Geosciences research in East Antarctica (0°E–60°E): present status and future perspectives

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Abstract: In both palaeoenvironmental and palaeogeographical studies, Antarctica plays a unique role in our understanding of the history of the Earth. It has maintained a unique geographical position at the South Pole for long periods. As the only unpopulated continent, the absence of political barriers or short-term economic interests has allowed international collaborative science to flourish. Although 98% of its area is covered by ice, the coastal Antarctic region is one of the well-studied regions in the world. The integrity and success of geological studies lies in the fact that exposed outcrops are well preserved in the low-latitude climate. The continuing programme of the Japanese Antarctic Research Expedition focuses on the geology of East Antarctica, especially in the Dronning Maud Land and Enderby Land regions. Enderby Land preserves some of the oldest Archaean rocks on Earth, and the Mesoproterozoic to Palaeozoic history of Dronning Maud Land is extremely important in understanding the formation and dispersion of Rodinia and subsequent assembly of Gondwana. The geological features in this region have great significance in defining the temporal and spatial extension of orogenic belts formed by the collision of proto-continents. Present understanding of the evolution of East Antarctica in terms of global tectonics allows us to visualize how continents have evolved through time and space, and how far back in time the present-day plate-tectonic regime may have operated. Although several fundamental research problems still need to be resolved, the future direction of geoscience research in Antarctica will focus on how the formation and evolution of continents and supercontinents have affected the Earth's environment, a question that has been addressed only in recent years.

The formation and evolution of continents has always been an intriguing topic in Earth Science studies. The complexity of continental evolution largely results from the protracted and recurring nature of geological processes that have taken place in the continental lithosphere. Decoding billions of years of complex history recorded in the continental crust is a daunting task. However, geologists have made great progress in understanding the processes involved in continental formation and their evolution through time. The Antarctic continental lithosphere is an important crustal fragment that provides us with an abundance of information on the formation of continents, and the temporal and spatial relationships involved in the assembly and dispersion of supercontinents.

The significance of Antarctica lies not only in its unique geographical position, whereby it has gained due importance in palaeoenvironmental studies, but also in its geological stability since incorporation in the supercontinent Gondwana at the beginning of the Phanerozoic Era. This is primarily because the Antarctic lithospheric plate has been surrounded by mid-ocean ridges since the Mesozoic (Fig. 1 inset), with the exception of the Antarctic Peninsula, which is its only active convergent plate margin with transform faults dividing the Antarctic Plate and Scotia Plate. This means that the Antarctic Plate is currently expanding relative to the surrounding plates. This is a feature that is at variance with most other lithospheric plates, and makes the Antarctic continent exceptionally stable, and isolated from all regional tectonic events during the Mesozoic and Cenozoic. Consequently, the older geological history of East Antarctica can be considered as one of the least overprinted records of crustal evolution in the Earth's history, preserved in a natural 'cold storage'. Its geological history records the formation of early Archaean protocontinents, and continues throughout the Proterozoic, until the amalgamation of East and West Gondwana at the beginning of the Palaeozoic. Therefore, the geological record in East Antarctica is an invaluable record of the origin and evolution of continents and supercontinents, and for understanding the secular changes in metamorphic conditions in orogenic belts (Brown 2007).

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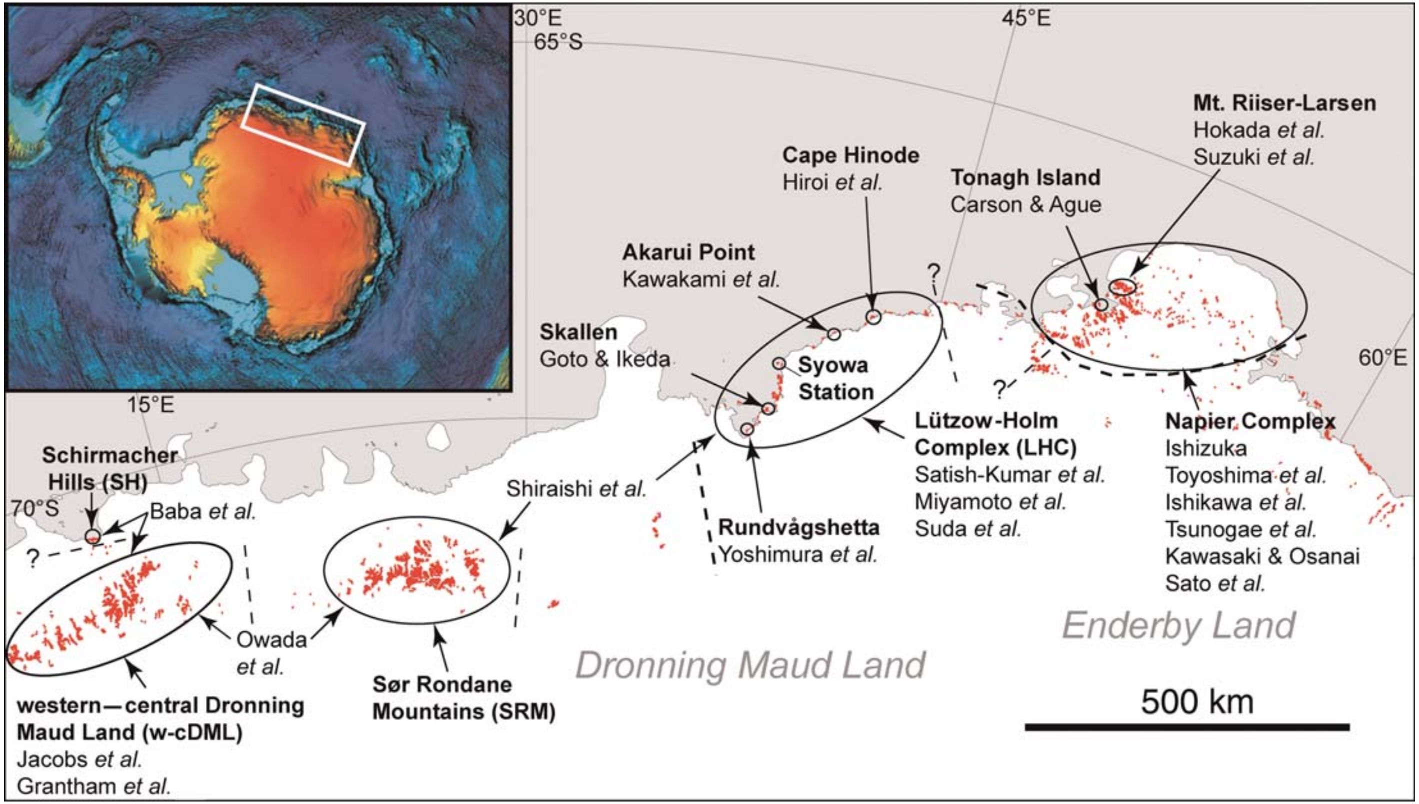

Fig. 1. Index map of geographical regions and localities in East Antarctica corresponding to the contributions in this Special Publication. Inset shows a topographic map of Antarctica and surrounding oceans. Red indicates topographically elevated places; blue indicates ocean floor. (Data source: Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical Data Center, 2006, 2-minute Gridded Global Relief Data (ETOPO2v2), http://www.ngdc.noaa.gov/mgg/fliers/06mgg01.html).

It is beyond the scope of this book to update the reader with the voluminous literature that has been produced in the past few decades on the geology of East Antarctica. However, we make an attempt to integrate the results of some recent studies from the eastern region of the Antarctic continent, where the Japanese Antarctic Research Expedition (JARE) has, over the past 50 years, conducted extensive investigations. We introduce the general geology of the region and summarize what is known to date, and in the process introduce the contributions in this volume. The contributions in the volume are related to the outcrops that are situated between 0°E and 60°E in Dronning Maud Land and Enderby Land of East Antarctica (Fig. 1). In addition, this paper also attempts to lay down 'a vision for future', based on the current status of geological knowledge.

East Antarctica: an integral part of Gondwana

The challenge of developing tectonic scenarios for the formation of the ice-covered Antarctic continent is uniquely difficult; no other continent presents such a blank sheet on which geological terranes can be drawn by inference only. Virtually all understanding of the geological architecture is drawn from intensive studies of coastal outcrops and mountain ranges near the continental margins. A full 180° arc of coastline, encompassing East Antarctica, provides an array of outcrops that almost exclusively share a Precambrian origin. This reflects the intracontinental nature of the East Antarctic coast in the supercontinent Gondwana, after its formation at the end of the Proterozoic. The stability of the continent throughout the Phanerozoic has also led to the concept of an East Antarctic Shield, one of the large areas of cratonized crust on Earth. The 'shield' concept also influenced tectonic interpretations of coastal geology before the formation of Gondwana. It was recognized that most localities in East Antarctica are represented by areas of high tectonic activity, dominated by moderate- to high-temperature metamorphic belts, shear zones, and regions of Proterozoic crustal growth, and that Archaean granite–greenstone and metamorphic terranes are mostly restricted to small discrete localities. This led to the development of tectonic models of a 'cratonized' East Antarctic Shield with extensive mobile belts, such as the *c.* 1 Ga Circum-Antarctic Mobile Belt of Yoshida (1992) and the Wegener–Mawson Mobile Belt of Kamenev (1991). These models implied the existence of a coherent Antarctic continent that was amalgamated during the formation of the supercontinent Rodinia at 1.3–0.9 Ga (Hoffman 1991). However, subsequent years have seen a steady increase in the volume and detail of tectonic and geochronological research from all areas of East Antarctica that has shown a more complex story of the diverse origins of various sectors of the East Antarctic margin, challenging the 'shield' paradigm. Late Mesoproterozoic metamorphic terranes located along the Antarctic coast at 30°W–35°E (the 1100–1000 Ma Maud Belt), 45°E–70°E (the 1000–900 Ma Rayner Complex) and 100°E–120°E (the 1300–1100 Ma Wilkes Province), were found not only to differ subtly in age, but also to be separated by areas of *c.* 600–500 Ma moderate- to high-temperature metamorphism and tectonism at Lützow-Holm Bay (40°E) and Prydz Bay (70°E; Fitzsimons 2000). Thus, instead of representing a continuous marginal mobile belt, each of the Mesoproterozoic metamorphic terranes could be correlated with discrete mobile belts in South Africa (Namaqua–Natal Belt), India (Eastern Ghats) and South Australia (Albany–Fraser Orogen). Furthermore, it was recognized that a large section of the Maud Belt was reworked by late Neoproterozoic metamorphism and deformation that could be correlated with the extensive East African Orogen, produced by the amalgamation of East and West Gondwana (Jacobs *et al.* 2003*a*). Recognition of unrelated pre-Rodinian cratons in East Antarctica was also achieved, with the correlation of the Mawson continent and the Gawler Craton in South Australia (Fanning *et al.* 1996), and the geochronological characterization of Archaean terranes south of a *c.* 550 Ma suture zone in the southern Prince Charles Mountains adjacent to Prydz Bay (Boger *et al.* 2001; Mikhalsky *et al.* 2001, 2006; Phillips *et al.* 2006).

New studies (e.g. Kelsey *et al.* 2008) continue to develop the latest paradigm of the assembly of East Antarctica from disparate continental bodies during the late Neoproterozoic formation of Gondwana. In particular, the complexity of crustal development in the sector between 0°E and 70°E, namely Dronning Maud Land, Enderby Land, Kemp Land and Mac Robertson Land, is the focus of recent and current research. **Shiraishi *et al.*** attempt to synthesize a large amount of new geochronological data obtained from eastern Dronning Maud Land, and discuss the variations in age distributions between the lithological units. Magmatic and metamorphic events between 1200 and 500 Ma are identified from zircon geochronology in different regions, providing insights into the formation and assembly of crustal fragments, Neoproterozoic sedimentation, and late Neoproterozoic to Cambrian episodes of metamorphism and magmatism. **Shiraishi *et al.*** further consider the geodynamic evolution of eastern Dronning Maud Land on the basis of published and new Nd model ages, which

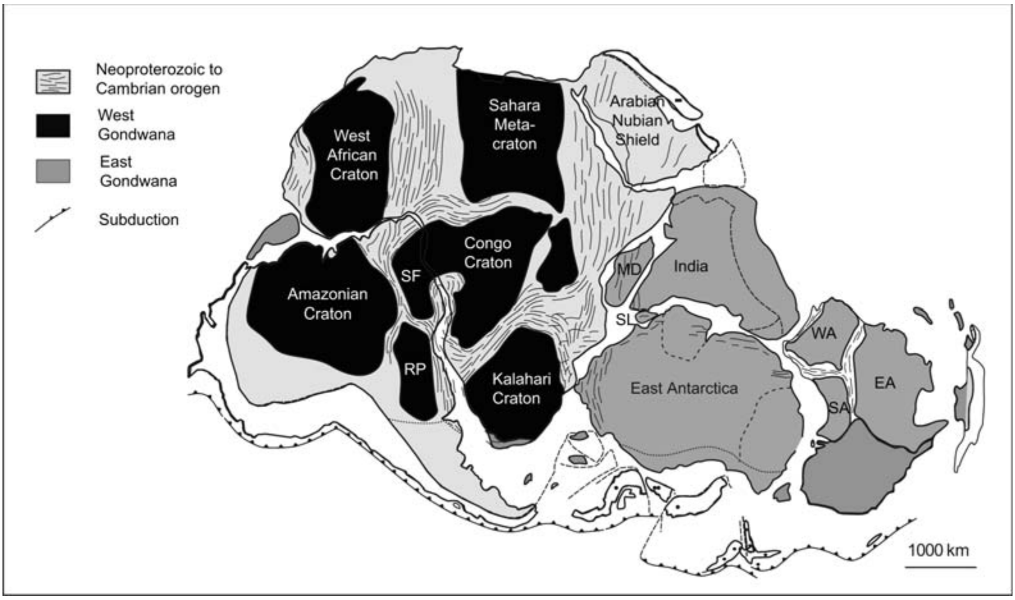

Fig. 2. Neoproterozoic Gondwana showing the cratonic regions and surrounding mobile belts. Simplified after Gray *et al.* (2008) and modified taking into consideration the Lawyer *et al.* (1998) tight-fit Gondwana configuration. SL, Sri Lanka; MD, Madagascar; WA, western Australia; EA, eastern Australia; SA, southern Australia; SF, São Franscisco; RP, Rio de la Plata.

indicate juvenile extraction of Mesoproterozoic crust in the Sør Rondane Mountains, in contrast to the mixed Archaean and Proterozoic derivation of continental crust in the Lützow-Holm Complex. In a Gondwanan perspective, these results will shift the attention of geodynamic modelling to eastern Dronning Maud Land, to clarify the complex orogenic processes involved in the amalgamation of East and West Gondwana (Fig. 2).

The significance of voluminous plutonic activity in Dronning Maud Land and northern Mozambique is discussed by **Jacobs *et al.***, who consider lateral southward extrusion and extensional collapse as the preferred tectonic scenario, potentially as a result of crustal delamination. The correlation of temporal variations with distinct shifts in geochemical affinities of magmatic regimes form the basis of a delamination model in association with orogenic collapse and escape tectonics, as proposed recently by Jacobs & Thomas (2004). The model remains to be tested in relation to Gondwanan geodynamics.

An intriguing conundrum of correlation of terranes in Gondwana is examined by **Grantham *et al.*** through a detailed comparison of lithological, structural, metamorphic and geochronological data from Mozambique with Sri Lanka and Dronning Maud Land. As a follow-up study to Grantham *et al.* (2003), a continuing ambitious mapping project of Mozambique has led these workers to propose a model dominated by nappe tectonics during the 590–550 Ma period of Gondwana assembly. Tectonic windows in Sri Lanka and Dronning Maud Land are considered as expressions of the *c.* 600 km displacement of crust from northern Gondwana by mega-thrusts. This concept will be tested by future developments.

Geological outline of East Antarctica (0°E–60°E)

Since the proposal of Gondwana and Rodinia reconstruction models by Dalziel (1991) and Hoffman (1991), geoscientists have conceived of the Antarctic continent as a single stable entity between 1000 and 500 Ma. However, recent palaeomagnetic, geological and geochronological studies have recognized several distinct Neoproterozoic orogenic events within the East Antarctic shield, and a new concept has emerged of East Antarctica as a collage of three distinct Mesoproterozoic provenances: the Wilkes (1330–1130 Ma), Maud (1090–1030 Ma) and Rayner (990–900 Ma) Provinces (Fitzsimons 2000; Meert 2003; and references therein). Moreover, two distinct age populations of 650–550 Ma and 580–500 Ma have emerged in extensive geochronological datasets from the so-called ‘Pan-African orogeny’ (Fig. 2), involving several discrete crustal blocks in East Antarctica and regions surrounding the East African–Antarctic Orogen (e.g. Jacobs *et al.* 2003*a*, *b*; Meert 2003; Hokada & Motoyoshi 2006).

Provinces of Archaean age in East Antarctica are found at 'Annadagstopane' in Grunehogna, western Dronning Maud Land; the Napier Complex and Oygarden Islands in Enderby Land; the southern Prince Charles Mountains, Vestfold Hills and Rauer Islands in Mac Robertson Land and Princess Elizabeth Land; the Denman Glacier in Queen Mary Land, and the Mawson Block in Terre Adélie (Fig. 3). The Grunehogna terrane is considered as a part of the Archaean Kalahari Craton in southern Africa (Jacobs *et al.* 1993*b*), and the Mawson Block has been correlated with the Gawler Craton in southern Australia (Fanning *et al.* 1996). Altogether, the terranes of East

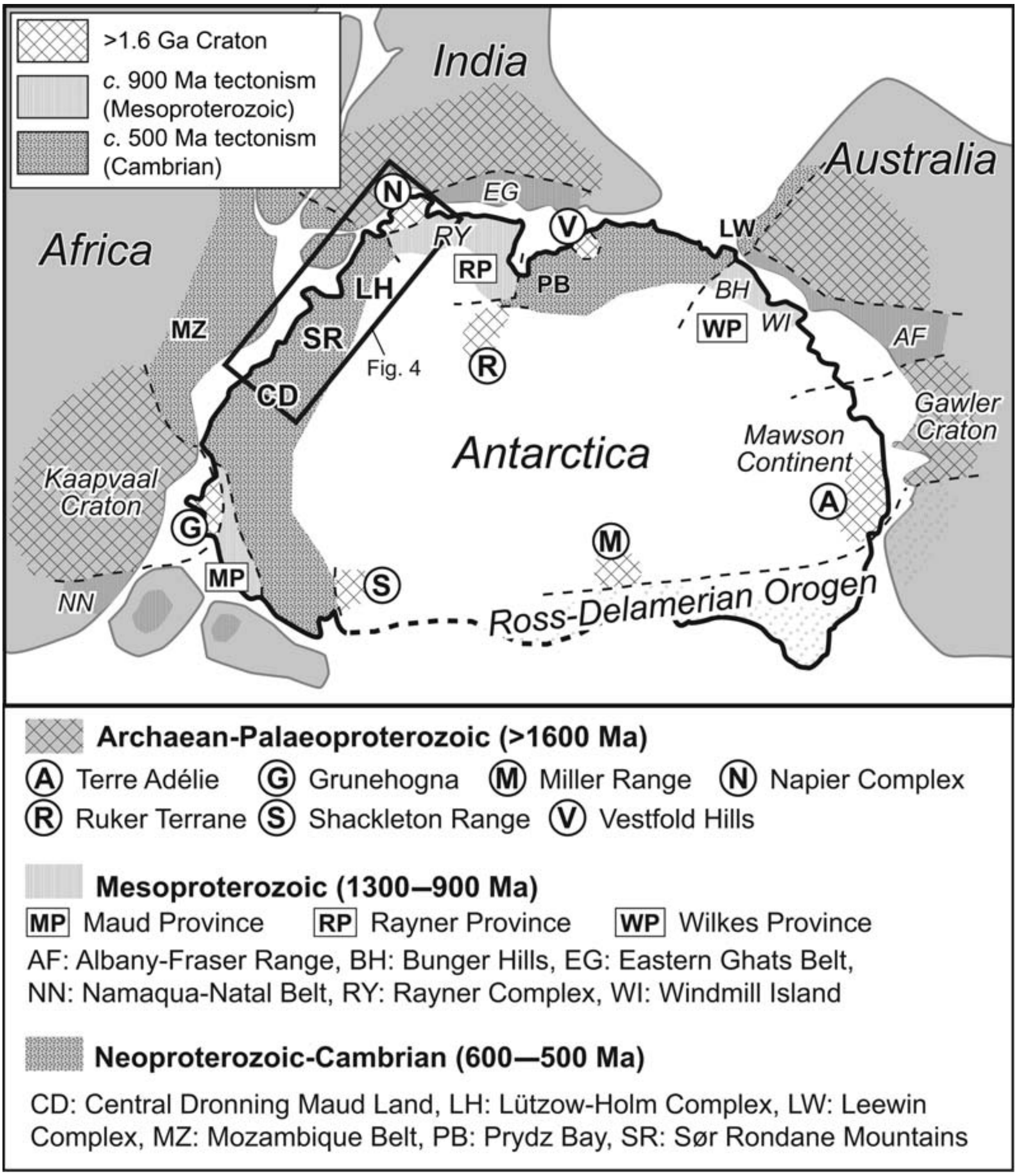

Fig. 3. Continents that surrounded Antarctica in the Neoproterozoic. Geological entities within East Antarctica are also shown.

Antarctica preserve a protracted crustal history from the oldest in the Napier Complex (*c.* 3850 Ma) to the last episode of post-collision magmatism (*c.* 450 Ma) in the waning stages of Gondwana amalgamation.

Enderby Land lies between longitudes 45°E and 60°E, and comprises Archaean to early Proterozoic crustal sequences, representing a continental core complex surrounded by Proterozoic–Cambrian mobile belts. To the east of Enderby Land, more than 1000 km of coastal areas in Dronning Maud Land (5°E–45°E) comprise late Proterozoic to Cambrian mobile belts (650–500 Ma) (Fig. 4). This mobile belt has been extrapolated to Prydz Bay (Boger *et al.* 2001) and as far as western Australia (Fitzsimons 2000; Meert 2003). The only recent equivalent of such an extensive mobile belt is the Cenozoic Alpine–Himalayan orogenic belt. How far are these two orogens comparable, and where do they differ? Although there are countless similarities between the two, the former lacks the expression of low-temperature/high-pressure metamorphic belts, which would provide clear equivalents to present-day subduction, accretion and collision-related tectonic settings that presumably would predate the amalgamation of continental blocks by the orogen.

Within Dronning Maud Land, the lithological contrast between the inland mountain chains of central–eastern Dronning Maud Land (including the Sør Rondane, Belgica and Yamato Mountains) and outcrops along the Soya and Prince Olav Coasts further east is striking (Fig. 4). The former region is dominated by felsic (granitic, granodioritic and syenitic) orthogneisses and post-tectonic plutons, with lesser mafic lithologies and metasedimentary sequences. In contrast, the latter region (Lützow-Holm and western Rayner Complexes) consist of voluminous metasedimentary rocks with mafic and calcareous rocks, and relatively little granitic material. It is important that any regional tectonic model accounts for this transition in the makeup of the mobile belt.

The Napier Complex

The Napier Complex is one of several Archaean cratonic terranes (Fig. 3) in the East Antarctic continent (e.g. the Grunehogna terrane, the Ruker terrane in the southern Prince Charles Mountains, the Vestfold Hills, the Mawson Block in Terre Adélie, the Miller Range and the Shackleton Range), but is unique in being entirely composed of high-temperature granulites. Early Archaean (>3850 Ma) protolith ages have been obtained from tonalitic orthogneisses (Black *et al.* 1986; Harley & Black 1997; Kelly & Harley 2005), which are the oldest in Antarctica and close to the age of the Earth's oldest known orthogneiss, the Acasta Gneiss in Canada (4000 Ma, Bowring *et al.* 1989). These 3850 Ma tonalitic orthogneisses occur at least in two localities (Mt. Sones and Gage Ridge; Harley & Black 1997; Kelly & Harley 2005), and subsequent tonalitic–granodioritic

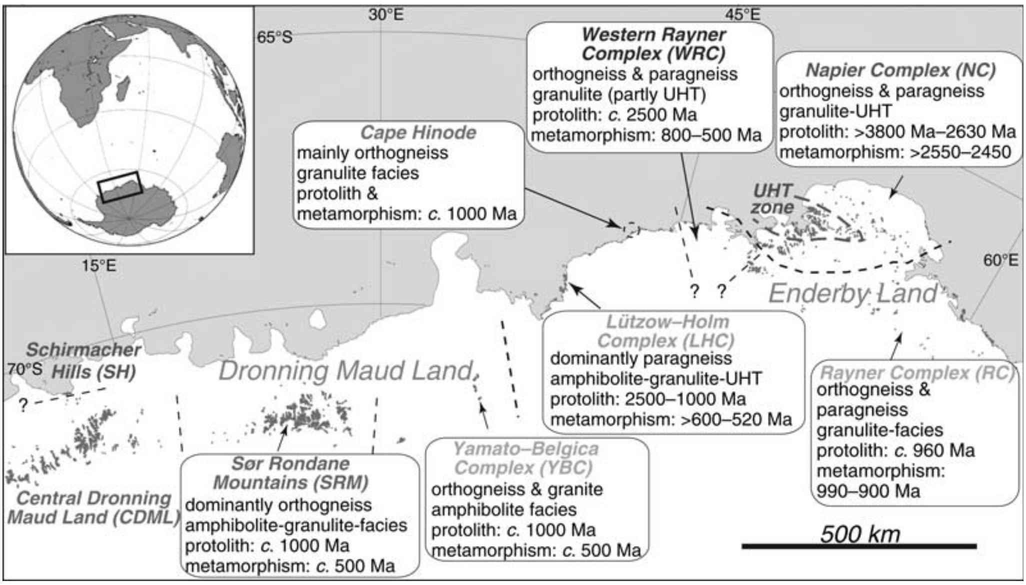

Fig. 4. Tectonic units in Dronning Maud Land and Enderby Land, East Antarctica, showing salient geological and geochronological features. Dashed lines represent suspect boundaries between the units.

magmatism is observed from 3270 Ma (Mt. Riiser-Larsen; Hokada *et al.* 2003) to 2630 Ma (Tonagh Island; Carson *et al.* 2002). The Napier Complex consists predominantly of tonalitic–granodioritic orthogneiss, but also includes mafic to ultramafic orthogneisses, garnet-bearing peraluminous granitic gneisses, and subordinate quartzo-feldspathic, siliceous and aluminous paragneisses. This lithological diversity indicates a complex and progressive development of the proto-metamorphic terrane, and provides insights into the development of continental crust during the Archaean. However, it is still unclear when and how the various crustal components were brought together, and what types of tectonic processes were functional in the Archaean. What is known is that the crustal components of the Napier Complex shared a common history after 2850 Ma, the timing of the first major regional magmatic–metamorphic event.

Following extensive field and laboratory work by geologists of the Australian National Antarctic Research Expedition (ANARE), who established the geological structure and history of this area (see Sheraton *et al.* 1987, and references therein), JARE has carried out geological fieldwork intermittently throughout the 1980s and 1990s. ***Ishizuka*** reviews the voluminous results obtained by various JARE expeditions to the Napier Complex. In addition to the preparation of detailed geological maps (Ishikawa *et al.* 2000; Osanai *et al.* 2001), the expeditions focused on the geochemical characterization of different lithological units within the Napier Complex, which represent an admixture of Archaean components with sedimentary, granite–greenstone and tonalite–trondhjemite–granite (TTG) affinities. The review emphasizes important results obtained in subject areas such as the processes of ultrahigh-temperature (UHT) metamorphism, stages of protolith formation and geochemical studies of dykes, to provide constraints on modelling the tectonic evolution of the region.

Our basic knowledge of the regional structural features in the Napier and Rayner Complexes is based on the mapping results carried out in the 1960s by the Soviet Antarctic Expedition (SAE; see Kamenev 1972, 1975) and further extensive geological mapping by ANARE until the late 1970s (Sheraton *et al.* 1987). **Toyoshima *et al.*** construct a regional form-line map based on structural data from published maps in the Napier and Rayner Complexes. They identify potential boundaries between different regions, based on the convergence of several structural parameters. The location of major tectonic boundaries is supported by geophysical evidence, as well as detailed field geological data from representative areas. In addition to the geological information from outcrops, the nature and properties of lower crustal materials deduced from geophysical studies are critical in imaging the present-day crust. **Ishikawa *et al.*** examine the seismic and elastic properties of lower crustal rocks from Enderby Land and Dronning Maud Land to provide insights into the lower crust of East Antarctica. They suggest a possible predominance of biotite-bearing continental crust.

The Napier Complex experienced unusually high temperatures during metamorphism of 900–1100 °C on a regional scale, providing the first recognized instance of UHT metamorphism. Mineral parageneses diagnostic of UHT metamorphism, including sapphirine + quartz, orthopyroxene + sillimanite + quartz and osumilite (Harley & Hensen 1990), have been recognized over a 200 km by 100 km area. The widespread distribution of UHT metamorphism, with estimated peak metamorphic temperatures in excess of 1120–1150 °C at relatively shallow crustal depths of 20–30 km (e.g. Harley & Motoyoshi 2000; Ishizuka *et al.* 2002; Harley 2004), requires explanation by unusual tectonic models to reasonably explain these crustal conditions. The terrane attracts great interest in how such extreme temperatures can be achieved in the mid- to lower crust, and represents a metamorphic end-member at the opposite extreme from the ultrahigh pressure (UHP) metamorphism found in continent–continent collision zones.

UHT metamorphism in the Napier Complex is a phenomenon that never has been found on such a scale anywhere else in the world. **Hokada *et al.*** model the thermal and barometric behaviour of the lower continental crust. Based on an extensive analysis of petrological, structural and geochronological data, they estimate the lateral and vertical extent of UHT lithologies, and discuss the difficulties in providing models that can sustain a >1000 °C thermal regime for crustal thicknesses of 4–5 km. It is stressed that an enormous quantity of heat is necessary for achieving this, and that modelling requires an active role for asthenospheric input. Experimental and empirical studies on various chemical systems in metamorphic mineral assemblages are essential in determining the temperatures and pressures prevailing under UHT conditions. The solubility of titanium in quartz under UHT conditions is evaluated with the help of experiments by **Kawasaki & Osanai** on samples from Bunt Island, from which they develop an empirical geothermometer, and they test it by applying it to selected localities in Enderby Land and Dronning Maud Land. This method should find application in many future studies, as quartz and titanium-bearing minerals such as rutile and ilmenite are common constituents in high-grade metamorphic rocks. **Sato *et al.*** examine the partitioning behaviour of Fe^{2+} and Mg between orthopyroxene and spinel from UHT assemblages. Although the partitioning does not seem to record UHT conditions because of retrograde exchange, the results are reliable indicators of post-peak conditions.

Fluid composition is a critical factor that controls metamorphism under UHT conditions without melting the rock. It is essential that the rocks should be anhydrous when the UHT conditions are attained. According to experimental studies (e.g. Johannes & Holtz 1996), even 1 wt% of water in a muscovite granite will lead to complete melting at UHT conditions. Therefore, the precursor rocks should either be essentially dehydrated during prograde metamorphism, or should have been previously anhydrous (by earlier metamorphism). The anhydrous mineral assemblages under UHT conditions were probably sustained by the presence of dry CO_2-rich fluid. Characterization of fluids in UHT rocks from the Napier Complex is elegantly carried out by **Tsunogae *et al.***, who apply Raman spectroscopy to obtain the precise chemical composition of the fluids that were present during peak metamorphism. The ubiquitous presence of CO_2 is demonstrated. Minor amounts of CH_4 and N_2 are also identified. Intriguingly, carbonate minerals present within the fluid inclusions further provide a unique window into the evolution of fluids during UHT metamorphism. CO_2-rich fluid has an important, if not instrumental, role in UHT metamorphism, because it can be an effective heat transfer medium. High-T carbonic fluids from asthenospheric mantle to crust can effectively transfer heat into the crustal rocks, much faster and more easily than thermal conduction or convection.

Enderby Land is also characterized by multiple episodes of dyke emplacement (Sheraton *et al.* 1987). The geochemical and tectonic significance of post-tectonic dykes is studied by **Suzuki *et al.***, who identify two distinct generations of dykes at Mt. Riiser-Larsen that exhibit contrasting source characteristics. An earlier 1.9–2.0 Ga generation of dykes is considered to have derived from a mantle wedge source, with possible connections with the continental crust formation of Rayner Complex. The less prominent 1.2 Ga dyke suite has ocean island basalt (OIB) or enriched mid-ocean ridge basalt (E-MORB) affinities. In addition to the emplacement of dykes, Enderby Land is also intruded by early Palaeozoic pegmatites. **Carson & Ague** evaluate geochemical element mobility associated with the infiltration of aqueous fluids in association with pegmatites, and model the depth of wall-rock metasomatism. They also suggest that the source for pegmatitic melts and aqueous fluids might be the underplating of sedimentary rocks by convergent tectonism between the Rayner Complex and the Napier Complex, implying an early Palaeozoic timing for the juxtaposition of these terranes in the western part of Enderby Land.

The Rayner Complex

The Rayner Complex was originally named for Proterozoic metamorphic lithologies adjacent to the Archaean Napier Complex (Kamenev 1972). It is made up of amphibolite- to granulite-facies orthogneisses and paragneisses, including pelitic, mafic, ultramafic and calcareous layers and boudins. Although the Rayner Complex was originally defined by lithologies south of the Napier Complex in Enderby Land, the main extent of the terrane is recognized to the east in Kemp Land and Mac Robertson Land. In the latter, the terrane is terminated eastwards by the late Neoproterozoic to Cambrian granulites of Prydz Bay, and southwards by metamorphic rocks and granitoids of similar age in the southern Prince Charles Mountains (Boger & Wilson 2005). The Rayner Complex involves the 990–900 Ma granulite-grade reworking of supracrustal lithologies, deposited on a basement that is mostly Palaeoproterozoic in the eastern section, with an Archaean component closer to the Napier Complex (Kelly *et al.* 2002; Halpin *et al.* 2005). Extensive intrusions of charnockite were emplaced during metamorphism along the eastern margin of the Rayner Complex (Young & Black 1991). The grade and timing of metamorphism and charnockitic magmatism, along with the nature of protolithic crust, are shared with the Eastern Ghats of the Indian peninsula, and the two terranes are now regarded as having been a single tectonic entity attached to the cratonic core of India before the Neoproterozoic (e.g. Dobmeier & Raith 2003). Metamorphic reworking of the eastern Rayner–Eastern Ghats terrane in the late Neoproterozoic is limited to its margins (east and south in the Rayner Complex, north in the Eastern Ghats; Mezger & Cosca 1999).

The geological evolution of the western part of the Rayner Complex is more problematic. A predominance of early Cambrian ages (Shiraishi *et al.* 1997; Motoyoshi *et al.* 2006) suggests that this area was reworked simultaneously with the metamorphism of the adjacent Lützow-Holm Complex. Metamorphic conditions, involving isothermal decompression after UHT peak metamorphism at Forefinger Point, are similar to those at Rundvågshetta, at the opposite end of the Lützow-Holm Complex. However, major differences between the Lützow-Holm and western Rayner complexes include the observation of prograde kyanite inclusions in garnet, and the eastward-decreasing grade of metamorphism in the former terrane. In addition, 800–700 Ma ages obtained in the western Rayner Complex (Asami *et al.* 1997, 2005; Shiraishi *et al.* 1997) have not been found in the Lützow-Holm Complex. Regardless, the extensive Cambrian reworking leads us to redefine this region as the 'Western Rayner Complex', in contrast to the main body of the Rayner Complex and the Lützow-Holm Complex (Fig. 4). The geological significance of the Western Rayner Complex is a subject of continuing and future research, and further field and analytical studies are required to understand this complicated section of East Antarctica.

The Lützow-Holm Complex

The Lützow-Holm Complex, located in eastern Dronning Maud Land (Fig. 4), is a late Neoproterozoic orogenic belt bounded by the late Mesoproterozoic Rayner Complex to the east and by the late Neoproterozoic to early Palaeozoic Yamato–Belgica Complex to the west (Shiraishi *et al.* 1992, 1994, 2003). It is a significant area for the investigation of the final collision between East and West Gondwana, because the Lützow-Holm Complex is considered to be a southern extension of the suture between them (e.g. Shiraishi *et al.* 1994; Fitzsimons 2000). The geology of this complex has been reviewed in several earlier studies (Hiroi *et al.* 1983, 1986, 1987, 1991; Shiraishi *et al.* 1994, 2003).

The Lützow-Holm Complex is composed of high-grade metamorphic rocks, including pelitic–psammitic gneisses, mafic to intermediate basic gneisses, subordinate lenses of ultramafic gneiss, marbles and calc-silicate rocks. Felsic pegmatitic dykes discordantly intrude the metamorphic rocks. Ultramafic lenses that were probably derived from oceanic crust are distributed across the central and southwestern part of the complex (Hiroi *et al.* 1986). Hiroi *et al.* (1991) postulated that the ultramafic lenses represent dismembered fragments of an ophiolite complex derived from the missing oceanic crust between older continents, now represented by the Yamato–Belgica and Rayner Complexes. The detailed structural evolution of the Lützow-Holm Complex has not yet been fully understood, although some parts of the complex have been structurally described in several studies (e.g. Kizaki 1962, 1964; Ishikawa 1976; Yoshida 1977, 1978; Matsumoto *et al.* 1979, 1982; Ishikawa *et al.* 1994; Motoyoshi & Ishikawa 1997; Ikeda & Kawakami 2004; Kawakami & Ikeda 2004*a*, *b*; Michibayashi *et al.* 2004; Osanai *et al.* 2004; Okamoto & Michibayashi 2005).

The metamorphic grade of the complex progressively increases from upper amphibolite facies on the Prince Olav Coast to granulite facies in Lützow-Holm Bay (Hiroi *et al.* 1991), with a 'thermal axis' of maximum peak temperature estimated to lie at the southern end of Lützow-Holm Bay, near Rundvågshetta (Motoyoshi 1986). Several lines of evidence suggest that the Lützow-Holm Complex has experienced a typical 'clockwise' $P–T$ path. These include prograde kyanite and staurolite as relict inclusions in garnet or plagioclase (Hiroi *et al.* 1983; Motoyoshi 1986; Kawakami & Motoyoshi 2004; Satish-Kumar *et al.* 2006*b*), and reaction textures in ultramafic rocks (Hiroi *et al.* 1986) are also significant. It has been observed that paragneisses from the Prince Olav Coast experienced the reaction staurolite = garnet + aluminosilicate + spinel + H_2O within the sillimanite stability field, whereas those from Lützow-Holm Bay experienced the reaction in the kyanite stability field (Hiroi *et al.* 1983, 1987). This petrographical evidence is peculiar among high-grade metamorphic terranes in East Antarctica, as no obvious prograde $P–T$ paths have been reported except for the Lützow-Holm Complex (Harley & Hensen 1990). UHT peak metamorphic conditions of about 1000 °C and 11 kbar, and subsequent isothermal decompression have been reported from Rundvågshetta (Kawasaki *et al.* 1993; Ishikawa *et al.* 1994; Motoyoshi & Ishikawa 1997). **Yoshimura *et al.*** present further petrological evidence for UHT metamorphism at Rundvågshetta (Fig. 1). The coexistence of sapphirine and quartz within garnet porphyroblasts, high Al contents of orthopyroxene and temperature estimates based on ternary feldspar thermometry suggest that the rocks in this region were metamorphosed above temperatures of 1000 °C. In the neighbouring Skallen region (Fig. 1), **Goto & Ikeda** present crystal size distributions (CSDs) of garnet in quartzo-feldspathic gneisses metamorphosed at above 800 °C. They attempt to provide reasons for the differences in garnet nucleation and growth between layers. Based on the crystal size distribution of garnet they predict less predominance of Ostwald ripening, even at granulite-facies conditions, in the absence of fluids.

The timing of the peak regional metamorphism has been estimated by sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon dating at between 521 ± 9 and 553 ± 6 Ma (Shiraishi *et al.* 1992, 1994, 2003). Zircon from syn-deformational leucosome has a U–Pb age of 517 ± 9 Ma, which is interpreted as a melt crystallization age (Fraser *et al.* 2000). Fraser *et al.* (2000) suggested from combined SHRIMP zircon analyses and Ar–Ar hornblende and biotite chronology that post-peak decompression and subsequent cooling to *c.* 300–350 °C took place within a time interval of *c.* 520–500 Ma. A summary of recent dating results, has been given by Nishi *et al.* (2002) and references therein. Recently, however, *in situ* monazite chemical Th–U–total Pb isochron method (CHIME) dating and zircon SHRIMP dating combined with the microstructural observation of monazite and zircon by Hokada & Motoyoshi (2006) yield ages of 650–580 Ma and 550–520 Ma for monazite in garnet-bearing felsic gneisses from the Skallen region. Based on the medium to heavy REE (MREE–HREE)-enriched nature of 650–580 Ma monazite, Hokada & Motoyoshi interpreted the older ages as monazite growth under prograde, garnet-absent conditions, whereas the 550–520 Ma age group represents monazite grown at peak metamorphism in the presence of garnet. Dunkley (2007), reporting a similar spread of ages from 600 to 500 Ma, interpreted the age range as also reflecting the progressive growth of zircon at various stages during a single clockwise *P–T* history of the complex. These contrasting interpretations will be tested in the near future by petrological and microstructural studies, to find out whether the unexpectedly long duration of a single metamorphism in the Lützow-Holm Complex is feasible (Dunkley 2007). **Miyamoto *et al.*** review the chronology of events after peak metamorphism, and present new Sm–Nd and Rb–Sr ages for key metamorphic rocks in the southwestern Lützow-Holm Complex. Two possible explanations are put forward for post-metamorphic thermal perturbations in the region, involving either cooling and uplift of the terrane, or reheating by magmatic and associated metasomatic activity.

Proterozoic and Archaean detrital cores of zircon grains from Rundvågshetta and West Ongul Island (Shiraishi *et al.* 1994; Fraser 1997) demonstrate ancient provenance in the metasediments of the Lützow-Holm Complex. **Satish-Kumar *et al.*** focus on isotopic compositions and geochemical characteristics of high-grade marbles from the Lützow-Holm Complex. From earlier studies the inferred depositional ages of sedimentary protoliths in the Mozambique Ocean that separated East and West Gondwana is some time between *c.* 630 Ma (the earliest metamorphic age reported by Hokada & Motoyoshi 2006) and the youngest Sm–Nd model age of *c.* 850 Ma (**Shiraishi *et al.***). Carbon, oxygen and strontium isotopic compositions indicate that most metacarbonate rocks were altered by multiple episodes of fluid activity, related to pre-peak, peak and post-peak metamorphic events. By applying multiple geochemical criteria, near-pristine sedimentary signatures were identified in some layers, which when compared with the non-metamorphic chemostratigraphic curves suggest a depositional age between 830 and 730 Ma.

Along the Prince Olav Coast, Cape Hinode (Fig. 1) is an exceptional outcrop where the late Neoproterozoic ages are completely absent and only a *c.* 1000 Ma age has been reported (Shiraishi *et al.* 1994, 2003). Grenvillian ages have been reported from three other localities from the Lützow-Holm Complex, including Skavsnes (Fraser 1997), Telen and Innhovde (Shiraishi *et al.* 2003). All of these represent inherited cores of zircon with magmatic zoning, and no *c.* 1000 Ma metamorphic overgrowths have been found. Therefore, Shiraishi *et al.* (2003) interpreted the *c.* 1000 Ma age as representing localized igneous activity. Hiroi *et al.* (2006) have suggested, on the basis of U–Th–Pb ages reported by Shiraishi *et al.* (1994, 2003) and Motoyoshi *et al.* (2004), that the gneisses of Cape Hinode are exotic to other parts of the Prince Olav Coast. Xenocrystic garnet and kyanite in adakitic trondhjemites and tonalities from Cape Hinode are treated by **Hiroi *et al.*** as phases that were entrained in Mesoproterozoic tonalitic magmas. Kyanite is a stable matrix phase in Cape Hinode metapelites, contrary to the mode of occurrence of kyanite as relic inclusions within garnet in other parts of the Lützow-Holm Complex. The lack of 600–500 Ma ages from Cape Hinode also supports the notion of an allochthonous block emplaced in the waning stages of amalgamation of East and West Gondwana. The major age population of 1080–1000 Ma reported from Cape Hinode is comparable with that of the Maud Province to the west, rather than with the 990–900 Ma ages of the closer Rayner Complex. Continuation from Cape Hinode to the Vijayan Complex of Sri Lanka is possible, with extensions to Mozambique and the Natal Belt (Hiroi *et al.* 2006). Alternatively, Cape Hinode may represent an isolated block, as implied by gravity and geomagnetic data (Nogi *et al.* 2006).

Pre- to syn-metamorphic granitic rocks are characterized by the irregular shape of the intrusive boundaries, intergradational contacts and intense deformation, and only one of them from Breidvågnipa has been dated at 576 Ma by the Rb–Sr whole-rock isochron method (Shimura *et al.* 1998). Post-tectonic granitic dykes intrude across gneissic fabrics throughout the Lützow-Holm Complex. These granites have been dated by the Rb–Sr whole-rock isochron method as younger than 500 Ma (e.g. Nishi *et al.* 2002; Ajishi *et al.* 2004). Suda *et al.* (2006) carried out a geochemical study of metabasites (mostly garnet-absent) in the Lützow-Holm Complex. **Suda *et al.*** further studied the geochemical and isotopic composition of metamorphosed ultramafic and mafic rocks, and distinguish those of the eastern part of the Lützow-Holm Complex as derived from immature continental crust during the Mesoproterozoic, from those in the western part as products derived from a matured crust. These results further establish the changing tectonic environment in eastern Dronning Maud Land during the Neoproterozoic.

Because of the systematic and gradual southwestward increase of metamorphic grade from upper amphibolite facies to UHT conditions, the Lützow-Holm Complex provides a good example for study of the behaviour of melts, fluids and accessory minerals under these conditions. Satish-Kumar *et al.* (2006*a*) studied scapolite boudins from Skallen and presented detailed petrographical and geochemical evidence for changing fluid composition from scapolite phase equilibria. Kawakami *et al.* (2006) reported the mode of occurrence of sulphide minerals throughout the Lützow-Holm Complex and found that sulphide inclusions are completely different in composition and species from those in the rock matrix, retaining information from peak metamorphism. Inclusion sulphides were mostly restitic in composition, suggesting the loss of sulphide melt from the rocks of the Lützow-Holm Complex during anatexis. **Kawakami *et al.*** characterize the occurrence of kornerupine in mafic and ultramafic rocks from Akarui Point. They propose possible sources for boron through aqueous fluids derived from sediments or hydrothermal alteration of protoliths by seawater.

The Yamato–Belgica Complex

The Yamato–Belgica Complex is also thought of as a late Neoproterozoic to Cambrian orogenic terrane between the Lützow-Holm Complex and the Sør Rondane Mountains (Fig. 4). It consists of two inland mountain ranges, the Yamato and Belgica Mountains. The area is characterized by widespread granite and syenite intrusions with minor amphibolite-facies metamorphic rocks of quartzo-feldspathic and intermediate composition (Shiraishi *et al.* 1994). Rare granulite-facies rocks with peak metamorphic conditions of 700–750 °C and <5 kbar are found, but the relationship between amphibolite-facies and granulite-facies rocks is uncertain.

Age constraints for this area are mainly from zircon SHRIMP data by Shiraishi *et al.* (1994, 2003) that range from 1000 to 500 Ma, with the exception of one spot yielding an age of *c.* 2500 Ma. Quartz monzonite and granitic gneiss from the Yamato Mountains yielded an age of 535 Ma, which is interpreted as the timing of amphibolite-facies metamorphism and magmatism. These events followed the widespread syenite magmatism of the area, but the actual timing is not well constrained. Although there are not enough data available to establish the Proterozoic–Cambrian history of this area, the lack of essential >1000 Ma ages suggests juvenile crustal formation in the late Mesoproterozoic, similar to the Sør Rondane Mountains and Central Dronning Maud Land to the west, and in marked contrast to the Lützow-Holm Complex.

The Sør Rondane Mountains

Outcrops in the Sør Rondane Mountains are dominated by Mesoproterozoic crustal lithologies that vary from predominantly arc-related material to continental materials from north to south (Shiraishi *et al.* 1991; Grew *et al.* 1992; Osanai *et al.* 1992). A semi-ductile shear zone divides the region into a northeastern granulite-facies terrane and a southwestern amphibolite-facies terrane. Recently, Asami *et al.* (2007) estimated peak granulite-facies metamorphism at temperatures of 860–895 °C and pressures of around 12 kbar for the NE terrane. Furthermore, they found evidence for retrograde metamorphism under amphibolite-facies conditions. Extensive geochronological results presented by **Shiraishi *et al.*** suggest that crustal formation in the Sør Rondane Mountains occurred in the late Mesoproterozoic, and that the NE and SW terranes were juxtaposed around *c.* 570 Ma under amphibolite-grade metamorphic conditions, subsequent to higher temperature metamorphism at *c.* 600 Ma that affected only the NW terrane. An exact picture of late Neoproterozoic to Cambrian terrane amalgamation and tectonic evolution of the Sør Rondane Mountains requires further field studies, which are being conducted by JARE between 2007 and 2010.

Central Dronning Maud Land

High-grade metamorphic rocks intruded by voluminous igneous bodies form coastal and inland mountainous outcrops in central Dronning Maud Land (CDML), from 2° to 14°E (Dallmann *et al.* 1990). Metamorphic rocks in this region comprise banded gneisses and migmatites, whereas igneous rocks are mainly of charnockitic, syenitic and granitic composition (Ohta 1999). Two tectonothermal events have been distinguished in the region, at *c.* 1100 Ma and between 560 and 490 Ma (Jacobs *et al.* 1998, 2003*a*; Paulsson & Austrheim 2003). The younger event is generally considered as part of the East African–Antarctic Orogeny and involves an early collisional event at *c.* 560 Ma followed by large-scale extension associated with voluminous granitic magmatism. A variety of rock types are found in the CDML, including pelitic granulites, garnet-, biotite- and/or hornblende-bearing gneisses, charnockites, mafic granulites and calc-silicate rocks. An early Grenvillian age (*c.* 1150 Ma) for granulite-facies metamorphism, followed by amphibolite-facies metamorphism at *c.* 560 Ma, is ascribed to these rocks. In addition, *c.* 630 Ma ages have been obtained from the coastal outcrop at Schirmacher Oasis, suggesting a different evolution of this area in the late Neoproterozoic compared with that of the inland mountains. A recent study by Bisnath *et al.* (2006) proposed a two-stage collision model, involving an initial arc–continent collision followed by continent–continent collision.

Baba *et al.* compare the metamorphic evolution of Schirmacher Hills with that of Mühlig-Hofmanfjella and find that, although there is no clear difference in peak P–T conditions, the retrograde P–T paths contrast between these two regions. They suggest that the Schirmacher Hills could be part of SE Africa, whereas the inland mountain regions were part of crust formed during the final amalgamation of East Gondwana. **Owada *et al.*** consider the geochemical characteristics of post-tectonic mafic dykes and find that the parental magma was derived from a metasomatized mantle source. Based on a detailed evaluation of Sr and Nd isotope systematics of CDML and the Sør Rondane Mountains, they suggest the possibility of a suture zone of East and West Gondwana transition between these two regions.

Emerging thoughts and future perspectives

Geophysical studies

The continuing compilation of aeromagnetic, marine and satellite-based surveys by the Antarctic Digital Magnetic Anomaly Project (ADMAP) provides the best picture of the internal architecture of East Antarctica, with the latest versions of the East Antarctic magnetic anomaly map and the Antarctic Digital Magnetic Anomaly Map published by Golynsky (2007) and von Frese *et al.* (2007), respectively (http://www.geology.ohio-state.edu/admap/). Geodynamic models of the assembly of various terranes between and during cycles of supercontinent formation need to take into account the regional-scale structural information that magnetic anomaly maps provide. A belt of high magnetic anomalies that curves around the coastal Grunehogna craton in western Dronning Maud Land is correlated with the *c.* 1.1 Ga Namaqua–Natal mobile belt in South Africa, which shows a similar pattern of anomalies (Golynsky & Jacobs 2001). In contrast, a broad area of low magnetic signature extends across central and eastern Dronning Maud, which corresponds well to the interpretation of this region as Mesoproterzoic felsic crust incorporated into the broad East African–Antarctic Orogen (**Jacobs *et al.***; **Shiraishi *et al.***). This geomagnetic domain has an abrupt north–south trending termination against a region of positive magnetic anomalies, just east of the Yamato Mountains, that corresponds exactly to the terrane boundary between the Sør Rondane Mountains and Yamato–Belgica Complex and the Lützow-Holm Complex inferred by **Shiraishi *et al.*** However, in other key areas of Late Neoproterozoic geological activity, especially around Prydz Bay and Lützow-Holm Bay, there is a significant discrepancy between the latest tectonic models made on the basis of surface geology (field geology, petrography and geochronology) and geophysics (aeromagnetic mapping). Golynsky *et al.* (2002) and Golynsky (2007) suggested that the presence of intense east–west linear anomalies, which extend across the Lambert Graben from the northern Prince Charles Mountains to Prydz Bay, and from the southern Prince Charles Mountains to the Grove Mountains, implies a tectonic association of these areas that predates late Neoproterozoic activity in the region. These features were associated by Golynsky (2007) with paired east–west-trending belts of negative and positive anomalies that extend from Prydz Bay to Lützow-Holm Bay, where the boundaries of these belts rotate into a trend perpendicular to the Prince Olav Coast. These belts are interpreted as late Mesoproterozoic terranes, corresponding to the Rayner Complex, that suture together the Archaean terranes of the Napier Complex and the Ruker terrane. The model implies that late Neoproterozic metamorphism and magmatism observed in Prydz Bay and the southern Prince Charles Mountains is unrelated to that found in Lützow-Holm Bay. Counter to tectonic models by Boger *et al.* (2001) and Phillips *et al.* (2006) that involve the collision of an Indo-Antarctic continent with inner Antarctica during the formation of Gondwana, Golynsky (2007) attributed all late Neoproterozoic activity to within-plate processes, similar to the concept proposed for the Grenvillian circum-Antarctic mobile belt (Yoshida 1992, 2007). However, such a interpretation neglects evidence of the heterogeneous nature of crust modified by late Proterozoic metamorphism in the Lützow-Holm Complex, as indicated by a diversity of protolith and crustal model ages (**Shiraishi *et al.***; **Suda *et al.***), and continental to oceanic geochemical signatures (**Satish-Kumar *et al.***; **Suda *et al.***; **Hiroi *et al.***). In the future, integration of geomagnetic data with surface petrology and geochronology should resolve these issues.

Another technique to obtain basement geological data inland is ice core drilling that continues to reach basement rocks. There is a two-fold benefit involved in continental ice core drilling, as both palaeoenvironmental and palaeocontinental problems can be solved in a single project. Ice core drilling projects at Vostok and Dome Fuji have returned promising results and technical know-how on pursuing drilling in subzero conditions. In fact, the Vostok drilling has succeeded in collecting sediment from the bottom of the ice sheet, and preliminary SHRIMP dating of zircon and monazite yielded a range of ages between 1.8 and 0.6 Ga, similar to those seen in coastal mobile belts and a further indication of the pervasive involvement of Mesoproterozoic and Neoproterozoic geological activity in the formation of East Antarctica (Rodionov *et al.* 2006). To solve the problems of palaeocontinental uncertainties relating to obscurity of the inland Antarctic continent it will be necessary to gather information from inland regions.

Field-based studies

Because of the low-latitude climate, lack of rainfall, and absence of vegetation (excepting mosses and lichen), outcrops in Antarctica provide high-quality field information for geological studies. Mechanical weathering by the action of wind and glacial abrasion, and limited chemical or hydrothermal alteration, results in the exposure of fresh outcrops that are perfectly suited for multidisciplinary geological studies (Fig. 5).

We have identified the following key localities in eastern Dronning Maud Land, which need further attention to improve our understanding of the Archaean to early Palaeozoic evolution of East Antarctica.

Enderby Land is a potentially important area for studies not only for clarifying the tectonism in the Archaean but also for understanding lower crustal processes. This region can enlighten us further about: (1) the formation of continental crust in the Archaean; (2) the causes and consequences of unusually high-temperature (>1000–1150 °C) metamorphism in the Napier Complex; (3) Proterozoic suturing between the Archaean cratons of India (e.g. Dharwar–Napier) and Archaean terranes in the southern Prince Charles Mountains of Antarctica; (4) subcontinental mantle dynamics,

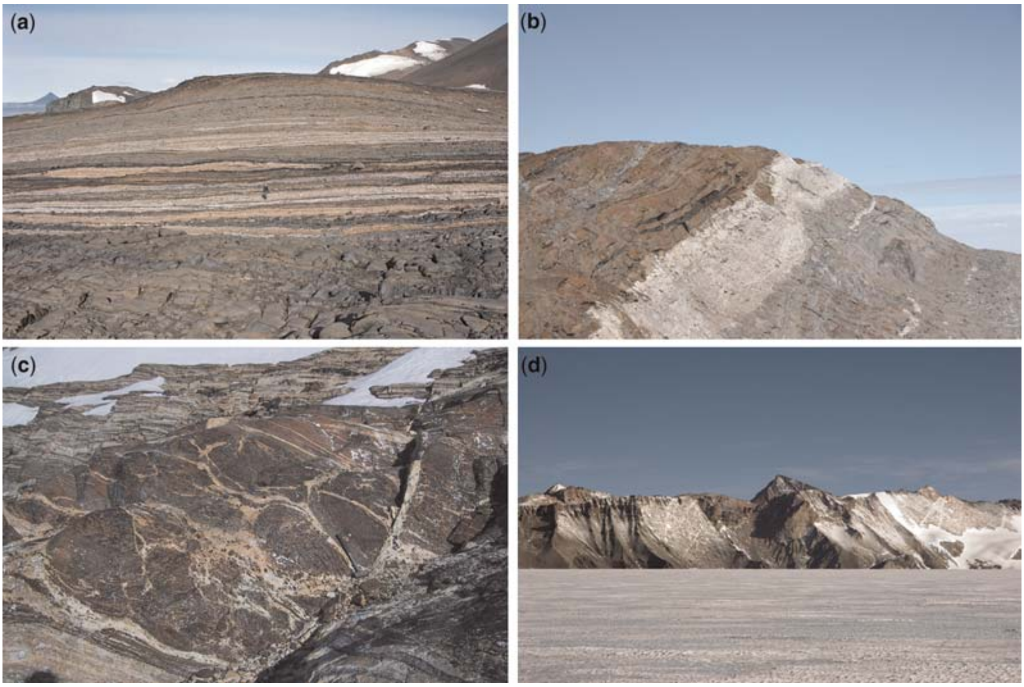

Fig. 5. Illustrative outcrops in East Antarctica, and their potential for future research. (**a**) Field photograph showing the regional distribution of UHT metamorphic rocks in the Napier Complex at Tonagh Island (JARE-38). The Napier Complex is a key area in understanding the crustal evolution in the Archaean. (**b**) Metacarbonate and paragneiss sequences at Skallevikshalsen (JARE-46), with potential for understanding the depositional environment of sediments between East and West Gondwana. (**c**) Partial melting and melt segregation as seen in the paragneisses at Skallevikshalsen (JARE-44); this is a topic of prime importance for understanding the generation, segregation and movement of melts in middle to deep continental crust. (**d**) The inland nunataks of the Sør Rondane Mountains (JARE-49). Geological evidence from these nunataks may clarify the history of amalgamation of East and West Gondwana.

as revealed by Proterozoic dyke swarms; (5) the amalgamation of the Napier and Rayner Complexes with other terranes in the formation of Gondwana.

Moving west, the Lützow-Holm Complex has well-preserved regional amphibolite to UHT metamorphic zones with classic clockwise $P-T$ trajectories. The problems that remain to be solved include: (1) the unravelling of the earlier peak granulite to UHT metamorphism and later extensive rehydration; (2) the significance of dual 600–550 and 550–500 Ma events in a regional context of Gondwana amalgamation; (3) the provenance and tectonic setting of volcano-sedimentary sequences and basement lithologies.

The Yamato and Belgica Mountains are constituted mostly of felsic orthogneisses and syntectonic plutonic rocks. There are fewer suitable lithologies for the detailed characterization of the metamorphic $P-T$ evolution for comparison with the neighboring Lützow-Holm Complex and the Sør Rondane Mountains. However, preliminary information regarding the geochemical features of plutonic rocks needs to be further developed to determine if the Mesoproterozoic juvenile crust identified in central Dronning Maud Land and the Sør Rondane Mountains extends to this area.

Further west, the Sør Rondane Mountains is an important area from a regional geological point of view. This area is seen as critical in finding solutions to longstanding problems on the suturing of East and West Gondwana. The variety of ages recorded in this region may be critical in distinguishing the 600–550 and 550–500 Ma conjugate tectonic belts and the order in which crustal fragments amalgamated to form Gondwana.

Understanding geological extremes

The geology of East Antarctica not only has provided a regional framework for supercontinent correlation studies but also has been critical in understanding some of the most extreme geological phenomena in crustal regimes. One such extreme is UHT metamorphism. It is increasingly accepted that UHT conditions exist in the continental crust; however, it is still a challenge to understand the factors that control such unusual thermal regimes. In this perspective, more accurate physical parameters and much tighter temporal constraints of such extreme conditions need to be determined. It is also essential to understand the total heat budget, the quantity of heat added to a certain initial or steady-state condition, and whether other factors such as fluids played a role.

Precise determination of physical conditions under extreme crustal metamorphism is essential in modelling crustal evolution. It is a challenge to duplicate these conditions in the laboratory, although recent developments in experimental petrology can achieve this, except for the time factor. Microstructures in minerals, especially exsolution textures, are now recognized as powerful tools for recovering high-pressure and -temperature conditions prior to cooling and exhumation. Typical examples are the recovery of pigeonite compositions from orthopyroxene with Ca-clinopyroxene lamellae (e.g. Harley 1987; Ishizuka *et al.* 2002), recovery of single-phase compositions from ternary mesoperthitic feldspar (Hokada 2001) and Ti exsolution in quartz or in garnet (**Kawasaki & Osanai**). However, this technique needs caution in selecting suitable compositional ranges to recover such information and thermodynamic models to be applied for temperature estimation (e.g. Hokada & Suzuki 2006).

The formation and preservation of UHT rocks in the crust is essentially controlled by the fluid regime during prograde metamorphism. Dehydration of rocks prior to partial melting is essential to restrict the melt fraction to a critical melting proportion, as larger proportions of melt can destroy the solid rock structure. In other words, UHT metamorphism should be observed only in rocks that are more or less in restitic nature, and potentially anhydrous UHT rocks may be widely distributed in the deepest continental crust worldwide. Composition of fluid also strongly controls the melt fraction. CO_2-rich fluid flow from deeper (and hotter) crust transfers heat to shallower crust more effectively than conduction or convection. In addition, we also need to pay attention to the different cooling and uplifting processes that result in the exposure of extremely metamorphosed rocks without completely destroying the original parageneses. UHT metamorphism with subsequent isothermal decompression can be readily achieved by crustal uplift, and internal radioactive heat production in thickened crustal is a potential source of heat. In contrast, UHT metamorphism with isobaric cooling is problematic; that is a scenario that may be achieved when the heat source is local and magmatic (e.g. Bamble terrane in Sveconorwegian or Wilson Lake in Canada, where UHT metamorphic zones are developed around anorthosite bodies). Therefore, our fundamental understanding of extreme crustal processes remains primitive. The Napier Complex in East Antarctica is perfectly suited to understand the occurrence and importance of geological extremes.

Nanoscience and supercontinents: recent technological realms

The past two decades have seen wide application of electron microprobe and ion microprobe techniques to investigate the chemical and isotopic composition of minerals, especially the accessory phases, on a micrometre scale. Accessory phase behaviour with regard to trace element geochemistry (including REE, P, Zr, Ti, U and Th) is a major topic in the microanalytical world and has potential in resolving many problems relating to the evolution of continents. In recent years, barriers have been broken in linking the isotopic record with petrology in complex and multiply metamorphosed and deformed terranes (Rubatto 2002; Müller 2003; Vance *et al.* 2003). Within our reach is a new phase in accessory mineral research that will unravel complicated metamorphic and tectonic histories. Submillimetre-scale techniques are required to distinguish events in the multiply reactivated mobile belts of East Antarctica. Effective strategies include: (1) U–Th–Pb dating on a sub-grain, micrometre scale of zircon, monazite, apatite, titanite, rutile, perrierite and other accessory minerals by ion microprobe, electron microprobe, and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS); (2) tying in the microstructural context of accessory phase growth with geochronology and chemistry, using high-resolution secondary electron, back-scattered electron, and cathodoluminescence imaging under a scanning electron microscope; (3) experimental and empirical approaches to understanding the stability and chemical behaviour of accessory phases during deformation, metamorphism and partial melting (e.g. Harrison & Watson 1983; Watson & Harrison 1983); (4) integration of metamorphic and magmatic ages obtained by microbeam techniques with Lu–Hf isotope model ages for understanding the crustal extraction history (e.g. Kemp *et al.* 2006); (5) understanding Precambrian crustal evolution from non-radiogenic isotopes such as oxygen (e.g. Cavosie *et al.* 2005). Application of these advanced analytical techniques in East Antarctica will help in formulating reasonable geodynamic models of pre-Gondwanan supercontinent evolution.

Supercontinent cycle, global tectonics and Earth's environment

The Neoproterozoic to early Cambrian period was a time of extensive global tectonic activity that culminated in the amalgamation of the supercontinent Gondwana. This time span is also well known for phenomenal changes in climatic conditions that predated the Cambrian explosion in biodiversity. However, extreme climate change models invoking a 'Snowball Earth' (Hoffman *et al.* 1998) or drastic changes in Earth's obliquity (Evans 2000) do not seem to satisfactorily explain the complex scenario (Meert 2007). Several lines of evidence have started to appear for the role of global tectonism in creating an environment conducive to biological activity (e.g. Maruyama & Santosh 2008; Meert & Liebermann 2008; Stern 2008).

Undisputedly, a key factor that controls global environment is CO_2 concentration in the atmosphere. Although volcanogenic-CO_2 input to the atmosphere seems to be a potential source of sudden large-scale climatic variations, other sources such as CO_2 transfer through orogenesis and oxidation of an earlier biosphere cannot be neglected. Variations in atmospheric CO_2 in the past are clearly recorded by carbon isotope excursions in carbonate sediments that record conditions in palaeo-oceans. Examples of Neoproterozoic carbon isotopic excursions combined with geological evidence convincingly indicate two major and several minor glaciation events (e.g. Halverson *et al.* 2005). It still remains unclear how much the closure of oceans between the continents has a bearing on global climate change. Furthermore, it is perceived that the spatial extent of Neoproterozoic orogenic belts retained in the present day continental crust must have been a few orders of magnitude larger than what we see in the Cenozoic Alpine–Himalayan Orogeny. The impact of Neoproterozoic amalgamation of the Gondwana supercontinent on the global environment is yet to be clarified and information from East Antarctica is crucial in solving this problem.

Concluding remarks

Studies on Antarctica have considerably refined our knowledge on the geodynamic evolution of continental crust. We envisage Antarctica as a model in Earth Science studies, in the advancement of science and for the peaceful living of mankind. However, because of its remoteness and extreme weather, Antarctica is still a difficult place to carry out geological fieldwork. As discussed above, many fundamental problems remain unsolved. However, progress through international collaboration can efficiently tackle this handicap. The future of Antarctic geoscience research seems bright through collective effort from different countries, and will be a driving force for the advance of our understanding of the history of the Earth.

Enormous progress has been achieved in the past 50 years of geological research in East Antarctica. However, technology has overwhelmingly overtaken the pace of basic scientific research. The incongruity between basic scientific research and the momentum with which information is provided by the latest technology is challenging the whole world of science itself. Geoscience research is no exception to this trend. Being part of the natural sciences, geoscience research can act as a link between progress achieved in basic science and technology that can effectively transfer information for society. Henceforth, the keyword for the future is 'Earth system science', where natural science can sustain life and vice versa. Antarctica is an ideal place for resolving the complex problems of geoscience studies.

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