

# THE GEOLOGY OF ANTARCTICA

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## Summary

Antarctica is the last discovered and most inhospitable of the continents. It is also the driest, the coldest and -- with a mean surface elevation of 2500 meters -- the highest of all continents. With 13,661,000 square kilometers it is nearly twice the size of Australia and only 2% of the continent is ice-free. However, this two percent is still roughly twice the size of the European Alps and -- because of the lack of vegetation and soil -- they are almost 100% outcrop and have puzzled geologists for nearly 200 years. Geologically, Antarctica is made up of two principal domains: Eastern Antarctica is the part that is covered by the main polar ice cap and is made up mostly of the Precambrian rocks of the East Antarctic Shield. It also includes the largest mountain range of the continent: the Trans Antarctic Mountains. In contrast, West Antarctica is located south of the Pacific and Atlantic oceans and includes the basins of the Ross and Weddell Seas and the intervening landmasses of the Antarctic Peninsula, Ellsworth Mountains and Marie Byrd Land. Western Antarctica is dominated by Mesozoic and Cenozoic geological evolution. This article discusses all major geological subprovinces including a brief overview of the glacial history.

## 1. Introduction

The discovery of coal measures and the famous Permian (285-245 Ma) plant leaves known as *Glossopteris* in the Trans Antarctic Mountains at the turn of the twentieth century ignited in earth scientists an intense and continuing quest to understand the geology of Antarctica, the most remote and hostile of the continents. Even though over 98% of its landmass is covered in ice and hence unable to be studied and sampled

directly, Antarctica is recognized as a key geological link between the other southern continents of the world. Indeed, Antarctica preserves a remarkable record of earth history from 3800 million years ago to the present, featuring important events in the formation, evolution and break-up of past supercontinents such as Gondwanaland (e.g. Dalziel, 1991; Moores, 1991).

At its most general level the geology of the present continent can be divided into two broad realms (Tingey, 1991*a, c*). East Antarctica is largely covered by the main polar ice cap and is bounded seawards by the long semi-circular coastline that extends from about 20°W through to 160°E and lies at between 66°S and 70°S for much of its length. East Antarctica is bounded to the west by the Trans Antarctic Mountains (TAM), a major mountain belt some 3000 km in length that rises to over 4500 metres in height (Fig. 1).



Figure 1: Antarctica, showing its broad division along the Transantarctic Mountain / Ross Sea / Weddell Sea region into the older East Antarctic Shield (pink) and the generally younger West Antarctic domain (green), which consists of a collage of microcontinental blocks and the magmatic arc of the Antarctic Peninsula. The intervening strip distinguished by the purple colour represents the region dominated by the Cambro-Ordovician Ross Orogen, the Devonian-Jurassic Beacon Supergroup sediments and the Jurassic Ferrar large igneous province. The South Pole is indicated by the cross symbol in East Antarctica.

West Antarctica, situated south of the Pacific and Atlantic Oceans, includes the basins of the Ross and Weddell Seas and the intervening landmass of the Antarctic Peninsula,

Ellsworth Mountains and Marie Byrd Land. This geographical distinction between East and West Antarctica reflects a marked set of geological distinctions. The major geological units and features of East Antarctica largely formed and developed in the Precambrian or Palaeozoic to early Mesozoic (largely pre-170 Ma). In contrast, West Antarctica is dominated by a Mesozoic and Cenozoic geological evolution related to the break-up of Gondwana, development of the Pacific plate and subduction of oceanic crust along a long-lived Andean margin. In this contribution the geology of Antarctica will be described and interpreted firstly for East Antarctica and then for West Antarctica, with the relations between the two domains considered through an appraisal of the evolution of the Ross Sea rift and the Cenozoic uplift of the TAM. The work will conclude with a brief summary of current knowledge and ideas on the spectacular glacial history of the continent.

Proceeding further into the simple two-fold division given above, East Antarctica can be considered to consist of two principal domains:

- a) *The so-called East Antarctica Shield (EAS)*. This comprises an as yet undefined number of distinct geological terranes or provinces that experienced their major phases of crust formation and development in the Precambrian or earliest Palaeozoic (Tingey, 1991a). These terranes were welded together during collision events either in the Precambrian or, as shown from the latest studies, in the Cambrian at 550-500 Ma. Permian – Triassic continental sediments are locally preserved as a cover to the older deformed rocks in the EAS; whilst Jurassic mafic magmatism is manifested as dyke swarms and plateau basalts in a few areas.
- b) *The Trans Antarctic Mountains (TAM) / Ross Belt*. In this domain a thick sedimentary cover sequence, the Devonian to Triassic / Jurassic Beacon Supergroup, and voluminous doleritic sills and basaltic lavas of the Ferrar Group overlie older rocks that were deformed, metamorphosed, and intruded by granites in the Ross Orogeny at 540-480 Ma. This deformed basement contains some relicts of Precambrian rocks of the EAS but is dominated by sedimentary and volcanic rocks formed marginal to the EAS or in distinct terranes accreted to the margin of East Antarctica by 480 Ma.

West Antarctica too can be considered to consist of two broadly defined domains:

- a) *The microplates, which preserve rotations and histories that are distinctive for certain periods of time in the Mesozoic*. Inboard microplates, such as the Ellsworth-Whitmore Mountains, preserve extensive Palaeozoic histories compatible with East Antarctica and do not record significant subduction-related magmatism in the Mesozoic. On the other hand, the outboard microplates of the Antarctic Peninsula, Thurston Island and Marie Byrd Land, record extensive arc-related magmatism or arc-related sedimentation in the Mesozoic, superimposed on Palaeozoic basement complexes.
- b) *The rift or extensional environments of the Weddell Sea and, in particular, the Ross Sea*. Early Cretaceous and Tertiary extension and rifting in the latter region has been linked with Cenozoic magmatism on the edge of East Antarctica and with the uplift of the TAM.

## 2. East Antarctic Shield

The East Antarctic Shield (Fig. 2) consists of a variety of Archaean and Proterozoic to Cambrian high-grade terranes that have distinct crustal histories and were amalgamated at various times in the Precambrian to Cambrian. The key tectonothermal events or cycles recorded in the EAS are late Archaean to earliest Proterozoic (<2840 Ma but >2480 Ma), Palaeoproterozoic (2200-1700 Ma), Mid- to Neoproterozoic (1400-920 Ma), and latest Proterozoic to Cambrian (600-500 Ma: “Pan African”). The recent recognition of intense high-grade metamorphism and deformation at 600-500 Ma in a number of regions, coupled with the preservation of distinct earlier crustal histories in intervening terranes, refutes the notion of a coherent circum-East Antarctic “Grenville” orogenic belt. Hence the concept, embodied in Rodinia models, of a ca. 1000 Ma collision of a unified East Antarctic Craton with other parts of East Gondwana is no longer viable.

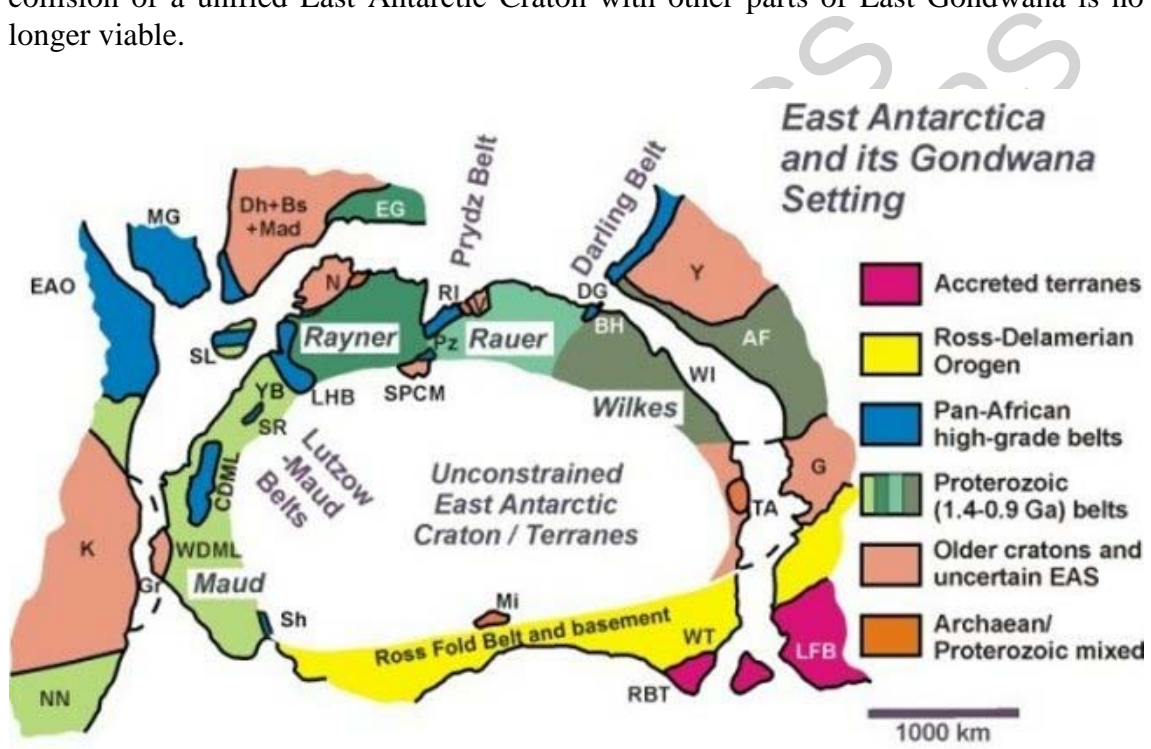


Figure 2: Map of East Antarctica in its reconstructed Gondwana context, modified and extended from Fitzsimons (2000b).

Areas mentioned in the text are labelled. Labels are as follows: AF (Albany-Fraser Province); BH (Bunger Hills); CDML (Central Dronning Maud Land); DG (Denman Glacier); Dh+Bs+Mad (Dhawar, Bastar and Madras cratons / provinces of India); EAO (East African Orogen); EG (Eastern Ghats); G (Gawler Craton); Gr (Grunehogna Craton); K (Kalahari/Kaapvaal Craton); LFB (Lachlan Fold Belt); LHB (Lutzow-Holm Bay); Mi (Miller Range); MG (Madagascar); N (Napier Complex); NN (Namaqua-Natal Belt); Pz (Prydz Bay); RBT (Robertson Bay Terrane); RI (Rauer Islands); Sh (Shackleton Range); SL (Sri Lanka); SPCM (Southern Prince Charles Mountains); SR (Sor Rondane Mountains); TA (terre Adelie, Mawson Craton); V (Vestfold Hills block); WDML (West Dronning Maud Land); WI (Windmill Islands); WT (Wilson Terrane); Y (Yilgarn Craton); YB (Yamato-Belgica Complex)

As a starting point the various areas or terranes of the EAS may be divided into four, partially overlapping, categories according to their age, degree of reworking, and nature and ages of the reworking events.

1. Archaean (> 2500 Ma) to Palaeoproterozoic (> 1700 Ma) terranes with limited or negligible later overprinting effects resulting from later tectonic events. In these terranes, which occur around the coast of the EAS, the Archaean-Palaeoproterozoic geological histories are largely intact. The principal examples of such terranes are the Napier Complex of Enderby Land, the Grunehogna Craton of western Dronning Maud Land, the Vestfold Block of Prydz Bay, and the Mawson Block of Adelie Land.
2. Archaean or mixed Archaean/Proterozoic areas with strongly polyphase histories in which the early record is partially to largely obscured as a result of overprinting by younger tectonic events, for example at 1100-930 Ma or 600-500 Ma or in both of these episodes. The key areas or terranes that fall into this category are the Ruker Terrane of the Southern Prince Charles Mountains, the Rauer Terrane of Prydz Bay, and the eastern margins of the Napier Complex.
3. Proterozoic terrains that largely preserve Mid- to Neoproterozoic histories (1400-930 Ma) only affected by minor or limited overprinting in younger (e.g. 550-500 Ma) events. These are grouped into three broad provinces - the Maud (Dronning Maud Land), Rayner (Enderby, Kemp and Macdonald Lands) and Wilkes (Wilkes Land coast) provinces.
4. Regions that preserve evidence for extensive Pan-African high-grade metamorphism, magmatism and deformation at times within the broad interval 650-500 Ma. Of course, these may also preserve evidence for metamorphism and deformation events that pre-date their main tectonism. The four regions in this category are the Dronning Maud Land belt, the Lützow-Holm belt, the Prydz Bay belt and the Denman Glacier belt.

## **2.1. Archaean Terrains/ Domains with Limited or Negligible Later Overprints**

### **2.1.1. The Grunehogna Craton, Dronning Maud Land**

On the far western side of the EAS a small area of 3000 Ma granitic basement that crops out in west Dronning Maud Land is termed the Grunehogna Craton (Gr, Fig. 2), interpreted to be a fragment of the Kalahari Craton of southern Africa that has accidentally been left attached to East Antarctica (Jacobs et al., 1993; Grantham et al., 1995). This Archaean basement is overlain by 1100-1000 Ma shelf or platform sediments and volcanics of the Ritscherflya Supergroup and intruded by 800 Ma mafic sills.

### **2.1.2. The Archaean Napier Complex, Enderby Land**

A major Archaean terrain, the Napier Complex (N, Fig. 2) occurs in Enderby Land, approximately south of Madagascar. This is a remarkable and unique ultrahigh temperature metamorphic complex that records the highest grades of metamorphism seen in rocks of any continental crust. The ancient precursors of granitic and tonalitic gneisses locally range in age up to 3800 Ma (Harley & Black, 1997), and hence are the

oldest rocks recognized from Antarctica. However, the dominant granulite facies orthogneisses were derived from the metamorphism of somewhat younger, 2980-2850 Ma granites and granodiorites (Sheraton et al., 1987; Harley & Black, 1997). These, the more ancient precursors, and gneisses derived from sedimentary and volcanic protoliths (supracrustals), were strongly deformed and interleaved under ultrahigh temperature metamorphic conditions in the late Archaean. The more homogeneous orthogneiss units are collectively referred to as the Raggatt Series, and the well-layered probable supracrustal units as the Tula Series (e.g. Sheraton et al., 1980). A strong and pervasive flat-lying gneissic fabric and early isoclinal folds are refolded and reoriented about several later phases of folds and high-strain zones, so that original relationships between the units are obscured and almost all fabrics are layer-parallel.

The Napier Complex is regarded as the best example of ultrahigh temperature (UHT) crustal metamorphism worldwide. The lithological diversity in the Tula Series, which includes mafic pyroxene granulites, metamorphosed ironstones and magnetite-quartz rocks, pelites and both Fe- and Mg-rich metaquartzites, has enabled the formation of spectacular minerals such as sapphirine, Al-rich orthopyroxene, Mg-rich garnet and pigeonite in the metamorphic rocks (Ellis et al., 1980; Grew, 1980). These indicate that Archaean metamorphism at 1050-1120°C at depths of 24-40 km in the crust was followed by long-lived cooling at considerable depths (20-30 km) into the Proterozoic (Harley & Motoyoshi, 2000; Hokada, 2001). The age of this UHT metamorphism is controversial, and estimates now range between 2840 Ma and 2530-2480 Ma (Harley & Black, 1997; Grew et al., 1998). Some workers infer a multi-event history, with more than one metamorphic event, but there is general agreement that all the pervasive high-grade deformation and UHT metamorphism was complete by the end of the Archaean. Mafic dyke swarms intruded the Napier Complex in the Proterozoic, and steep shear zones and high-strain zones of Grenvillian (ca. 1000 Ma) and probably Cambrian age also cut and offset the Archaean gneisses (Harley, 1985; Sheraton et al. 1987, Sandiford, 1985).

### **2.1.3. The Archaean Vestfold Block, Prydz Bay**

The Vestfold Hills (V, Fig. 2) is an orthogneiss-dominated granulite terrain that experienced its main magmatic accretion events and crust formation in the time interval 2520-2480 Ma (Black *et al.*, 1991). An older (2520-2000 Ma) group of tonalitic orthogneisses and pyroxene granulites, and supracrustal rocks including metavolcanics, Fe-rich semipelitic and quartzitic sediments and unusual Mg-Al rich claystones, underwent high-grade metamorphism and intense deformation prior to 2500 Ma (Snape et al., 1997). The intrusion and subsequent deformation of a varied group of granitic to gabbroic magmatic rocks, the 2500-2480 Ma Crooked Lake Gneisses, then followed. Granulite facies metamorphism at 800-900°C and depths of 16-24 km was broadly contemporaneous with the main magmatism and complete by the earliest Proterozoic (2470 Ma). The gneiss complex was exhumed to within 12 km of the Earth's surface shortly afterwards, by 2460 Ma, and cut by mylonites, pseudotachylites and shear zones and intruded by extensive dyke swarms and larger igneous complexes at various times in the Proterozoic (e.g. >2470, 2240, 1754, 1380 and 1241 Ma: Lanyon et al., 1993). The relatively rapid cooling of this terrane, and its lack of high-grade overprinting later in the Proterozoic and Pan-African, are confirmed by Archaean to early Proterozoic

cooling ages (2460 Ma) even in gneisses affected by later retrogression.

#### **2.1.4. Archaean in the Denman Glacier / Obruchev Hills Area**

In the Denman Glacier region (DG, Fig. 2) granitic and tonalitic orthogneiss precursors with ages between 3000 and 2640 Ma have been recorded, and a granulite facies metamorphic event proposed at 2890 Ma (Black et al., 1992). However, the overall geological setting and deformational history of these ancient gneisses, which are intruded by 515 Ma syenites and granites, are not yet known.

#### **2.1.5. The Archaean to Palaeoproterozoic Mawson Block, Adelie Land**

A major region of recognized Archaean-Proterozoic complexity is the “Mawson Block” of Adelie Land and other areas on the eastern fringe of the EAS (TA, Fig. 2; Peucat et al., 1999). This region is correlated with the Gawler Craton and adjacent areas of Australia, and also correlates with age-event features in the Nimrod Group of the Miller Range in central Trans Antarctic Mountains (Mi, Miller: Fig. 1; Goodge et al. 2001). The basement geology in the Terre Adélie region includes vestiges of 3050-3150 gneisses and 2560-2450 Ma supracrustals that were metamorphosed in the earliest Proterozoic (2440 Ma). Pelites, greywackes and volcanics were deposited later, probably in a rift environment, between 1775 and 1700 Ma. These younger units were then metamorphosed at 1710-1690 Ma to high grades (5-6.5 kbar and 700-750°C) in the west of the region and mainly to greenschist and amphibolite grades in the east.

The 1710-1690 Ma Kimban tectonothermal event in the higher-grade domain involved extensive melting of cordierite-bearing pelites, accompanied by early recumbent folding and shearing that reflect north-south extension related to horizontal flattening (Peucat et al. 1999). The resulting flat-lying fabrics are variably overprinted by sub-vertical high-grade shears and coeval melt veins that in some areas dominate the final structure (Peucat et al. 1999). In lower-grade areas this event is manifested only in minor magmatism and localised retrograde schist zones. The overall Palaeoproterozoic evolution of the Terre Adélie area is considered to reflect a rapid cycle of sedimentation and high-temperature, low-pressure metamorphism in response to lithospheric thinning without any significant prior crustal thickening (Peucat et al. 1999). This style of metamorphism differs from that recorded in the Nimrod Group of the Miller Range of the central Trans Antarctic Mountains, where Goodge et al. (2001) have identified eclogite facies metamorphism of comparable age (1700 Ma).

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### **Biographical Sketch**

**Simon Harley** is originally from Australia and received his PhD at the University of Tasmania. He is now a full professor in the geology department at Edinburgh University where he teaches metamorphic petrology. His principle research interests lie in deep-crustal high-grade metamorphism, in mineral-fluid melt interactions in the deep crust and in tectonic models of crustal evolution. He has a long-standing involvement with the geology of Antarctica where he has spent many field seasons.