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Ultra-High Temperature (UHT) Metamorphism of the Napier Complex, East Antarctica

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ABSTRACT. The Archaean Napier Complex in Enderby Land, East Antarctica, preserves diagnostic mineral assemblages including sapphirine + quartz, orthopyroxene + sillimanite + quartz, spinel + quartz and osumilite-bearing assemblages in metapelitic rocks and meta-quartzite. These mineral assemblages invariably suggest ultra-high temperature (UHT) condition as high as 1000°C, or even higher, in the middle to lower crust. Occurrences of inverted pigeonite, mesoperthitic alkali feldspar and recent finding of fluorine-rich phlogopite also support the UHT conditions. P-T trajectory of the Napier Complex is represented by a number of reaction textures suggesting a nearly apparent isobaric cooling. Meanwhile, a little information has been obtained on the prograde history. Geochronological studies suggest that the Napier Complex has undergone multi-stage metamorphic and igneous events between *ca.* 4.0 Ga and 0.5 Ga. It has been proposed that 2.8-2.9 Ga or 2.4-2.5 Ga indicate the age of the regional UHT metamorphism, but this problem has not been fixed yet. Intraplating of plutonic mass or crustal delamination, or a combination of both, is a possible tectonic model to explain the UHT conditions at the middle to lower crust.

Key Words: ultra-high temperature metamorphism, Napier Complex, Antarctica, Archaean, sapphirine, osumilite

Introduction

Extremely high temperature condition of metamorphism has recently been referred to as "ultra-high temperature (UHT) metamorphism" (*e.g.* Spear 1993; Harley 1998), and along with the ultra-high pressure (UHP) metamorphic rocks, they provide us with a new insight into the dynamic tectonics of continental crust.

The UHT metamorphism can be seen such metamorphic terranes over the world as in Canada, India, Algeria, Africa, Siberia and Scotland in addition to Antarctica (Harley 1998). In these terranes, the peak metamorphic temperatures exceeded 900°C at middle to lower crust.

In this paper, I review a metamorphic perspective of the Archaean Napier Complex as one of the typical examples of UHT metamorphic terrane, and discuss its significance with respect to crustal evolution.

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Geology

The Napier Complex is located in western Enderby Land and its distribution is approximately 60,000 km^2 (Fig. 1). It is surrounded by the Rayner Complex which is a Proterozoic lower granulite-facies metamorphic terrane. The Lützow-Holm Complex, an early to middle Cambrian metamorphic terrane (520-550 Ma, Shiraishi *et al.* 1994), is distributed to the west of the Rayner Complex.

The bed rocks are exposed as a number of steep nunataks, and they are separated by glacier and continental ice shelf from each other. The complex is composed mainly of felsic, basic and metapelitic gneisses together with subordinate meta-ultramafic

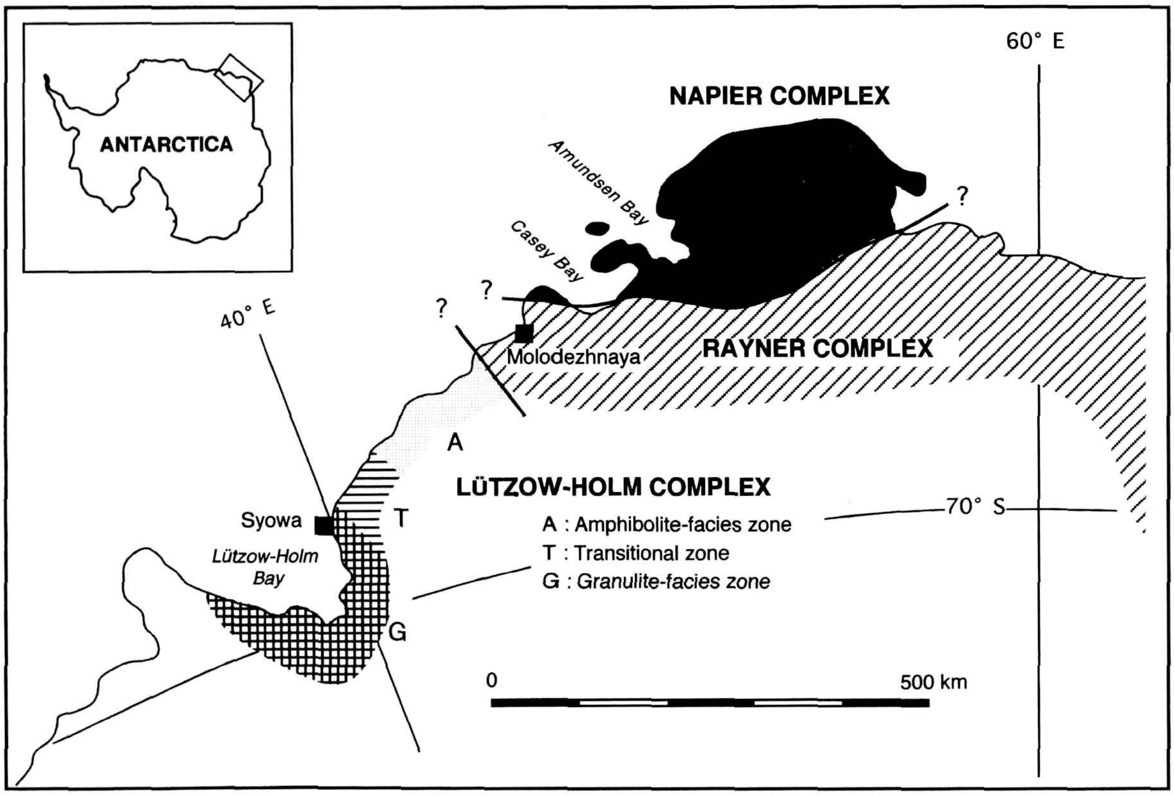

Fig. 1. Geological outline involving the Napier Complex and surrounding areas. The estimated boundary between the Napier and Rayner Complexes is after Sheraton *et al.* (1987). Metamorphic zonation of the Lützow-Holm Complex is after Hiroi *et al.* (1991).

rocks, meta-ironstones and local pegmatites. Calc-silicates are extremely rare. Non-metamorphosed dolerite dyke, which has been referred to as "Amundsen dyke" is observed locally. The Amundsen dyke has been dated to be 1.2 Ga (Sheraton and Black 1981). Because the Amundsen dyke has not been metamorphosed, the whole Napier Complex has already been cooled down at this stage. In spite of the UHT conditions, evidence for an extensive partial melting is not observed, probably due to extremely low water activity (Sheraton *et al.* 1980, 1987).

Mineralogical evidence for UHT conditions

Geothermobarometries do not play a major role in recovering the UHT conditions, as Fe-Mg exchange reactions, for example, still continue even during cooling, and they should only record "closure temperatures" of geothermobarometries rather than "peak metamorphic temperatures". In this chapter, I present mineralogical evidence for the UHT conditions.

Sapphirine + quartz, orthopyroxene + sillimanite + quartz and spinel + quartz assemblages

Since the first finding of sapphirine + quartz assemblage in meta-quartzite from Enderby Land (Dallwitz 1968), the Napier Complex has been considered to have undergone extremely high-temperature conditions of metamorphism (Grew 1980; Ellis *et al.* 1980; Sheraton *et al.* 1980, 1987; Harley and Hensen 1990, and references therein). Prior to that, sapphirine + quartz was produced by Hensen (pers. comm.) in his experimental runs at 9 kbar and 1100°C, and he predicted that natural sapphirine + quartz can be found in high-grade granulite-facies terrain. Such high temperature conditions are also supported by the occurrences of hypersthene + sillimanite + quartz and spinel + quartz assemblages in metapelites. In FMAS grid (Fig. 2), these mineral assemblages are stable at higher temperature conditions relative to garnet + cordierite + sillimanite

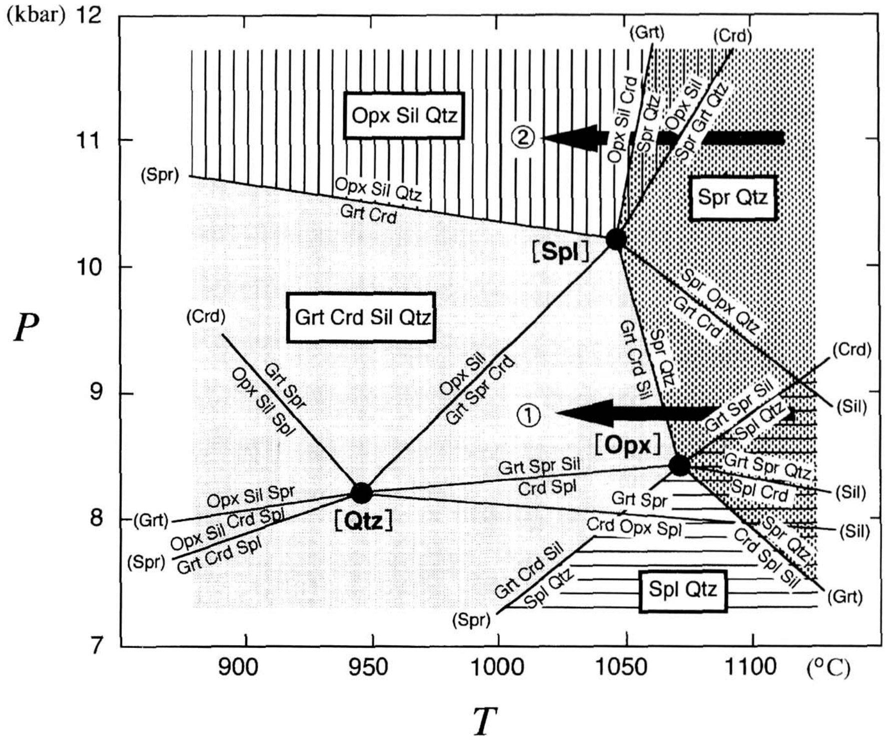

Fig. 2. Petrogenetic grid in the FMAS system (modified after Hensen and Harley 1990; Harley 1998). Sapphirine + quartz, orthopyroxene + sillimanite + quartz and spinel + quartz stability fields are all high-temperature side relative to garnet + cordierite assemblages. Solid arrows denote isobaric cooling P-T paths obtained from the northern part (1) and the southern part (2), respectively. Mineral abbreviations are after Kretz (1983). See text for details.

assemblages.

Osumilite

The occurrence of osumilite being associated with sapphirine-bearing assemblages has been one of the characteristic features of the Napier granulites. Osumilite was originally found in rhyodacite from the Osumi Peninsula, Kyushu, Japan (Miyashiro 1956). It was generally believed that osumilite was a high-T and low-P mineral. In late 1970's to early 1980's, osumilite has been reported from many granulite-facies terranes over the world, but due to the lack of thermodynamic data, the stability field of osumilite has been debated (Ellis *et al.* 1980; Grew 1982). Motoyoshi *et al.* (1993) conducted an experimental work on the stability of osumilite in KMAS system, and concluded that the petrogenetic grid proposed by Grew (1982) seemed to be more likely. That is, osumilite stability field is expanded to a lower temperature side beyond sapphirine + quartz stability field at middle crustal level. On the basis of the recent refinement of thermodynamic data by experimental works and theoretical considerations, more reliable petrogenetic grids involving osumilite and melt have been established (Carrington and Harley 1995a, b). These grids can be applicable to the Napier granulites, and have given constraints as to the maximum pressure conditions of UHT metamorphism, that is ~8 kbar at 950°C. It implies that the UHT metamorphism has taken place at middle to lower crustal level, rather than deep crust.

Inverted pigeonite

In meta-ironstones, distinctive lamellae textures are often observed in pyroxenes. Grew (1982), Sandiford and Powell (1986) and Harley (1987) pointed out that these lamellae have been formed through the breakdown of pre-existing pigeonite during cooling. It suggests a primary coexistence of orthopyroxene, clinopyroxene and pigeonite and an equilibrium temperature to be nearly 1000°C (Sandiford and Powell, 1986).

Fluorine phlogopite/biotite

Hydrous phases, such as micas and amphiboles, have been considered to be less significant in the

Napier granulites, as these minerals are not considered to be stable under the UHT conditions. If they are present, they will be a secondary phase due to hydration during cooling. However, some biotite grains do not look like secondary phases, then the chemical compositions were measured with an electron microprobe by using CaF_2 as the standard. They are turned out to be F-rich phlogopite with up to 8 wt% fluorine and little OH. On the basis of the recent experimental results, such high-F phlogopite can exist under 1000°C, or even higher (Peterson *et al.* 1991; Skjerlie and Johnston 1993; Hensen and Osanai 1994; Dooley and Patiño Douce 1996). Since F-bearing biotite is occasionally found as inclusions in orthopyroxene and osumilite, the reaction textures involving F-biotite suggests prograde metamorphic history of the Napier granulites. The formation of F-rich phlogopite/biotite under the UHT conditions is greatly concerned with the role and nature of metamorphic fluid during the UHT metamorphism.

Mesoperthite

Distinct lamellae textures are also observed in alkali feldspars in felsic and pelitic gneisses. By integrating the chemical compositions of exsolved lamellae and the host, the original composition of feldspar was obtained, and suggested a solvus temperature as high as 1050-1100°C (Hokada, unpublished).

P-T trajectory

With respect to the P-T trajectory for the Napier Complex, a number of reaction textures formed through cooling have been documented. They are as follows:

sapphirine + quartz = garnet + cordierite + sillimanite,

sapphirine + orthopyroxene + quartz = garnet + cordierite,

spinel + quartz = sapphirine + garnet + sillimanite,

sapphirine + quartz = orthopyroxene + sillimanite, and

orthopyroxene + sillimanite + quartz = garnet.

These reactions have been interpreted to suggest nearly isobaric cooling after the peak metamorphic conditions (Ellis 1980; Black *et al.* 1983; Ellis and Green 1985; Sandiford 1985; Harley 1983, 1985). In Fig. 2, possible P-T trajectories are illustrated; one is from a relatively low-pressure area, and the other is from a higher-pressure area of the Napier Complex. The rocks from both areas have been cooled as represented by solid arrows.

On the other hand, the prograde P-T trajectory has been little concerned as the UHT conditions are expected to promote reactions to completion and any traces of recrystallization have been "wiped out" easily. Ellis (1987) and Harley (1989) proposed "clockwise" trajectory, *i.e.* the Napier granulites have been subjected to very high pressure condition prior to the UHT event, based on the chemical characteristics of felsic gneisses with granitic compositions, which occur predominantly in the Napier Complex. On the contrary, Motoyoshi and Hensen (1989) proposed "counterclockwise" trajectory based on the interpretation of sapphirine + quartz symplectite which is chemically equivalent to cordierite. Prograde P-T trajectory of the Napier Complex has not been fixed yet, and further studies are needed.

Geochronology

The oldest ages yet reported from the Napier Complex are over 3900 Ma (3955 Ma, Williams *et al.* 1984; 3927 Ma, Black *et al.* 1986). The obtained ages so far are roughly classified into the following categories: *ca.* 4.0~3.7 Ga, 3.1~2.8 Ga, 2.5~2.4 Ga, 1.0 Ga and 0.5 Ga (Sheraton *et al.* 1987). Among them, 1.0 Ga and 0.5 Ga are related with local pegmatite activity, and other ages denote regional metamorphic and igneous events. Recent SHRIMP dating also reported wide range of ages 3840~2410 Ma (Harley and Black 1997). However, the age of the UHT event has not been specified yet. Harley and Black (1997) interpreted that UHT event occurred at 2.8 Ga, and that 2.4-2.5 Ga corresponds to the second event under lower temperature conditions. On the other hand, Grew and Manton (1979), Owada *et al.* (1994), Tainosho *et al.* (1994, 1997) and Asami *et al.* (1998) considered 2.4-2.5 Ga for UHT metamorphism. I also believe that UHT metamorphism occurred at 2.4-2.5 Ga, because zircon and monazite inclusions in osumilite yielded around 2.5 Ga by means of CHIME dating (Hokada, unpublished).

Mechanism of UHT metamorphism

Several lines of mineralogical and geochronological evidence have revealed that the Napier Complex has been subjected to UHT metamorphism, as high as 1000-1100°C, in Archaean. The origin of heat source to have generated such high-temperature conditions at middle to lower crust is still controversial. In view of the fact that the maximum pressure condition of the Napier Complex is up to 11 kbar, and the rocks have been cooled nearly isobarically after the peak metamorphic conditions, a huge plutonic intrusion, for example anorthositic mass in the mid to lower crust, may be responsible for the heat source as proposed by Grew (1980) and Hensen & Motoyoshi (1992). Crustal delamination is another possibility. One point we must note is that in order to achieve UHT metamorphism, the rocks of the Napier Complex had to be almost dry in advance, otherwise it should be melted to produce "igneous rocks" rather than "metamorphic rocks". In this respect, some melt-segregation processes are required to assume volatile-free environment. Or rather, the protoliths of the UHT metamorphic rocks have been already dehydrated due to an externally-derived water-free metamorphic fluid.

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References

Asami M., Suzuki K., Grew E.S., and Adachi M. 1998. CHIME ages for granulites from the Napier Complex, East Antarctica. *Polar Geoscience* **11:** 172-199, National Institute of Polar Research, Tokyo.

Black L.P., James P.R., and Harley S.L. 1983. Geochronology, structure, and metamorphism of early Archaean rocks at Fyfe Hills, Enderby Land, Antarctica. *Precambrian Research* **21:** 197-222.

Black L.P., Williams I.S., and Compston W. 1986. Four zircon ages from one rock: the history of a 3930 Ma-old granulite from Mount Sones, Antarctica. *Contributions to Mineralogy and Petrology* **94:** 427-437.

Carrington D.P. and Harley S.L. 1995a. Partial melting and phase relations in high-grade metapelites: an experimental petrogenetic grid in the KFMASH system. *Contributions to Mineralogy and Petrology* **120:** 270-291.

Carrington D.P. and Harley S.L. 1995b. The stability of osumilite in metapelitic granulites. *Journal of Metamorphic Geology* **13:** 613-625.

Dallwitz W.B. 1968. Coexisting sapphirine and quartz in granulites from Enderby Land, Antarctica. *Nature* **219:** 476-477.

Dooley D.F. and Patiño Douce A.E. 1996. Fluid-absent melting of F-rich phlogopite + rutile + quartz. *American Mineralogist* **81:** 202-212.

Ellis D.J. 1980. Osumilite-sapphirine-quartz granulites from Enderby Land, Antarctica: P-T conditions of metamorphism, implications for garnet-cordierite equilibria and the evolution of the deep crust. *Contributions to Mineralogy and Petrology* **74:** 201-210.

Ellis D.J. 1987. Origin and evolution of granulites in normal and thickened crusts. *Geology* **15:** 167-170.

Ellis D.J. and Green D.H. 1985. Garnet-forming reactions in mafic granulites from Enderby Land, Antarctica - implications for geothermometry and geobarometry. *Journal of Petrology* **26:** 633-662.

Ellis D.J., Sheraton J.W., England R.N., and Dallwitz W.B. 1980. Osumilite-sapphirine-quartz granulites from Enderby Land, Antarctica: mineral assemblages and reactions. *Contributions to Mineralogy and Petrology* **72:** 123-143.

Grew E.S. 1980. Sapphirine + quartz association from Archaean rocks in Enderby Land, Antarctica. *American Mineralogist* **65:** 821-836.

Grew E.S. 1982. Osumilite in the sapphirine-quartz terrane of Enderby Land, Antarctica: implications for osumilite petrogenesis in the granulite facies. *American Mineralogist* **67:** 762-787.

Grew E.S. and Manton W.I. 1979. Archean rocks in Antarctica: 2.5 billion-year uranium-lead ages of pegmatites in Enderby Land. *Science* **206:** 443-445.

Harley S.L. 1983. Regional geobarometry-geothermometry and metamorphic evolution of Enderby Land, Antarctica. *In: Antarctic Earth Science* (eds Oliver, R.L., James, P.R. & Jago, J.B.), 25-30, Australian Academy of Science, Canberra.

Harley S.L. 1985. Garnet-orthopyroxene bearing granulites from Enderby Land, Antarctica: metamorphic pressure-temperature-time evolution of the Archaean Napier Complex. *Journal of Petrology* **26:** 819-856.

Harley S.L. 1987. A pyroxene-bearing metaironstone and other pyroxene-granulites from Tonagh Island, Enderby Land, Antarctica: further evidence for very high temperature (> 980°C) Archaean regional metamorphism in the Napier Complex. *Journal of Metamorphic Geology* **5:** 341-356.

Harley S.L. 1989. The origin of granulites: a metamorphic perspective. *Geological Magazine* **126:** 215-247.

Harley S.L. 1998. On the occurrence and characterisation of ultrahigh-temperature (UHT) crustal metamorphism. *In: What Drives Metamorphism and Metamorphic Reactions?* (eds Treloar, P.J. & O'Brien, P.), 75-101, The Geological Soceity, London.

Harley S.L. and Black L.P. 1997. A revised Archaean chronology for the Napier Complex, Enderby Land, from SHRIMP ion-microprobe studies. *Antarctic Science* **9:** 74-91.

Harley S.L. and Hensen B.J. 1990. Archaean and Proterozoic high-grade terranes of East Antarctica (40-80°E): a case study of diversity in granulite faceis metamorphism. *In: High-temperature Metamorphism and Crustal Anatexis* (eds Ashworth, J. R. & Brown, M.), 320-370, Unwin Hyman, London.

Hensen B.J. and Harley S.L. 1990. Graphical analysis of P-T-X relations in granulite facies metapelites. *In: High-temperature Metamorphism and Crustal Anatexis* (eds Ashworth, J. R. & Brown, M.), 19-56, Unwin Hyman, London.

Hensen B.J. and Motoyoshi Y. 1992. Osumilite-producing reactions in high-temperature granulites from the Napier Complex, East Antarctica: tectonic implications. *In: Recent Progress in Antarctic Earth Science* (eds Yoshida, Y., Kaminuma, K. & Shiraishi, K.), 87-92, Terrapub, Tokyo.

Hensen B.J. and Osanai Y. 1994. Experimental study of dehydration melting of F-bearing biotite in model pelitic compositions. *Mineralogical Magazine* **58A:** 410-411.

Hiroi Y., Shiraishi K., and Motoyoshi Y. 1991. Late Proterozoic paired metamorphic complexes in East Antarctica, with special reference to the tectonic significance of ultramafic rocks. *In: Geological Evolution of Antarctica* (eds Thomson, M.R.A., Crame, J.A. & Thomson, J.W.), 83-87, Cambridge University Press, Cambridge.

Kretz R. 1983. Symbols for rock-forming minerals. *American Mineralogist* **68:** 277-279.

Miyashiro A. 1956. Osumilite, a new silicate mineral and its crystal structure. *American Mineralogist* **41:** 104-116.

Motoyoshi Y. and Hensen B.J. 1989. Sapphirine-quartz-orthopyroxene symplectites after cordierite in the Archaean Napier Complex, Antarctica: evidence for a counterclockwise P-T path? *European Journal of Mineralogy* **1:** 467-471.

Motoyoshi Y., Hensen B.J., and Arima M. 1993. Experimental study of the high-pressure stability limit of osumilite in the system K_2O-MgO-Al_2O_3-SiO_2: implications for high-temperature granulites. *European Journal of Mineralogy* **5:** 439-445.

Owada M., Osanai Y., and Kagami H. 1994. Isotopic equilibration age of Sm-Nd whole-rock system in the Napier Complex (Tonagh Island), East Antarctica. *Proceedings of the NIPR Symposium on Antarctic Geosciences* **7:** 122-132.

Peterson J.W., Chacko T., and Kuehner S.M. 1991. The effects of fluorine on the vapor-absent melting of phlogopite + quartz: implications for deep-crustal processes. *American Mineralogist* **76:** 470-476.

Sandiford M. 1985. The metamorphic evolution of granulites at Fyfe Hills: implications for Archaean crustal thickness in Enderby Land, Antarctica. *Journal of Metamorphic Geology* **3:** 155-178.

Sandiford M. and Powell R. 1986. Pyroxene exsolution in granulites from Fyfe Hills, Enderby Land, Antarctica: evidence for 1000°C metamorphic temperatures in Archaean continental crust. *American Mineralogist* **71:** 946-954.

Sheraton J.W. and Black L.P. 1981. Geochemistry and geochronology of Proterozoic thleiite dykes of East Antarctica: evidence for mantle metasomatism. *Contributions to Mineralogy and Petrology* **78:** 305-317.

Sheraton J.W., Offe L.A., Tingey R.J., and Ellis D.J. 1980. Enderby Land, Antarctica — an unusual Precambrian high-grade metamorphic terrain. *Journal of the Geological Society of Australia* **27:** 1-18.

Sheraton J.W., Tingey R.J., Black L.P., Offe L.A., and Ellis D.J. 1987. Geology of Enderby Land and western Kemp Land, Antarctica. *Bureau of Mineral Resources, Bulletin* **223:** 51p.

Shiraishi K., Ellis D.J., Hiroi Y., Fanning C.M., Motoyoshi Y., and Nakai Y. 1994. Cambrian orogenic belt in East Antarctica and Sri Lanka: implications for Gondwana assembly. *Journal of Geology* **102:** 47-65.

Skjerlie K.P. and Johnston A.D. 1993. Fluid-absent melting behavior of an F-rich tonalitic gneiss at mid-crustal pressures: implications for the generation of anorogenic granites. *Journal of Petrology* **34:** 785-815.

Spear F. 1993. *Metamorphic Phase Equilibria and Pressure-Temperature-Time paths.* Mineralogical Society of America, Washington, D.C., 799pp.

Tainosho Y., Kagami H., Hamamoto T., and Takahashi Y. 1997. Preliminary result for the Nd and Sr isotope characteristics of the Archaean gneisses from Mount Pardoe, Napier Complex, East Antarctica. *Proceedings of the NIPR Symposium on Antarctic Geosciences* **10:** 92-101.

Tainosho Y., Kagami H., Takahashi Y., Iizumi S., Osanai Y., and Tsuchiya N. 1994. Preliminary result for the Sm-Nd whole-rock age of the metamorphic rocks from Mount Pardoe in the Napier Complex, East Antarctica. *Proceedings of the NIPR Symposium on Antarctic Geosciences* **7:** 115-121.

Williams I.S., Compston W., Black L.P., Ireland T.R., and Foster J.J. 1984. Unsupported radiogenic Pb in zircon: a cause of anomalously high Pb-Pb, U-Pb and Th-Pb ages. *Contributions to Mineralogy and Petrology* **88:** 322-327.

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