Multiple timings of garnet-forming high-grade metamorphism in the Sør Rondane Mountains, East Antarctica

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Many recent studies focus on Gondwana reconstructions in Dronning Maud Land, East Antarctica, in order to understand the temporal and spatial assemblage of continental fragments during Late Proterozoic-Early Paleozoic orogenic belts (e.g., Fitzsimons, 2000a, b; Shiraishi et al., 2008; Osanai et al., 2013; Jacobs et al., 2015; Elburg et al., 2016; Kitano et al., 2016; Ruppel et al., 2020). Among the several amalgamation models proposed recently, the Sør Rondane Mountains (SRM) is interpreted to be one of the key areas where two orogens crossed (e.g., Satish-Kumar et al., 2013 and references therein); the East African-Antarctic Orogen at ca. 750-620 Ma (EAAO; Jacobs et al., 2003; Jacobs and Thomas, 2004) and the Kuunga Orogen at ca. 570-530 Ma (Meert, 2003). In the SRM, the Northeastern-terrane (NE-terrane) and the Southwestern-terrane (SW-terrane) are considered to have collided at 650-600 Ma during which the thrust-up movement of the NE-terrane took place over the SW-terrane (Osanai et al., 2013). Osanai et al. (2013) suggested that the timings of peak metamorphism (650-600 Ma) and retrograde metamorphism under andalusite-stability field (590-530 Ma) are simultaneous in the NE- and SW-terranes. The previous studies mainly used separated zircon grains, and mainly used Th/U ratio to discriminate metamorphic zircon domains. In order to understand the tectonic evolution in the SRM, however, it is important to precisely link zircon geochronology with metamorphic events. Distribution coefficient of rare earth elements (D_{REE}) between zircon and garnet is a useful tool to evaluate equilibrium zircon-garnet pairs (e.g., Harley et al., 2001; Rubatto, 2002; Taylor et al., 2017). However, only limited number of previous studies examined D_{REE} between zircon and garnet in the SRM (e.g., Hokada et al., 2013), and limited number of studies performed *in situ* zircon dating as well (e.g., Higashino et al., 2013; Higashino et al., 2015; Kawakami et al., 2017). In this study, therefore, taking the microstructural constraints into account, the D_{REE} between zircon and garnet and *in situ* U-Pb dating of zircon are utilized in order to reliably determine the timing of garnet-forming metamorphism in selected regions of the SRM.

Seven samples of pelitic and mafic gneisses are selected from both the NE- and SW-terranes in the SRM. By comparing D_{REE} between zircon and garnet with published equilibrium D_{REE} values between these minerals (Taylor et al., 2017), garnet-zircon equilibrium pairs are recognized in five samples from Balchenfjella, Perlebandet, Brattnipene, and Pilten. In addition, *in situ* U-Pb zircon ages are obtained from the same zircon domains as REE analysis, in order to constrain the timing of garnet-zircon equilibrium/disequilibrium. As a result, in the NE-terrane (Balchenfjella), garnet core and garnet rim from Bt-Grt gneiss are considered to be in equilibrium with zircon, and the timing is constrained to be ca. 560 Ma. The garnet core from Grt-Bt-Sil gneiss is also evaluated to be in equilibrium with zircon at ca. 600 Ma. In the SW-terrane, on the other hand, timing of garnet formation in equilibrium with zircon is constrained to be ca. 580 Ma for garnet overgrowing sillimanite from Grt-Sil-Bt gneiss (Perlebandet), ca. 620 Ma for garnet core in the wall rock of Grt-Opx-Hbl gneiss cut by Grt-Hbl selvage (Brattnipene), and ca. 550 Ma for garnet core from Grt-Bt gneiss (Pilten). In some samples, timing of garnet rim formation in equilibrium with zircon is not constrained. This is because zircon rim was too thin for REE analysis. Therefore, there is a possibility that the unanalyzed thin zircon rims could be an equilibrium counterpart of the garnet rims.

Garnet-forming metamorphism occurred at 620-550 Ma in the SRM. This is simultaneous with the timing of Kuunga orogeny and the final stage of EAAO. The garnet-forming ages of < 600 Ma are recognized in both the NE- and SW-terranes. The timing of garnet-forming metamorphism can be interpreted as that of the peak or near-peak metamorphism. The peak metamorphic ages of < 600 Ma are not consistent with the previous tectonic model of the SRM based on peak metamorphism at 650-600 Ma (Osanai et al., 2013). In addition to the NE- and SW-terranes, smaller blocks with different metamorphic history are likely. Such young metamorphic ages (< 600 Ma) are previously reported elsewhere in the SRM (e.g., Shiraishi et al., 2008; Adachi et al., 2013; Grantham et al., 2013; Higashino et al., 2013). Constraining the *P-T-t* paths of the metamorphic rocks having different metamorphic timings is indispensable to further discuss the tectonic evolution of the SRM.

References

Adachi, T., Osanai, Y., Hokada, T., Nakano, N., Baba, S., Toyoshima, T. (2013). Timing of metamorphism in the central Sør Rondane Mountains, eastern Dronning Maud Land, East Antarctica: Constrains from SHRIMP zircon and EPMA monazite dating. Precambrian Research, 234, 136-160.

Elburg, M.A., Andersen, T., Jacobs, J., Läufer, A., Ruppel, A., Krohne, N., Damaske, D. (2016). One hundred and fifty million years of intrusive activity in the Sør Rondane Mountains (East Antarctica): Implications for Gondwana Assembly. Journal of Geology 124, 1-26.

Fitzsimons, I.C.W. (2000a). Grenville-age basement provinces in East Antarctica: evidence for three separate collisional orogens. Geology 28, 879-882.

Fitzsimons, I.C.W. (2000b). A review of tectonic events in the East Antarctic Shield and their implications for Gondwana and earlier supercontinents. Journal of African Earth Sciences 31(1), 3-23.

Grantham, G. H., Macey, P. H., Horie, K., Kawakami, T., Ishikawa, M., Satish-Kumar, M., Tsuchiya, N., Graser, P., Azevedo, S. (2013). Comparison of the metamorphic history of the Monapo Complex, northern Mozambique and Balchenfjella and Austhameren areas, Sør Rondane, Antarctica: Implications for the Kuunga Orogeny and the amalgamation of N and S. Gondwana. Precambrian Research, 234, 85-135.

Harley, S.L., Kinny, P.D., Snape, I., Black, L.P. (2001). Zircon chemistry and the definition of events in Archaean granulite terrains. In: Cassidy, K.F., Dunphy, J.M., van Kranendonk, M.J. (Eds.), Extended Abstracts of 4th International Archaean Symposium. AGSO-Geoscience Australia Record 2001/37, Canberra, pp. 511–513.

Higashino, F., Kawakami, T., M. Satish-Kumar, Ishikawa, M., Maki, K., Tsuchiya, N., Grantham, G.H., Hirata, T. (2013). Chlorine-rich fluid or melt activity during granulite facies metamorphism in the Late Proterozoic to Cambrian continental collision zone- An example from the Sør Rondane Mountains, East Antarctica. Precambrian Research 234, 229-246.

Higashino, F., Kawakami, T., Tsuchiya, N., Satish-Kumar, M., Ishikawa, M., Grantham, G.H., Sakata, S., Hattori, K., Hirata, T. (2015). Geochemical behavior of zirconium during Cl-rich fluid or melt infiltration under upper amphibolite facies metamorphism – A case study from Brattnipene, Sør Rondane Mountains, East Antarctica. Journal of Mineralogical and Petrological Sciences 110, 166-178.

Hokada, T., Horie, K., Adachi, T., Osanai, Y., Nakano, N., Baba, S., Toyoshima, T. (2013). Unraveling the metamorphic history at the crossing of Neoproterozoic orogens, Sør Rondane Mountains, East Antarctica: Constraints from U-Th-Pb geochronology, petrography, and REE geochemistry. Precambrian Research 234, 183-209.

Jacobs, J., Thomas, R.J. (2004). Himalayan-type indenter-escape tectonics model for the southern part of the late Neoproterozoic-early Paleozoic East African-Antarctic orogeny. Geology 32, 721-724.

Jacobs, J., Bauer, W., Fanning, C.M. (2003). Late Neoproterozoic/Early Paleozoic events in central Doronning Maud Land and significance for the southern extension of the East African Orogen into East Antarctica. Precambrian Research 126, 27-53.

Jacobs, J., Elburg, M., Läufer, A., Kleinhanns, I.C., Henjes-Kunst, F., Estrada, S., Ruppel, A.S., Damaske, D., Montero, P., Bea, F. (2015). Two distinct Late Mesoproterozoic/Early Neoproterozoic basement provinces in central/eastern Dronning Maud Land, East Antarctica: The missing link, 15-21ºE. Precambrian Research 265, 249-272.

Kawakami, T., Higashino, F., Skrzypek, E., Satish-Kumar, M., Grantham, G., Tsuchiya, N., Ishikawa, M., Sakata, S., Hirata, T. (2017). Prograde infiltration of Cl-rich fluid into the granulitic continental crust from a collision zone in East Antarctica (Perlebandet, Sør Rondane Mountains). Lithos 274-275, 73-92.

Kitano, I., Osanai, Y., Nakano, N., Adachi, T. (2016). Detrital zircon provenances for metamorphic rocks from southern Sør Rondane Mountains, East Antarctica: A new report of Archean to Mesoproterozoic zircons. Journal of Mineralogical and Petrological Sciences 111, 118-128.

Meert, J. (2003). A synopsis of events related to the assembly of eastern Gondwana. Tectonophysics 362, 1-40.

Osanai, Y., Nogi, Y., Baba, S., Nakano, N., Adachi, T., Hokada, T., Toyoshima, T., Owada, M., Satish-Kumar, M., Kamei, A., Kitano, I. (2013). Geologic evolution of the Sør Rondane Mountains, East Antarctica: Collision tectonics proposed based on metamorphic processes and magnetic anomalies. Precambrian Research 234, 8-29.

Rubatto, D. (2002). Zircon trace element geochemistry: partitioning with garnet and the link between U-Pb ages and metamorphism. Chemical Geology 184, 123-138.

Ruppel, A. S., Jacobs, J., Läufer, A., Ratschbacher, L., Pfänder, J. A., Sonntag, B.-L., Krasniqi, K., Elburg, M., Krohne, N., Damaske, D., Lisker, F. (2020). Protracted late Neoproterozic–early Palaeozoic deformation and cooling history of Sør Rondane, East Antarctica, from $^{40}Ar/^{39}Ar$ and U–Pb geochronology. Geological Magazine 1-21.

Satish-Kumar, M., Hokada, T., Owada, M., Osanai, Y., Shiraishi, K. (2013). Neoproterozoic orogens amalgamating East Gondwana: Did they cross each other?. Precambrian Research 234, 1-7.

Shiraishi, K., Dunkley, D. J., Hokada, T., Fanning, C. M., Kagami, H., Hamamoto, T. (2008). Geochronological constraints on the Late Proterozoic to Cambrian crustal evolution of eastern Dronning Maud Land, East Antarctica: a synthesis of SHRIMP U-Pb age and Nd model age data. Geological Society, London, Special Publications 308, 21-67.

Taylor, R.J.M., Clark, C., Harley, S.L., Kylander-Clark, A.R.C., Hacker, B.R., Kinny, P.D. (2017). Interpreting granulite facies events through rare earth element partitioning arrays. Journal of Metamorphic Geology 35(7), 759-775.