyamoto et al. (2023 in this issue) report the occurrence and geochemistry of unusual ultrapotassic mafic dykes that intruded the high-*T* to UHT metamorphic rocks.

Tonian (980–930 Ma) outliers in the Lützow-Holm Complex

The Hinode Block (Figs. 3 and 4), a Tonian-age outlier which is geographically located within the Lützow-Holm Complex, has previously attracted attention due to its exotic nature (Shiraishi et al., 2003, 2008; Dunkley et al., 2014, 2020). Recently, Baba et al. (2022) discovered new occurrence of Tonian-aged rocks from the Akebono Rock, neighboring the Hinode Block. Following this finding, Kitano et al. (2023 in this issue) conducted a detailed U-Pb zircon dating on several rock units surrounding Hinode Block, and successfully obtained Tonian metamorphic ages from Akebono Rock and Niban Rock, which are located on the west and east sides of Hinode Block, expanding the regional distribution of Tonian-aged rocks in the region Mori et al. (2023 in this issue), who have investigated the detailed metamorphic *P*–*T* conditions and metamorphic monazite ages of Niban-nishi Rock, summarize the *P*–*T*–*t* evolution of this particular locality, suggesting a possible overprint by Cambrian metamorphism. Comparison and correlation with the similar age Meso-Neoproterozoic granulite-facies terrane, the Rayner Complex (e.g., Shiraishi et al., 1997), further east in Enderby Land, is a topic which needs future investigation.

ARCHEAN (>2550–2480 MA) CRUSTAL EVOLUTION OF THE NAPIER COMPLEX

The Archean Napier Complex in East Antarctica consists of felsic-intermediate orthogneisses, mafic granulite and a variety of paragneisses metamorphosed under granulite-facies and UHT conditions at around ~ 2550–2480 Ma (e.g., Kelly and Harley, 2005; Suzuki et al., 2006; Horie et al., 2012). The oldest protolith of the complex is dated as >3850–3770 Ma at Mt. Sones and Gage Ridge (Black et al., 1986; Harley and Black, 1997; Kelly and Harley, 2005), followed by long-lived magmatic and detrital zircon age populations from various localities in the age range of

3700–2630 Ma (e.g., Kelly and Harley, 2005; Hokada et al., 2008; and references therein). The Napier Complex has attracted great interest because of its unusually high-*T* metamorphic conditions in Archean times. The area was surveyed by the Russian (Soviet) expeditions in 1960–1965 and by the Australian expeditions since 1930 (extensively in 1975–1980). Japanese expeditions also conducted field surveys since 1980 and published detailed geological maps of two key outcrops of the Complex (Ishikawa et al., 2000; Osanai et al., 2001). Since the area is significantly distant from the Japanese base Syowa Station, Japanese expeditions find it logistically difficult to conduct frequent surveys. Using the Australian archived samples collected between 1975–1980, Król et al. (2023 in this issue) conducted geochemical studies and U-Pb zircon dating for samples from some remote regions in the Napier Complex and provide results which give further compelling evidence for the variety of Archean protolith blocks which are combined to form the Napier Complex in the latest Archean. Suzuki et al. (2023 in this issue) discuss the evolution of Archean TTG based on geochemistry and Sm-Nd systematics of the samples collected in JARE expedition and indicate the consistency of Nd isotope evolution and U-Pb ages of the Archean TTG in the multiple domains within the Napier Complex. A recent Japanese expedition (2016–2017) visited a small nunatak in the Napier Complex, from which Takehara et al. (2023 in this issue) have investigated zircon and monazite geochronology and oxygen isotope, Li and Cl geochemistry that enable them to discuss the geochemical characteristics of zircon in regional metamorphism at UHT conditions. All these new results points to the necessity for further detailed studies to understand the processes accompanying the hottest crustal metamorphism and Archean crustal evolution.

In summary, the present thematic issue presents valuable scientific outcome from JARE expeditions and provides a trigger for conducting further geological expeditions that result in understanding the hidden nature of continental crust below the Antarctic ice sheet. Further directions of research should also involve how technological innovations can overcome limitations of nature for observations on subsurface ground truth below the ice sheet to enlighten our knowledge on the geology of Antarctica.

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