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Multiple thermal events recorded in metamorphosed carbonate and associated rocks from the southern Austkampane region in the Sør Rondane Mountains, East Antarctica: A protracted Neoproterozoic history at the Gondwana suture zone

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ABSTRACT

This paper provides a detailed analysis of the geological evolution of the southern Austkampane region in the Sør Rondane Mountains, Antarctica, using geological and petrographical observations, geochemical, geochronological, radiogenic, and stable isotopic data, and metamorphic petrological techniques. The study area is dominated by felsic gneisses intercalated with mafic and carbonate rocks. Carbonate rocks include several calc-silicate and mafic to ultramafic blocks with carbonatite-like characteristics. The new data presented here indicate the presence of five important thermal events in the geological history of the region, at c. 1060, 770–750, 655–635, 560–545, and <545 Ma. The c. 1060 Ma event is characterized by granitic volcanic arc magmatism, possibly in an active continental margin setting, involving magmas that may have been sourced from enriched mantle formed by subduction of older crustal material during the formation of Rodinia. The oldest $T_{(DM)}$ age for this suite is 3.4 Ga. The 770–750 Ma event is characterized by both mafic and felsic magmatism in an active continental margin setting, with magmas being similar to bulk earth composition. The 655–635 Ma thermal event is represented by granulite-facies metamorphism along an anticlockwise pressure–temperature path, involving heating of the lower crust at a continental margin, and subsequent obduction of a cratonic counterpart during collision. Granitic and basaltic magmatism at 560–545 Ma is also associated with retrograde metamorphism and hydration-related partial melting of marble. The carbonate melt, and granitic and basaltic magmas during this event coexisted with each other and formed metasomatic calc-silicates and hornblendites, respectively. The final event at <545 Ma is characterized by the intrusion of an undeformed quartz syenite dyke, which may be related to either (1) collision and melting of preexisting lower crustal material, or (2) melting of slightly enriched mantle material in an extensional tectonic setting following the earlier collisional event. The five thermal events between c. 1100 and 500 Ma recognized in this study from a narrow region of the Sør Rondane Mountains, suggest that a combination of geochronological, whole-rock, and isotope geochemical analyses of metamorphic rocks and the pressure–temperature evolution could constrain the processes that operated during the amalgamation and break-up of Rodinia and the formation of Gondwana. A similar approach is essential in neighboring Gondwana terranes for modeling the protracted events of Neoproterozoic orogenesis.

1. Introduction

Gondwana is relatively well studied compared with other supercontinents known to have formed in the Earth's history. Although several models that address the formation of Gondwana have been proposed (e.g., Jacobs et al., 2003a,b; Meert, 2003; Grantham et al., 2008; Boger, 2011), the details of the amalgamation of this supercontinent still remain controversial, most probably because these models are primarily based on dating of igneous and metamorphic rocks. Although geochronology can provide useful constraints on the timing of igneous and metamorphic activity, and enables the linking of individual terranes within a single orogenic belt, a combination of geochemical and isotopic data with metamorphic

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characterization is more likely to provide critical insights into the tectonic evolution of an area. Several key facts about the formation of Gondwana remain unknown including the number of thermal events that occurred, the tectonic settings of the periods before continental collision, and how continental crust was subducted, obducted, and exhumed during these periods.

The Sør Rondane Mountains (22°–28°E, 71.5°–72.5°S) of eastern Dronning Maud Land, East Antarctica, are considered a prime example of a metamorphic and igneous terrane within one of the Gondwana suture zones. In two major models, these mountains either represent the collision zone between East and West Gondwana (i.e., the East African Antarctic Orogen (EAAO); Jacobs et al., 2003a,b; Fig. 1a), or were formed as part of the Kuunga Orogen (Meert, 2003; Fig. 1b) that developed after the main Pan-African collision. This indicates that the Sør Rondane Mountains are located in a paleogeographically important position and, as such, studying this area is an important step in understanding the formation and growth of the Gondwana supercontinent.

A significant amount of geochronological research has been undertaken on igneous and metamorphic rocks in the Sør Rondane Mountains. Recently, Shiraishi et al. (2008) summarized this research, which identified five thermal events at c. 1130, 1000, 800, 650–600, and 570–500 Ma. The earliest thermal events are considered to be magmatic, with the three later events interpreted as periods of magmatism and metamorphism, primarily based on zircon zoning textures. However, detailed major, trace, and rare earth element (REE) geochemical analysis, isotopic geochemical studies, and characterization of the metamorphic pressure–temperature (*P–T*) evolution of the area have not as yet been undertaken on dated samples. This means that the tectonic setting of each thermal event is not well understood so far. In this study, we provide a detailed description of the regional geology of the southern Austkampane area of the central Sør Rondane Mountains, where all the major rock types of the overall region (felsic gneisses, amphibolites, marbles, calc-silicate rocks, and granitic dikes) are exposed. We also present geochemical, isotopic, metamorphic petrological, and geochronological data for all major lithologies, which provide important information on the tectonic setting of individual thermal events from 1100 to 500 Ma in the study area. The findings provide a valuable resource for improving our understanding of the formation of the Sør Rondane Mountains during the amalgamation of Gondwana.

2. Geological outline and mode of occurrences

The Sør Rondane Mountains are dominated by medium- to high-grade metamorphic rocks and a variety of granitoid intrusions (Fig. 1c). The mountains are divided into NE and SW terranes, separated by the Main Tectonic Boundary (MTB, Fig. 1c; see Osanai et al., 2013). These terranes underwent metamorphism along different metamorphic *P–T* paths during their formation (Osanai et al., 2013). The NE terrane is dominated by typical granulite-facies rocks with clockwise *P–T* paths. On the other hand, anticlockwise *P–T* path has been identified from the northeastern part of the SW terrane (Brattnipene region; Adachi et al., 2012; Baba et al., 2013). Granulite-facies rocks from both terranes contain zircons with c. 650 Ma metamorphic overgrowths (Shiraishi et al., 2008). The southwestern part of the SW terrane (units C, D, and D' in Fig. 1c) contains granite and amphibolite- to greenschist-facies metamorphic rocks that yield 570–550 Ma metamorphic ages (Shiraishi et al., 2008). A detailed geological overview is provided by Osanai et al. (2013).

The dominant rock types in granulite facies regions are hornblende–biotite ± orthopyroxene, and garnet–biotite ± hornblende ± orthopyroxene felsic gneisses. Metamorphosed mafic rocks, such as amphibolites and hornblende-bearing mafic granulites, marbles, and pelitic and calc-silicate rocks are common as layers within these felsic gneisses. The degree of hydration during retrograde metamorphism controlled the presence or absence of orthopyroxene in felsic gneisses and amphibolites (Adachi et al., 2010). The *P–T* conditions of metamorphism in the NE terrane have been estimated in previous studies (e.g., Asami et al., 1992, 2007; Ishizuka et al., 1996), with the highest *P–T* conditions being 860–895 °C at pressures of 12 kbar, as determined from a sapphirine- and kyanite-bearing aluminous granulite within the Balchenfjella region of the NE terrane (Asami et al., 2007) and 850–900 °C at 8–9 kbar from sillimanite–orthopyroxene–garnet granulite in Brattnipene region of SW terrane (Baba et al., 2013).

The southern Austkampane area, the focus of this study, contains rocks that are typical of the Sør Rondane Mountains, with felsic gneisses dominating the geology of the area (Fig. 1d). These gneisses do not contain migmatitic structures, and are often interlayered with mappable- and unmappable-scale amphibolites, marbles, and calc-silicate rocks (Fig. 2a–c). These metamorphic rocks are intruded by both deformed and undeformed granitoids (Fig. 2b). Marbles in this area contain unusual blocks of calc-silicate and mafic to ultramafic rocks (Fig. 2a and d–f). These calc-silicate blocks are commonly rounded or vermicular (Fig. 2a), and range from a few centimeters to a meter in size (Fig. 2a). The rounded mafic blocks are also commonly larger than the calc-silicate blocks, with sizes ranging from 20 cm to a few meters in diameter (Fig. 2d and e). Ultramafic blocks in the area are generally composed of olivine or serpentine. They are rounded and are generally small, varying up to 15 cm in diameter (Fig. 2f). These features suggest that carbonates in the study area may be carbonatites and have a magmatic origin. Carbonatites are generally considered to form during partial melting of a carbonated mantle peridotite (e.g., Dalton and Wood, 1993; Harmer and Gittins, 1998; Zhang et al., 2007). This indicates that the presence of these carbonate rocks (note that here we use the term “carbonate rock” for rocks previously described as “marble”) may provide significant information on the tectonic setting of this region. In this paper, we focus on carbonate genesis and associated rock types within the Sør Rondane Mountains. The samples were obtained from three localities in the southern Austkampane area (Fig. 1d); major lithology of sample localities and analyzed samples are listed in Table 1.

3. Petrography

3.1. Carbonate rocks

Carbonate rocks are commonly not pure carbonate and contain calcite, dolomite, olivine, spinel, phlogopite, graphite, and sulfide (Fig. 3a), with modal mineralogical proportions varying considerably between samples. Olivine and spinel are rounded and spinel commonly includes (Fe, Mg)TiO_3 needles (Fig. 3b). Olivine in the carbonate rocks is occasionally surrounded by rims of clinopyroxene, with anhedral phlogopite occurring along grain boundaries with calcite, dolomite, olivine, and spinel.

3.2. Calc-silicate blocks

The calc-silicate blocks are massive and do not have a gneissic fabric. They commonly contain clinopyroxene, scapolite, wollastonite, phlogopite, titanite, and apatite (Fig. 3c and d). Plagioclase and calcite are also present in some samples. All mineral phases are anhedral, especially scapolite and plagioclase, which occur as interstitial phases between clinopyroxene and wollastonite (Fig. 3a and b). The modal proportions of clinopyroxene, scapolite, and wollastonite vary from sample to sample.